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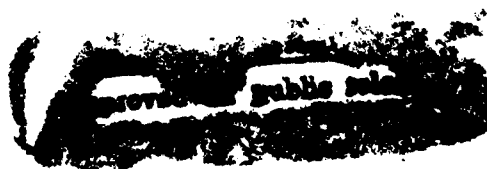
Management of Bottom Sediments
Containing Toxic Substances

Proceedings of the 15th U.S./Japan
Experts Meeting

Thomas R. Patin, Editor

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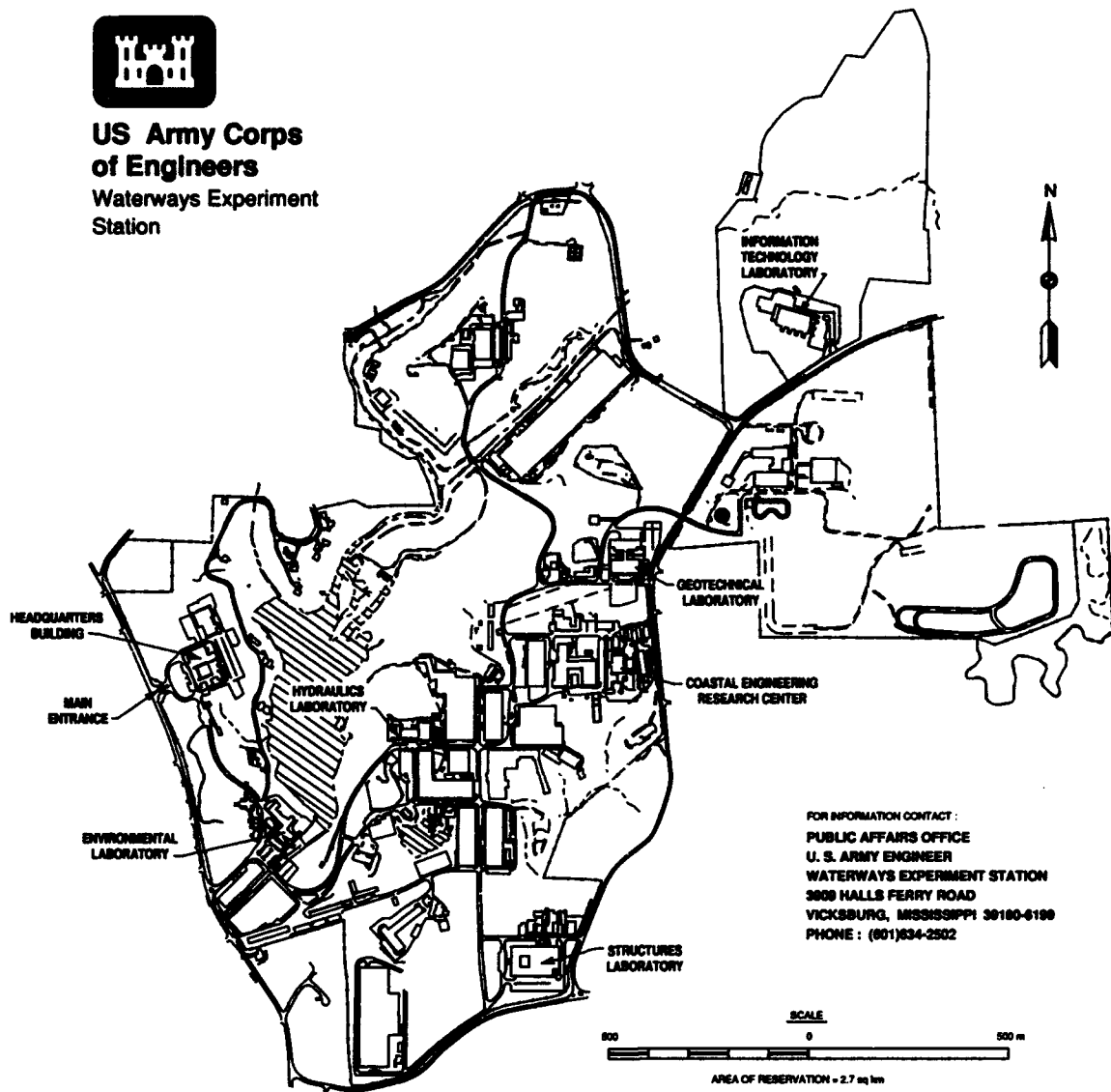
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May 1994

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VICKSBURG, MISSISSIPPI 39180-6199
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SCALE

500   0   500 m

AREA OF RESERVATION = 2.7 sq km

PREFACE

The 15th U.S./Japan Experts Meeting on Management of Bottom Sediments Containing Toxic Substances was held 19-21 November 1991 in San Pedro, California. The meeting is held annually through an agreement with the U.S. Army Corps of Engineers and the Japan Ministry of Transport to provide a forum for presentation of papers and in-depth discussions on dredging and disposal of contaminated sediment.

Mr. Jimmy Bates, Chief, Policy and Planning Division, Headquarters, U.S. Army Corps of Engineers, was the U.S. Chairman. Mr. Yasuhiro Kawashima, Director, Environment Division, Ports and Harbors Bureau, Ministry of Transport, was the Japanese Chairman.

Coordinator of the organizational activities was Mr. Paul Rub. U.S. Technical Topic organizer and editor of this report was Mr. Thomas R. Patin, program manager, Dredging Operations Technical Support Program (DOTS), U.S. Army Engineer Waterways Experiment Station (WES), Vicksburg, Miss.

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DELEGATES

15TH U.S./JAPAN EXPERTS MEETING ON MANAGEMENT
OF BOTTOM SEDIMENTS CONTAINING
TOXIC SUBSTANCES

Japanese Delegation

Yasuhiro Kawashima
  Co-chairman
	Director, Environment Division,
	  Ports and Harbors Bureau,
	  Ministry of Transport

Taizo Nakano	Port Development Department,
	  Comprehensive Planning Division,
	  Port and Harbor Bureau, Osaka City

Takeo Maekawa	Japan Dredging and Reclamation Engineering Association
Akira Teramoto	Japan Sediments Management Association
Hiroyuki Sakamoto	Japan Sediments Management Association
Makoto Natori	Supervisor, Experiment Group of Rikuzen Takata City
Hideo Hamabata	Japan Sediments Management Association
Yusuke Suda	Japan Sediments Management Association
Nobuaki Wada	Japan Sediments Management Association
Kiyoshi Nikaido	Japan Sediments Management Association
Mitsumasa Okado	Laboratory of Environmental Chemistry, Hiroshima University

U.S. Delegation

Jimmy F. Bates
  Co-chairman
	Chief, Policy and Planning Division,
	  Headquarters, U.S. Army Corps of
	  Engineers

Dwayne G. Lee	Port of Los Angeles

Norman R. Francingues, Jr.   U.S. Army Engineer Waterways
                                    Experiment Station

James Brannon   U.S. Army Engineer Waterways
                                    Experiment Station

Thomas Fredette   U.S. Army Corps of Engineers,
                                    New England Division

James Allen   U.S. Bureau of Mines

Jay Semmler   U.S. Army Corps of Engineers,
                                    Chicago District

Thomas Myers   U.S. Army Engineer Waterways
                                    Experiment Station

Steve Garbaciak   U.S. Environmental Protection
                                    Agency

AGENDA

15TH U.S./JAPAN EXPERTS MEETING ON MANAGEMENT
OF BOTTOM SEDIMENTS CONTAINING
TOXIC SUBSTANCES

San Pedro, California
19-21 November 1991

Co-Chairman

Mr. Yasuhiro Kawashima
Director, Environment Division
Ports and Harbors Bureau, Ministry of Transport

Mr. Jimmy Bates
Chief, Policy and Planning Division
Headquarters, U.S. Army Corps of Engineers

<u>Monday, November 18, 1991</u>

7:00-8:00 p.m.	Meeting of the Co-Chairmen at the Sheraton Los Angeles Harbor

<u>Tuesday, November 19, 1991</u>

8:00-8:30 a.m.	Arrival at Port of Los Angeles Administrative Building - Conference registrants package available
8:30-9:00 a.m.	Opening remarks: Mr. Yasuhiro Kawashima Opening remarks and introduction of Keynote Speaker: Mr. Jimmy Bates
9:00-9:30 a.m.	Keynote address by Dr. Tudor Davies, Director, Office of Science and Technology, U.S. Environmental Protection Agency, Washington, DC
9:30-9:45 a.m.	BREAK
9:45-10:25 a.m.	Mr. Dwayne G. Lee, "The Challenge of an Effective Marriage of Good Science and Good Policy"
10:25-11:05 a.m.	Mr. Taizo Nakano, "Improvements of Water and Bottom Sediment Quality in the Osaka Port Area by Removal of Accumulated Organic Sludge"
11:05-11:45 a.m.	Mr. Norman R. Francingues, Jr., "Technologies for Remediation of Contaminated Sediments in the Great Lakes"

11:45-12:00 a.m.	Transfer to Port of Los Angeles dock for afternoon tour
12:00-3:00 p.m.	Lunch and tour of the Ports of Los Angeles and Long Beach hosted by the Port of Long Beach
6:00-8:00 p.m.	Welcome reception hosted by the Port of Los Angeles at the Port of Los Angeles Administrative Building

Wednesday, November 20, 1991

8:00-8:40 a.m.	Dr. James M. Brannon, "Development of a Leaching Protocol for Evaluating Ground Water Impact From Contaminated Sediment"
8:40-9:20 a.m.	Mr. Takeo Maekawa, "Prediction of Surplus Water Density at Reclamation Site"
9:20-10:00 a.m.	Dr. Thomas Fredette, "A Summary of Recent Capping Investigations with Dredged Sediments in New England"
10:00-10:15 a.m.	BREAK
10:15-10:55 a.m.	Mr. Akira Teramoto, "The Development of a Clean and Dense Dredging System"
10:55-11:35 a.m.	Dr. James Allen, "Physical Separation Techniques for Contaminated Sediments"
11:35-12:15 p.m.	Mr. Hiroyuki Sakamoto, "Introduction of New Method of Disposing Dredged Muddy Soil Without Disturbing Marine Environment"
12:15-12:30 p.m.	Return to Sheraton Los Angeles Harbor Hotel
12:30-1:30 p.m.	Luncheon sponsored by the Western Dredging Association, National Association of Dredging Contractors, and Dredging Contractors Association of California
1:45-2:25 p.m.	Mr. Makoto Natori, "Restoration of Lakes and Marshes to Apply the Treatment of Bottom Sediments Using Bio-Reactors (Biotechnology)"
2:25-3:05 p.m.	Dr. James Brannon, "Assessing Volatile Organics From Highly Contaminated Sediments in Confined Disposal Areas"
3:05-3:15 p.m.	BREAK
3:15-4:00 p.m.	Mr. Hideo Hamabata, "Sea Blue Plan: A Case Study on the Port of Amagasaki-Nishinomiya-Ashiya"

4:00-4:40 p.m.   Mr. Yusuke Suda, "Sea Blue Plan: Experiment of Sea
                      Water Purification by Porous Bed Contact
                      Purification Method"

7:00-9:00 p.m.   Evening reception hosted by the Government of Japan

                      Thursday, November 21, 1991

8:30-9:10 a.m.   Mr. Nobuaki Wada, "Stabilizing Method by
                      Solidification for Dredged Bottom Sediments"

9:10-9:50 a.m.   Mr. Thomas Myers, "Solidification/Stabilization
                      Technology for Reducing the Mobility of Heavy Metals
                      in Polluted Sediments"

9:50-10:05 a.m.   BREAK

10:05-10:45 a.m.   Mr. Kiyoshi Nikaido, "Reforming Test on Dredged
                      Sediment With Polymer Solidifying Agent and a Study
                      of its Effectiveness"

10:45-11:25 a.m.   Mr. Steve Garbaciak, "Bench-Scale Evaluation for
                      Contaminated Sediments in the Great Lakes"

11:30-12:30 p.m.   LUNCH

12:45-1:25 p.m.   Dr. Mitsumasa Okada, "Origin and Transportation of
                      Air-Born Micropollutants into Bottom Sediments in an
                      Urban River"

1:30-2:30 p.m.   Closing remarks by Japanese and United States
                      Co-Chairmen

OVERVIEW OF US DREDGING PROGRAM

Jimmy F. Bates

Chief, Policy and Planning Division
Directorate of Civil Works
US Army Corps of Engineers
Washington, DC

As a brief introduction to the US technical papers, the focus in this country in terms of contaminated bottom sediments is still on problem identification, technology development (pilot field and laboratory studies, bench-scale modeling, and demonstrations), and predictive testing and related impact assessment methodologies.

With but few exceptions (i.e. capping), the implementation of actual remediation projects, while a reality for upland contamination problems for some years now, still awaits a better national definition of the scope and magnitude of the problem and, of course, adequate and appropriate funding sources. We do, however, anticipate a very significant project management need in future years in this area.

Examples of major accomplishments since our last meeting are:

- Pilot demonstration of clean-up technologies at New Bedford Harbor (Superfund Site). A number of technical reports on various aspects of that initiative are now available.

- Significant advances in developing innovative technologies and problem identification for contaminated sediments in the Great Lakes.

- The Corps of Engineers and the USEPA are in the midst of a broad initiative to revise and update our contaminant testing procedures for dredged sediments. Revised testing procedures for the ocean disposal program were published in the spring of 1991. A major joint initiative with EPA is now under way to appropriately revise our testing procedures for inland waters.

CHALLENGE OF AN EFFECTIVE MARRIAGE
OF GOOD SCIENCE AND GOOD POLICY

Dwayne G. Lee

Port of Los Angeles
P. O. Box 151, San Pedro, CA 90733-0151

ABSTRACT

In resolving a dredged disposal problem, good science
and good policy are responding to different concerns
and frequently their respective responses will con-
flict. A current case study demonstrating these con-
flicts is the on-going debate over the meaning of the
term "precautionary principle" as it applies to
dredging and dredged disposal. This debate clearly
highlights the science-policy dichotomy. While a com-
prehensive discussion of resolution of these conflicts
is not attempted, some general observations can be
made.

INTRODUCTION

Good morning, it is a pleasure for me to be here today. Let me say how
delighted we are at the Port of Los Angeles to be one of your hosts for this
meeting. My name is Dwayne Lee, and I am the Deputy Executive Director of
Development for the Port of Los Angeles. I also serve as the Chairman of the
Dredging Task Force for the International Association of Ports and Harbors and
represent them at the London Dumping Convention. It is in that capacity that
I am primarily associated with dredging issues from a policy perspective. The
views that I will express today are my own and do not necessarily reflect the
view of either the Port of Los Angeles or the International Association of
Ports and Harbors.

TEXT

What I would like to share with you today is my understanding and defi-
nition of a problem; provide you with a case study of a current issue working
in the international arena that serves as an excellent example of this chal-
lenge of marrying good science with good policy; and conclude with some gen-
eral observations. My discussion will definitely not be a comprehensive
treatment of this subject. It is intended to be a thought-piece to provide a
few ideas and stimulate additional thinking.

What is the problem as I see and understand it? First, let me talk
about good science. Good science, in my judgement, is the responsibility of
the scientist and the engineer. Although there is a difference between the
role of the scientist and the role of the engineer, in my discussion I incor-
porate both of those responsibilities under the term "good science". Given
the physical manifestations of nature or some natural process, science

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attempts to find answers to certain questions. Typical questions would include a determination of:

a. What do we know and what do we not know?

b. For those things that we do not know, what is the risk associated with the absence of that information?

c. What is the interrelationship of all of the physical variables associated with this natural process which I, the scientist, am investigating?

d. What are the forcing functions? What processes in nature are driving the physical phenomena that is being witnessed and experienced?

e. What are the cause and effect relationships among those variables that produce the necessary results?

Once the scientist has answered these questions, the results are passed to the engineer who then seeks to merge together all of the knowns to make some reasonable prudent assumptions about the unknowns and then seek the technique or process which will produce a solution yielding a desired result. Normally, that result will be some physical modification of an existing system. If you treat this whole endeavor by both the scientist and the engineer as some intellectual process, generally it must be repeated with each iteration producing an incrementally more effective solution than the last until some acceptable level of optimization is reached. That is my understanding and my definition of "good science".

Good policy, on the other hand, is the responsibility of the manager and the politician. Given the social-economic interactions among people, the policymaker attempts to answer a different set of questions similar to the following:

a. Which solutions will be acceptable to the political constituencies that are impacted and affected by this particular policy?

b. What is the cost effective solution to the business units involved?

c. And, perhaps most importantly, what is politically achievable? Given the political climate in which I now work and function and given the nature of this particular problem, politically what is the most I can expect to achieve and accomplish?

It has been my observation that the questions posed and answered by the scientist and engineer, when compared to the questions posed and answered by the manager and policymaker, often conflict with each other and thereby create a dynamic tension. The problem, therefore, is to find a good way to reconcile the differences in the conflicts.

A current case study that I am familiar with, that is working as we speak in the international dredging arena, has to do with an acceptable definition of the term "the precautionary principle." First, let me provide a definition of international environmental organizations, such as Greenpeace or

Friends of the Earth International. Friends of the Earth International has the following definition for "the precautionary principle":

> "The precautionary principle comprises the idea that no substance may be discharged into the marine environment as long as there exists uncertainties about the impact on the environment even if there is no scientific proof of possible harmful effects of these substances."

The definition as posed by Friends of the Earth needs to be taken in context of their particular agenda in the international dredging community. They are very open and up front in stating this as their particular goal. They are promoting industrial production technologies which are clean production systems, and I believe they would define clean as 100% so that, in effect, the industrial processes throughout the world that produce effluent or outflows would be such that the production process is 100% clean. Second, their desire is that there be no discharge of any man-made material or processes into the ocean waters. Finally, they desire, through this definition and approach of the precautionary principle, to shift the burden of proof for permitting a dredge disposal project. Currently, once an applicant demonstrates that no significant environmental damage will result from a dredged disposal project, his project is permitted to proceed. Some level of environmental impact is accepted and some areas where possible impacts cannot be scientifically established by a cause-and-effect relationship are not considered. At this point, an opponent to the project has the burden of proof to show, by scientific arguments, that significant environmental impacts do result from the project. Friends of the Earth would propose to shift that burden to the project sponsor who must now prove up front that there is no environmental damage nor uncertainty of any environmental damage. Even if there is no scientific proof of possible harmful effects, in the Friends of the Earth view, dredge disposal should then be prohibited. In their particular approach, policy is predominant to science. The policy makes science focus on the issue and presumes that that focus will ensure some answer will be found. To quote an American expression, "necessity becomes the mother of invention." I would call this an idealistic approach since the approach sets an unattainable goal with the intent of forcing science to rise to the occasion and find and develop the technology to meet that goal. It was this concept that was accepted by the Congress of the United States, for example, in regulating fuel consumption of automobile manufacturers in the 1970's by setting higher mile-per-gallon attainment targets for U.S. automobiles that was currently within the state-of-the-art at the time the law was passed. It was also accepted by the Congress with the adoption of the Clean Air Act amendments in 1990.

On the other hand, is the definition of the Group of Experts on the Scientific Aspects of Marine Pollution, or GESAMP for short, which is a United Nations organization of scientific experts tasked under U.N. authority, to look at the technical and scientific issues associated with various international problems. In their response to definitions of the precautionary principle similar to the Friends of the Earth, they have the following to say:

> "The concept of precaution is intrinsic to scientific prediction and allows the inherent uncertainties associated with scientific analysis and assessment to be accommodated. This concept has recently been adopted as a specific instrument of environmental

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protection policy under the titles of "The Principle of Anticipatory Environmental Protection" and "The Precautionary Approach." The assimilative capacity concept does not conflict with these expressions of precaution. Several recent interpretations of the precautionary principle would seem to imply that protection of the marine environment can be obtained solely by progress towards a zero discharge policy. This is a flawed approach. Rejection of scientifically based impact assessments will prevent proper allocation of properties and rational evaluation of alternative options."

The GESAMP organization also has an agenda which is first to ensure that there is a recognition from a scientific and policy standpoint the ocean environment has a certain assimilative capacity; that it is po: without significant environmental damage or impacts for the ocean to ab.,   and assimilate certain man-made effluents. Secondly, part of their agenda is to ensure that in assessing a particular dredge disposal activity, all the disposal options and alternatives are evaluated. If in that evaluation process, ocean disposal is determined to be the least environmentally damaging alternative, then it is the best alternative to implement. In this particular view, science conditions and frames the proposed policy setting attainable limits as established and defined by science. I would call this approach the pragmatic approach because it sets an objective that is technically attainable. This is the approach, incidentally, that is currently in place in the London Dumping Convention Guidelines for the disposal of dredge material and, therefore, from an international perspective, is the framework in which most national dredge disposal laws and regulations are to be implemented.

What is the status of this idealistic versus pragmatic approach in the international dredge disposal community? There is support for the idealistic approach. That support comes primarily from the Nordic countries, from the Federal Republic of Germany, and from the environmental groups who are very active in the international arena. There also is a majority of support for the pragmatic group. GESAMP is its strongest scientific advocate in the international community, but a majority of the developed nations and developing nations support that approach as well. The debate continues, and the United Nations Council on Economic Development, which will convene in Rio de Janeiro in June of 1992, will be the next major forum at which this issue may surface for discussion. I believe the outcome of the debate is not clear. The environmental pendulum is constantly swinging, but the length of the arc and the period of that swing remain unknown.

Let me close with some general observations, which are my own personal views, as to how this effective marriage must ultimately be resolved. First, I believe it is absolutely essential to achieve and attain an effective marriage of science and policy. Neither can be ignored. Policy that ignores science will not work. It will be ridiculed by those at the implementation level because they know they cannot implement something that is scientifically not possible. Conversely, science that ignores policy does so at its own peril. Regardless of how scientifically correct a particular point of view may be, if it is not acceptable to those people who are charged with living or implementing that science, it will not be done. Therefore, an effective marriage is absolutely essential.

Second, I do not believe that there is any sweeping, all inclusive answer or solution to this challenge of an effective marriage. The alchemist will never produce gold. What is required in each case, in each scientific problem, is hard work, issue by issue, looking at each of the specific problems to forge that marriage and to make it work.

Third and finally, there will be some failures. Some marriages will end in divorce, some will end in annulment, some will be successful. But simply because there are some failures does not mean that the institution of this marriage of science and policy is flawed. The challenge we have is to look at the particular issues with which we are wrestling and identify the terms and conditions under which the marriage of science and policy can work. One answer that will not work is to exclude one at the expense of the other.

I would apologize if you feel that in those conclusions I have not answered the question as comprehensibly as you might have wished. But as I stated at the beginning, my intent is to provide a thought-piece on how to proceed and to stimulate some discussion on this particular issue. I appreciate your time and patience, and I will be happy to entertain questions as time permits.

IMPROVEMENT OF WATER AND BOTTOM SEDIMENT QUALITY IN THE OSAKA PORT AREA BY REMOVAL OF ACCUMULATED ORGANIC SLUDGE

Taizo Nakano
Port Development Department,
Comprehensive Planning Division,
Port and Harbor Bureau, Osaka City
2-8-24 Chikko, Minato-ku, Osaka City 552

ABSTRACT

This report has been prepared to explore the improvement in water and bottom sediment quality accomplished by the dredging and removal of organic sludge in the Osaka Port area. The present survey has clarified the following points:

a. Osaka City is currently dredging and removing organic sludge accumulated in the Aji and other rivers for use in sea reclamation in the Southern area of North Port (Yumeshima). The results of water quality monitoring conducted in the sea areas around the disposal site show that the water quality thus revealed is roughly on a level with that of the Osaka Port water area, indicating the appropriateness of these measures for excess water to be discharged from the disposal site.

b. Sulfides and n-hexane are decreasing, indicating improvement of the bottom sediment quality. The chemical oxygen demand (COD), however, shows fluctuations.

c. The water quality of Aji River shows the most favorable results, as the biochemical oxygen demand (BOD) has registered below 2 mg/ℓ in recent years. The Shirinashi River has been registering, in recent years, even below 3 mg/ℓ.

INTRODUCTION

Osaka Port, situated at the center of Osaka Bay and enjoying good meteorological and marine weather conditions, has developed historically as a favorable port and serves presently as Japan's leading international trade port at the heart of a vast hinterland.

The extensive hinterland around Osaka City, with a population of some 15 million, comprises a major area of production and consumption. It is one of the two largest industrial and economic centers in Japan, the Tokyo area being the other. Inevitably, Osaka City and its hinterland produce large quantities of water-polluting substances which are carried into the Osaka Port

area via rivers, causing severe deterioration of water quality and bottom sediment.

Thus, the Port and Harbor Bureau of Osaka City has been carrying out a port and harbor pollution control project since 1974, in accordance with the Osaka Area Pollution Prevention Plan. To improve the water and bottom sediment quality, accumulated organic sludge is being dredged and removed from rivers and estuaries in the heavily polluted port and harbor area. Dredging and removal in the central section of rivers were mostly completed by the end of 1990.

This report has been prepared to explore the improvement in water and bottom sediment quality accomplished by the dredging and removal of organic sludge, as implemented in the bottom sediment improvement project in the Osaka Port area.

REMOVAL OF ORGANIC SLUDGE IN OSAKA PORT

Outline of Removal and Disposal

Water pollution in the Osaka Port area is characterized by the predominance of artificial organic contamination, caused by rapid industrial development and urbanization in and around the watershed of rivers flowing into Osaka Bay.

The water quality of the inner port , in which the river water stagnates, is particularly affected by the Neya River and other rivers in Osaka City. The lower reaches of these rivers, the Aji, Shirinashi, and Kizu Rivers, are tidal rivers in which sludge is accumulated especially easily, and dissolved oxygen consumption, foul smell, and noxious gas generation are caused by sedimented organic sludge stirred up by passing sea vessels.

Thus, in accordance with the Osaka Area Pollution Prevention Plan, since 1974 Osaka City has been dredging and removing accumulated organic sludge in the heavily contaminated port and harbor area to stop the stirring-up of sedimented sludge and to improve the water quality, as well as to maintain aquatic life-sustaining conditions by removing sulfides and oily substances from the bottom sediment.

Figure 1 shows rivers in Osaka City and the areas in which organic sludge removal is being carried out.

Removal Standard

The standard for accumulated organic sludge removal in Osaka City is set at ignition loss of 15 percent or more because, as shown in Figure 2, a remarkable correlation is found between ignition loss and COD, sulfides, and oily substances (normal hexane extracts).

The concentration of substances contained in sludge which are fatal to life forms is believed to be 500 ppm for sulfides and 15,000 ppm for COD. While oily substances (N-hexane extracts) can arrest the transfer of dissolved oxygen (DO) and block the respiratory systems of fish resulting in death, the concentration that brings suffocation to fish in an extremely short period of time is believed to be 2,000 ppm. Surveys of sludge accumulated in areas

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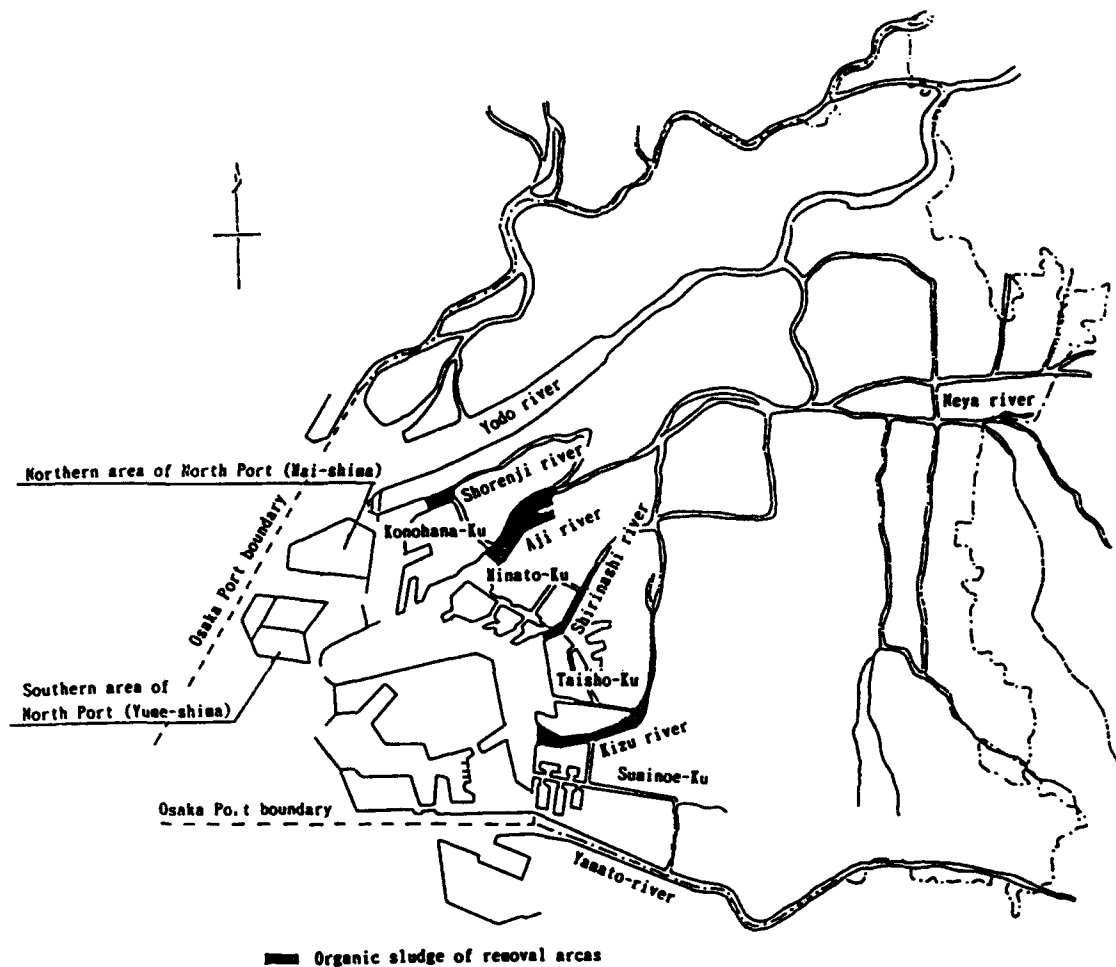
Figure 1. Organic sludge removal areas

stretching over rivers and the port area show close correlation among ignition loss, COD, sulfides, and oily substances, which serve as indices of organic substance content. Thus, the removal standard is set at ignition loss of 15 percent or more, so that the clear clay of lower layers can be exposed by removing sludge of 15 percent or more ignition loss to improve the quality of flowing water, restore life-sustaining conditions, and improve the environment.

DISPOSAL OF ORGANIC SLUDGE

Outline of Terminal Disposal Areas

Osaka City is currently dredging and removing organic sludge accumulated in the Aji and other rivers to use it in sea reclamation areas.

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Legend
O Sludge layer
△ Clay layer
× 4 spots in the Port area
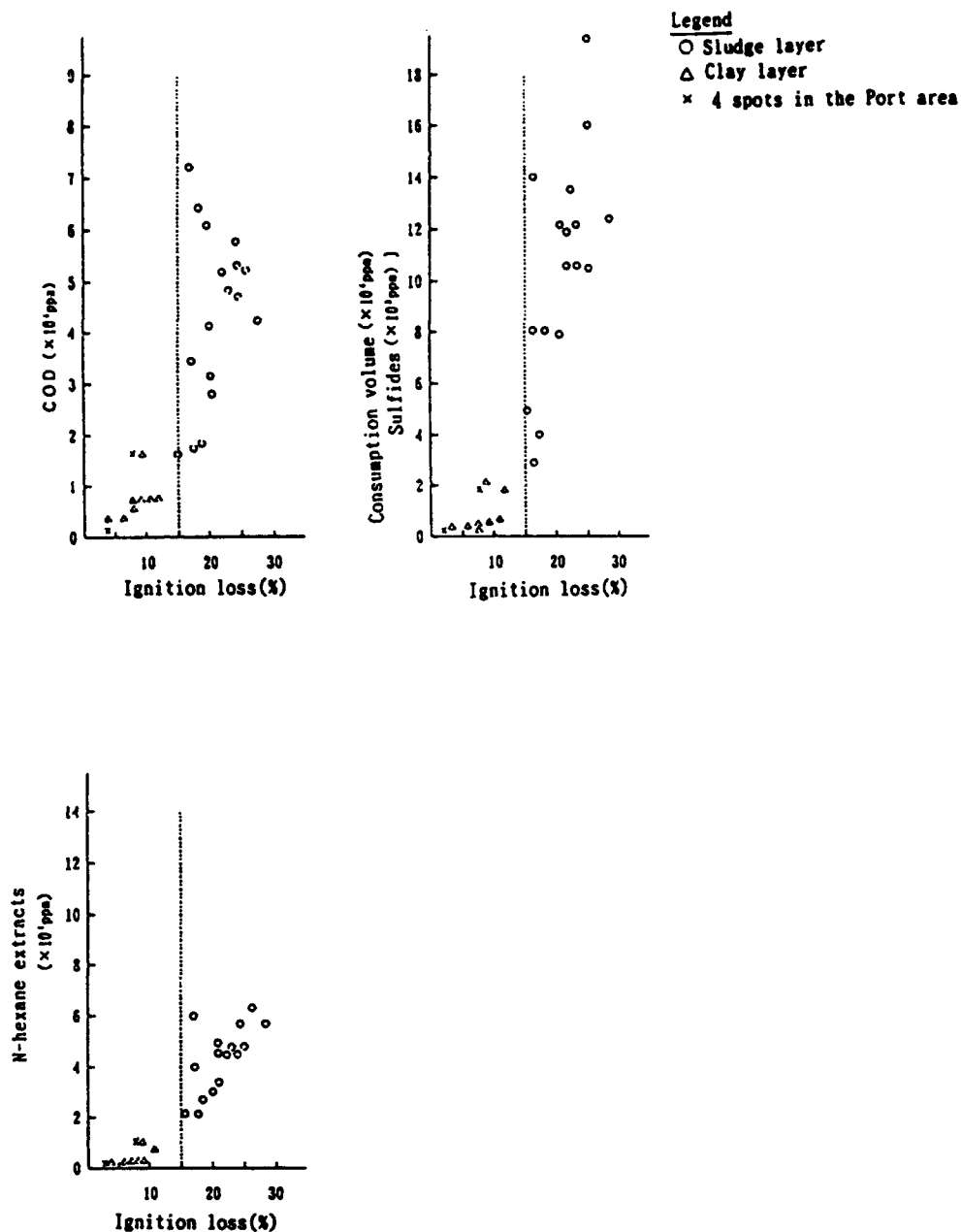
Figure 2. Correlation diagrams

There are two terminal disposal sites for dredged sludge, the northern and southern disposal sites, both located at the farthest end of Osaka Bay, west of Osaka City. Sludge was accepted at the northern site (Maishima) until 1986 and has been accepted at the southern site (Yumeshima) since 1987.

Table 1 and Figure 3 show some details of the southern disposal site in North Port (Yumeshima). On the disposal site, dredged sludge is disposed of in the second and third areas, along with excavated earth and dredged earth and sand from within the port area.

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TABLE 1.   SOUTHERN DISPOSAL SITE IN NORTH PORT

Southern Disposal Site in North Port	
Area	288 ha (First area: 73 ha; Second & Third areas: 215 ha)
Capacity	50,000,000 m^3
Total length of seawall	9,742 m
Construction period	1977-1989
Acceptance period	1985-1995
Acceptance condition	15,810,000 m^3 (approx 32%)
Types of waste accepted	First area: ordinary waste, industrial waste; Second & Third areas: dredged earth and sand, excavated earth from construction sites
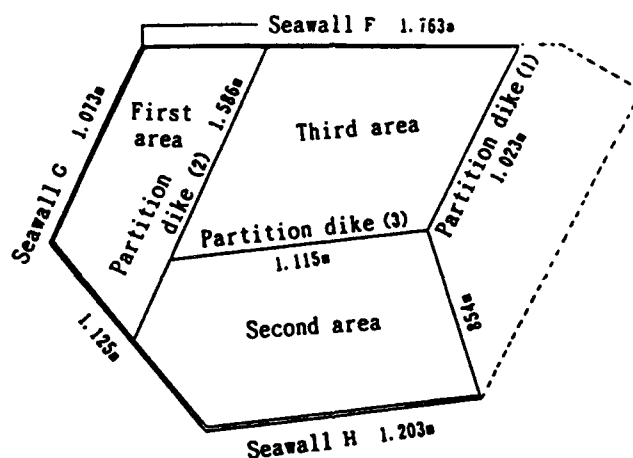
Note: The North Port disposal site is Osaka City's terminal disposal site,
whose First Area accepts ordinary waste and sludge from city water
and sewerage systems.

Figure 3.   Layout of the southern disposal site (Yumeshima)

Structure of the Seawall and the
Partition Dike on the Disposal Site

Figures 4-7 show the structure of the seawalls and the partition dikes
of the North Port southern disposal site, which is presently accepting organic
sludge.

Seawall F

It is necessary to minimize interference with a ship's navigational
route which faces this seawall (Figure 4). For this reason, as well as for
reliable and economical construction, the caisson structure is being adopted.
For subsoil improvement, the sand compaction pile method is employed to

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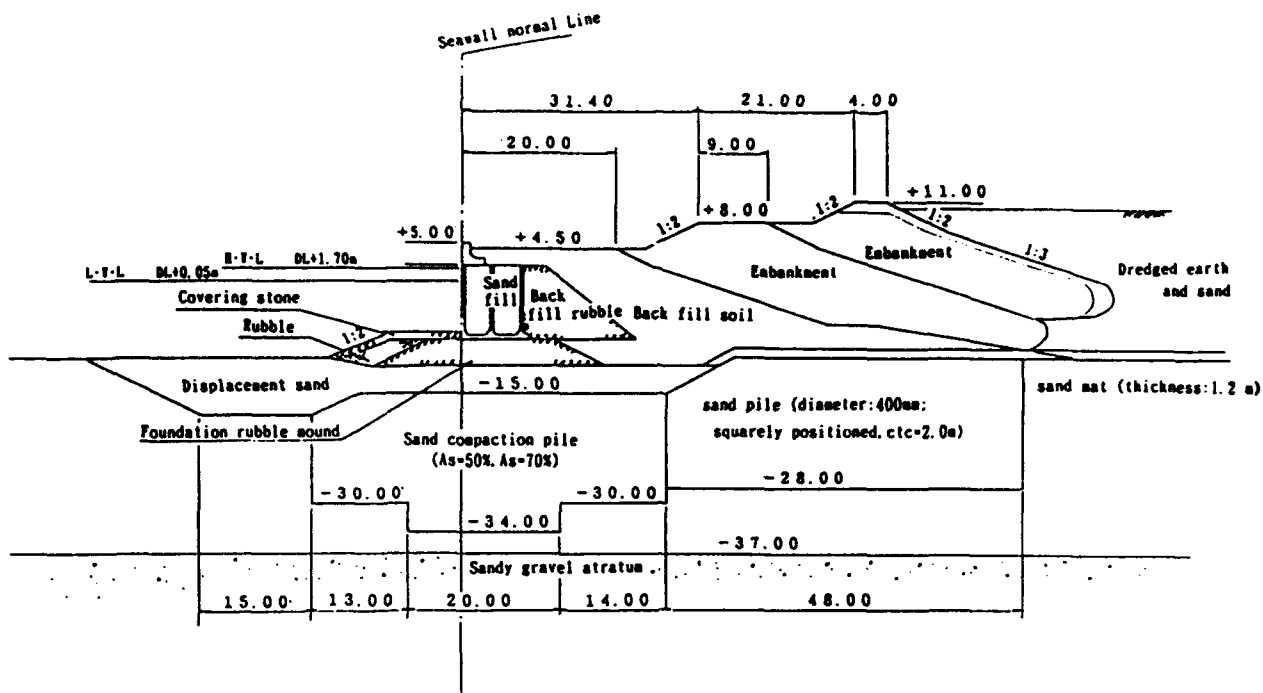
Figure 4. Seawall F

minimize the amount of excavated earth and sand. Moreover, the embankment method with sand mound is employed to secure complete disposal of excavated earth and sand.

Seawall H

The wave dissipation caisson structure is employed for this seawall (Figure 5) since it is exposed to rough waves, especially during winter, from the open sea. For subsoil improvement, the sand compaction pile method is adopted to minimize the amount of excavated earth and sand. Moreover, the embankment method with sand mound is employed to secure complete disposal of excavated earth and sand.

Partition Dike

Since the North Port disposal site accepts various types of waste for landfill, including organic sludge and ordinary waste, partition dikes of the double steel sheet pile structure are erected to separate disposal areas (Figure 6). Moreover, since the partition dikes can handle traffic on their top surface, they also serve to facilitate reclamation work and maintenance and control.

The steel sheet piles of the partition dike (Figure 7) in the first area are made longer than usual and driven into the clay stratum to secure better water-tightness.
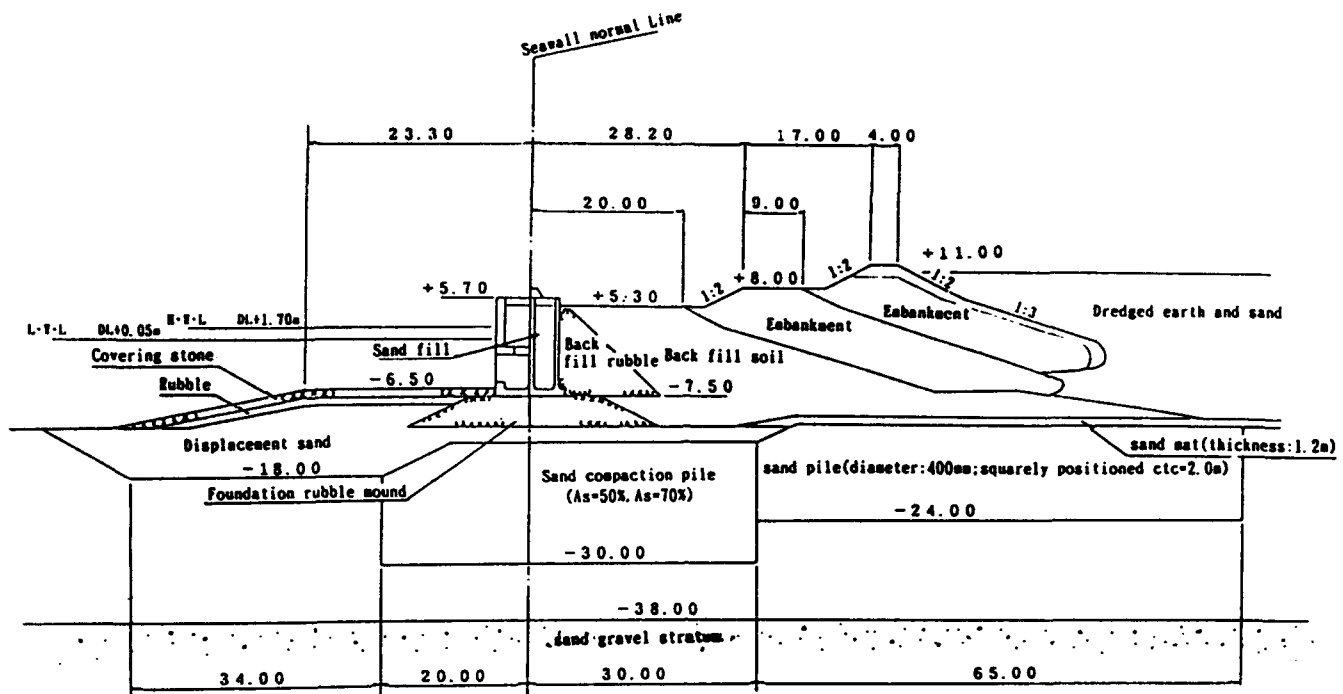
Figure 5. Seawall H
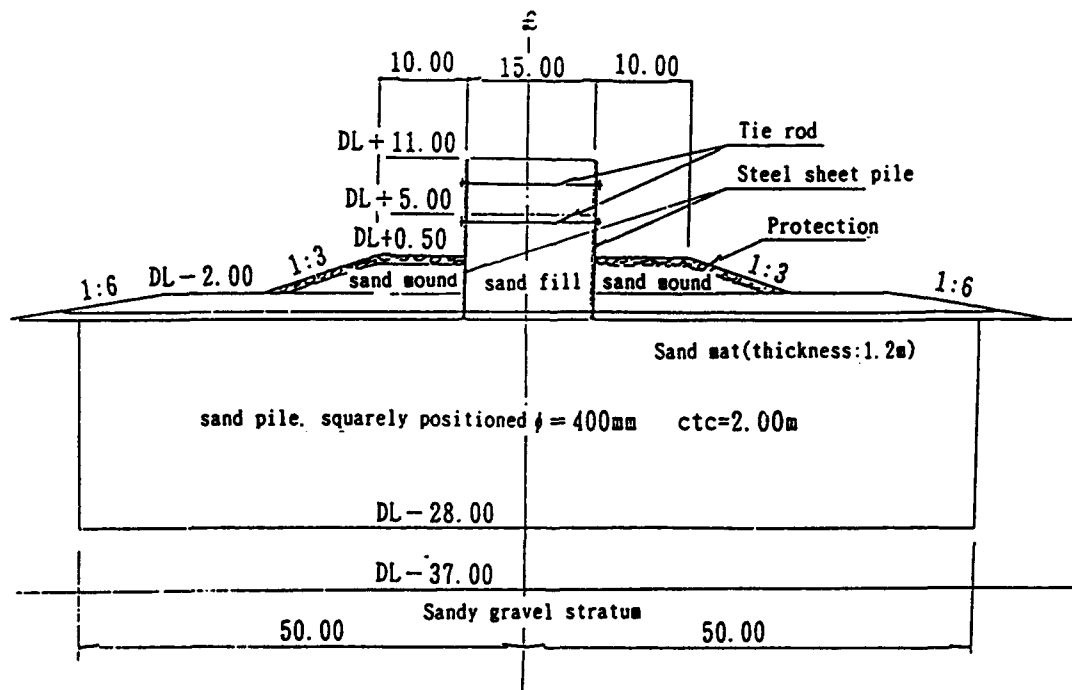
Figure 6. Standard cross section of the partition dike

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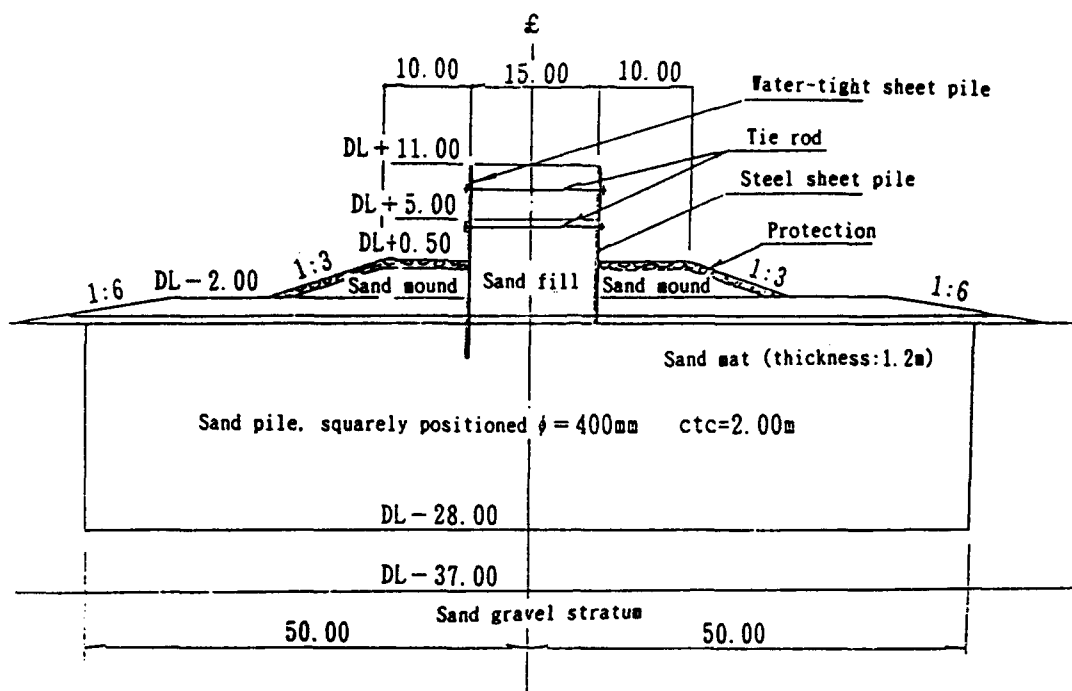
Figure 7. Partition dike with longer sheet piles in
first area

Environmental Preservation Measures

Measures to Prevent Muddy
Water and Oil Contamination

In the southern disposal site of North Port (Yumeshima), waste water is
released into the open sea via the weir from the second-area outlet when
dredged earth and sand are accepted in the third area, and from the third-area
outlet when dredged earth and sand are accepted in the second area (Figure 8).
This process is devised so as to expedite sedimentation.
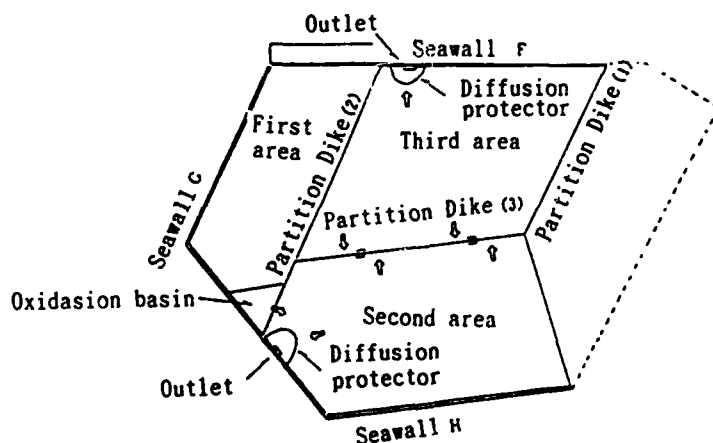
Figure 8. Wastewater flow in the southern disposal site

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Since dredged earth and sand are disposed through discharge pipes by an unloader ship, it is possible to conduct surveys on the spread of muddy water. Identifying the spread allows diffusion protectors to be installed accordingly to prevent secondary pollution; that is, the spread of muddy water in surrounding sea areas caused by the disposal of organic sludge.

Surveys of Excess Water

After use of the northern site, in 1987 the second area of the southern disposal site of North Port started accepting dredged earth and sand. On transfer of the disposal site from north to south, it was deemed necessary to carry out relevant surveys prior to disposal to secure optimal, long-term management of excess water produced in the process of reclamation.

The surveys relate to the water quality, bottom sediment, and biological conditions within the disposal site, as well as phytoplankton primary production--which is a factor for eutrophication--sedimentation speed, and the spread of discharged earth and sand which accompanies reclamation work.

The survey on phytoplankton primary production is conducted to examine the correlation between phytoplankton growth and COD and other indices, since it is surmised that the increase of nutrient slats eluting from discharged earth and sand (such as N and P) causes eutrophication and extraordinary proliferation of phytoplankton at the disposal site, which in turn raises pH and COD values.

The estimated results of the COD balance within the disposal site (1990 survey) can be summarized as follows:

a. The COD at the time of disposal of dredged earth and sand into the site was 7.0 - 25.0 t/month.

b. The COD generated within the site by the growth of phytoplankton was 44.4 - 102 t/month.

c. The majority of the COD released into the site and generated there underwent sedimentation, decomposition, and ingestion in the site. The COD value at the time of discharge out of the site was 9.9 - 38.7 t/month, roughly the same as the value at the time of release into the site.

The survey on the spread of discharged earth and sand accompanying reclamation work is conducted to measure turbidity, flow direction, and flow speed inside the disposal site, in order to determine the staying flow time required to expedite the sedimentation of earth particles. The survey results are then examined to determine the position and direction of sand discharge pipes, methods of installing diffusion protectors, and so on.

Constant Monitoring of the
Quality of Discharged Water

In the North Port southern disposal site (Yumeshima), water discharged via the excess water outlet into the sea is automatically monitored 24 hr a day to fulfill the voluntarily set quality standards shown in Table 2. The monitoring methods shown in Table 3 are followed. The continuous monitoring

TABLE 2. TARGET WATER QUALITY STANDARDS

Item		Target Standard	Notes
Hydrogen-ion concentration (pH)		5-9	Effluent standards 5-9
Dissolved oxygen (DO)		2 mg/ℓ or above	Environmental standards 2 mg/ℓor above
Normal hexane extracts (oily substances)	Plant and animal oil	10 mg/ℓ or below	Effluent standards 30 mg/ℓ or above
	Mineral oil	3 mg/ℓ or below	Effluent standards 5 mg/ℓ or below
Suspended substances (SS)		50 mg/ℓ or below	Effluent standards 150 mg/ℓ or below
Chemical oxygen demand (COD)		40 mg/ℓ or below	Effluent standards 120 mg/ℓ or below

Note: "Effluent standards" are in compliance with the Water Pollution
Control law; SS and COD refer to daily average values.

TABLE 3. OUTLINE OF CONSTANT WATER QUALITY MONITORING

Item	Measuring method	Notes
Water temperature	Platinum thermometer	
pH	Glass electrode	
Turbidity	Diffused light method	
SS	(Turbidity meter)	Calculated from turbidity by a correlation formula
COD	(UV meter: UV photometer)	Calculated from UV value by a correlation formula
DO	Galvanic method	

is carried out in order to promptly devise appropriate measures to prevent
secondary pollution which may be caused by discharged water into the surround-
ing sea areas during the reclamation process.

ENVIRONMENTAL MONITORING IN THE SEA
AREAS SURROUNDING THE DISPOSAL SITE

Outline

In the sea areas surrounding the North Port southern disposal site
(Yumeshima), water quality and bottom sediment surveys are periodically
carried out to monitor the environment. Table 4 and Figure 9 show the details
of the surveys.

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TABLE 4. ENVIRONMENTAL MONITORING SURVEYS

Category	Item	Frequency	Measuring items
Water quality	General	Monthly	Color tone, smell, pH, BOD,* COD, DO, SS, clorine ion, S-BOD, S-COD, S-TOC
	Special health related	Once every 4 months	Cadmium, lead, arsenic, cyan, copper, iron, zinc, PCB,** manganese, total chromium, nickel, fluorine, n-hexane, extracts, organic phosphorus, hexavalent chromium, general bacteria, coliform group
	Others	Monthly	Total nitrogen, ammoniac nitrogen, nitrate nitrogen, nitrite nitrogen
		Once every two months	Total mercury, alkyl mercury, total phosphorus, phosphoric acid phosphorus, chlorophyll a, pheophytin
Bottom sediment	General special health-related	Annually	Water consent, pH, ignition loss, sulfides, COD, cadmium, lead, arsenic, copper, iron, total mercury, zinc, manganese, total chromium, nickel, PCB, organic phosphorus, hexavalent chromium, alkyl mercury

* BOD - bochemical oxygen demand
** PCB - polychlorinated biphenyls

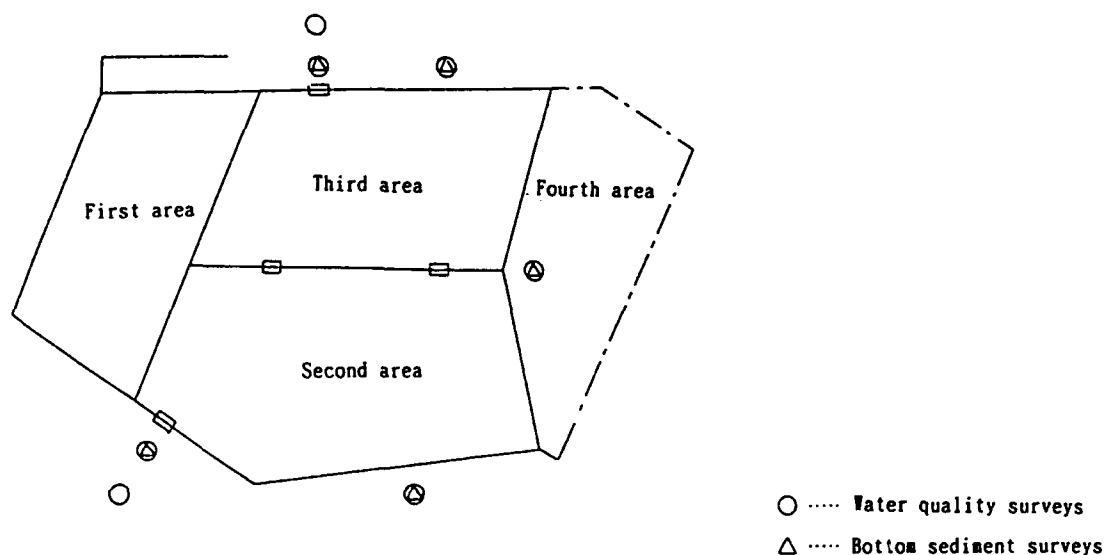O ----- Water quality surveys

△ ----- Bottom sediment surveys

Figure 9. Locations of environmental monitoring surveys

Monitoring Results

The results of water quality monitoring conducted in the sea areas around the North Port southern disposal site recorded values for COD and DO,

representative water pollution indices, as shown in Table 5. The water quality thus revealed is roughly on a level with that of the Osaka Port water area, indicating the appropriateness of these measures for excess water to be discharged from the disposal site.

TABLE 5. RESULTS OF ENVIRONMENTAL MONITORING

	Areas surrounding the disposal site		Osaka Port water area	
	COD	DO	COD	DO
1987	5.3 (6.3-3.7)	8.5 (9.0-7.8)	4.3 (5.3-3.0)	6.5 (7.6-4.9)
1988	4.5 (5.4-3.9)	8.9 (9.4-8.5)	4.3 (5.3-3.5)	6.7 (8.5-5.2)
1989	4.3 (4.9-3.2)	7.5 (8.9-7.0)	4.0 (5.1-3.0)	6.7 (8.4-5.4)
1990	4.6 (4.8-4.0)	7.2 (7.4-7.0)		

Note: Surveys in the surrounding sea areas are conducducted by the Port and Harbor Bureau, and those in the Osaka Port water area by the Environmental Department.

Figure 10 illustrates monthly changes in COD during 1989. It also shows that remarkable differences in the COD values measured in spring and summer existed between the areas around the North Port southern disposal site and the Osaka Port water area, while there was little difference in the values measured in autumn and winter.

Figure 11 shows monthly changes in pH, drawn to examine the difference between the two areas. The pH values show a tendency similar to COD, i.e., a large difference in pH existed between the two areas measured in spring and summer as well.

It is assumed that abnormally active photosynthesis, at the time of extraordinary emergence of phytoplankton (red tide) accompanying eutrophication, accounts for the higher pH values.

RESULTS OF ORGANIC SLUDGE REMOVAL AND IMPROVEMENT
OF WATER AND BOTTOM SEDIMENT QUALITY

Results of Organic Sludge Removal

Since 1974, organic sludge dredging and removal have been carried out as a port and harbor pollution control project. Table 6 shows the annual volume of earth dredged from three rivers.
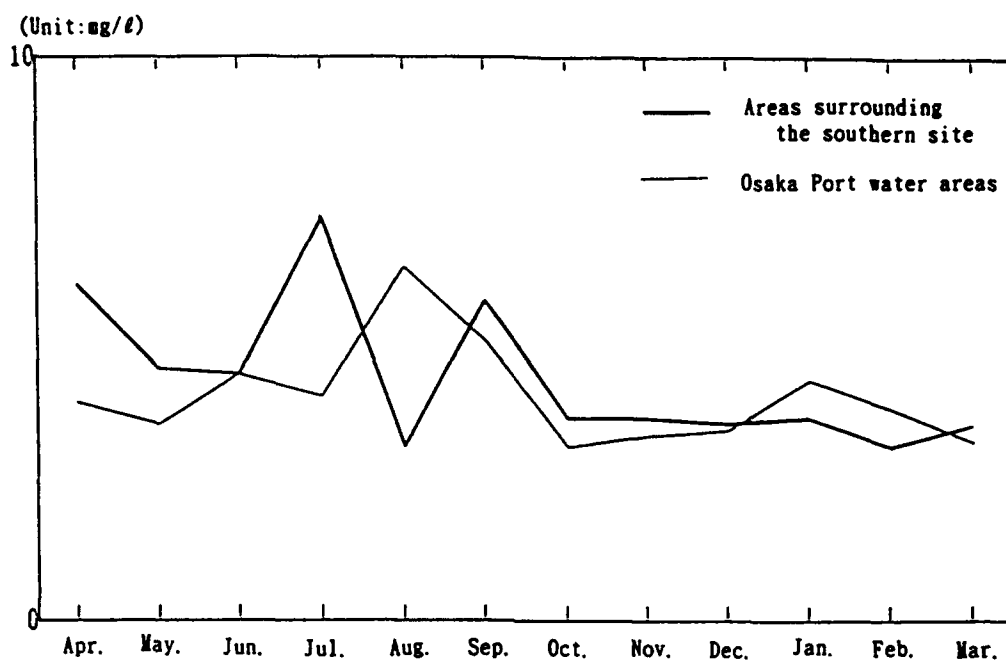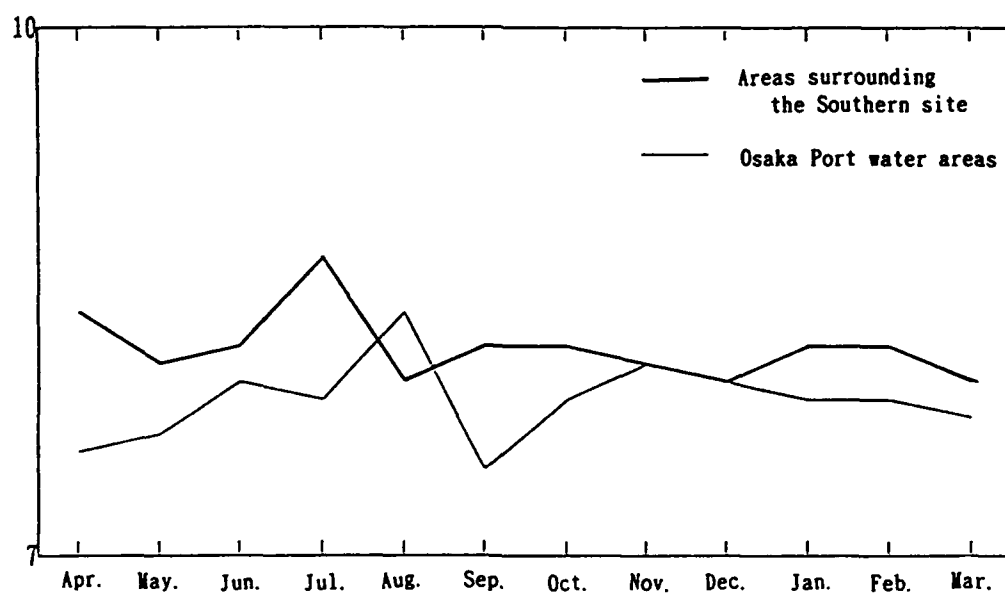
18

(Unit:mg/ℓ)

Figure 10.　Monthly changes in COD

Figure 11.　Monthly changes in pH

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TABLE 6. AMOUNT OF DREDGED ORGANIC SLUDGE

(Unit: 1,000 m³)

	1974	1975	1976	1977	1978	1979	1980	1981	1982
Shirinashi River	--	--	141	46	--	--	--	52	--
Aji River	110	244	48	115	179	256	120	21	146
Kizu River	--	--	--	124	111	--	136	178	141
Total	110	244	189	285	290	256	256	251	287

	1983	1984	1985	1986	1987	1988	1989	1990	Total
Shirinashi River	--	--	73	37	--	--	--	--	349
Aji River	279	252	178	14	149	103	131	9	2,354
Kizu River	--	--	24	149	138	124	135	129	1,389
Total	279	252	275	200	287	227	266	138	4,092

In the future, continued removal of accumulated sludge is planned for the Aji, Shirinashi, Kizu Rivers to improve the water quality. The five-year plan from 1991 to 1995 includes removal of sludge from the central section of the Shorenji River and along the shores of the Aji and Kizu Rivers. Table 7 shows the dredging volume planned for the five-year period starting in 1991.

TABLE 7. PLANNED AMOUNT OF ORGANIC SLUDGE TO BE DREDGED

(Unit: 1,000 m³)

	1991	1992	1992	1994	1995	Total
Shirinashi River	--	--	10	10	16	36
Aji River	20	60	60	60	57	257
Kizu River	--	--	--	10	20	30
Total	20	60	70	80	93	323

Improvement of Bottom Sediment

The annual changes in the respective bottom sediment quality of the Shirinashi, Aji, and Kizu Rivers, in which organic sludge dredging and removal have been carried out, are shown in Figures 12-15.

Dredging and removal are almost completed in the Shirinashi and the Aji, and the ignition loss of these two rivers, originally some 20 percent, has been reduced to 13.5 and 11.6 percent, respectively, each below the target 15 percent. In the Kizu River, where dredging is still in progress, the

20

(Unit:%)
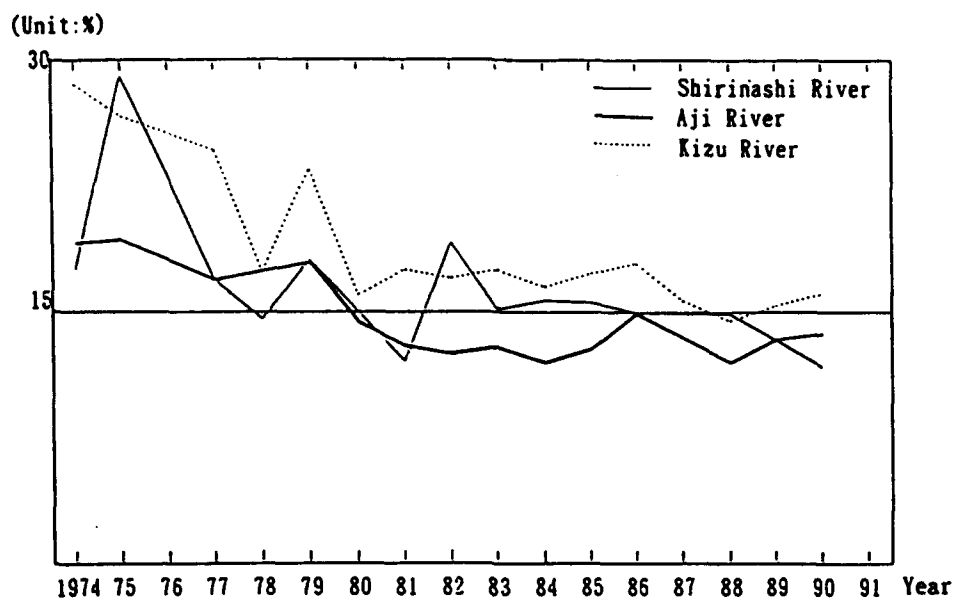
Figure 12. Ignition loss

(Unit:㎎/d-g)
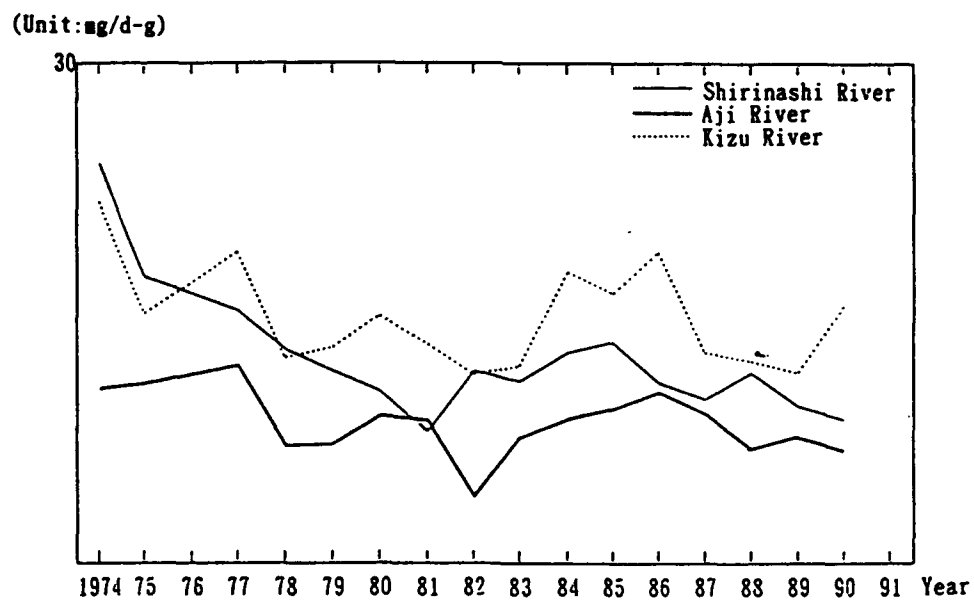
Figure 13. Sulfides

21

(Unit:mg/d-g)

Figure 14. Hexane

(Unit:mg/d-g)
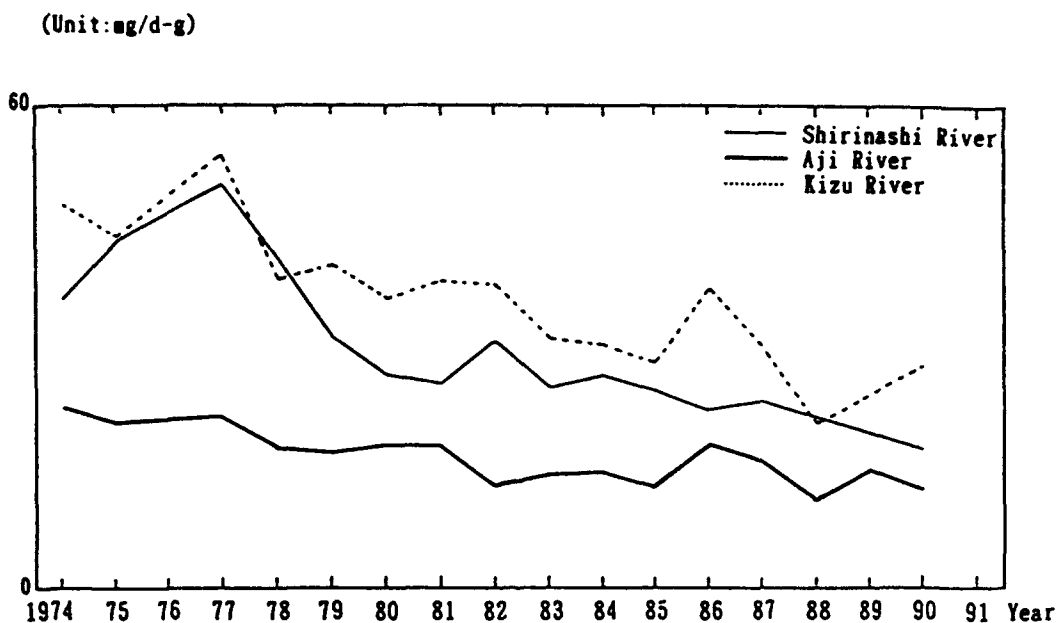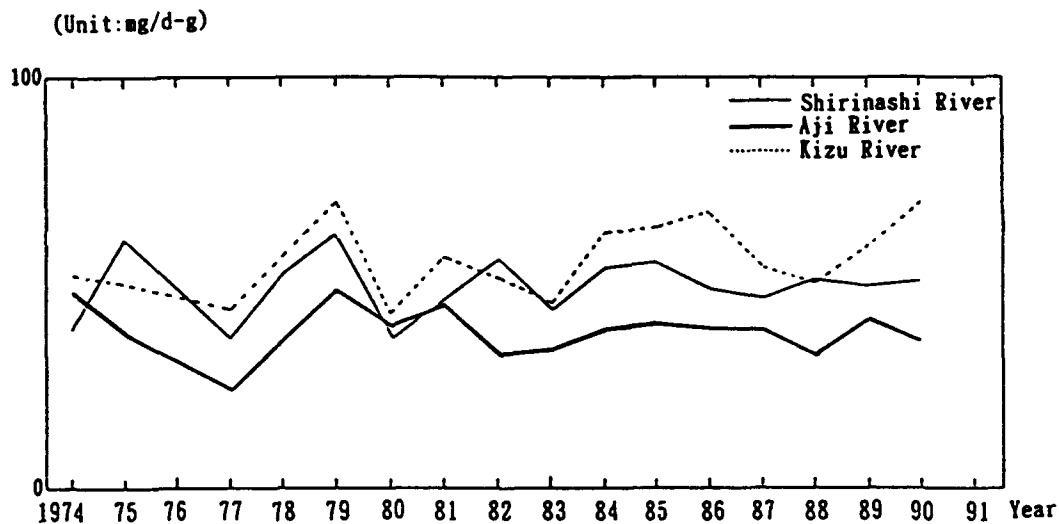
Figure 15. COD

ignition loss has been reduced from the initial figure of about 30 percent but is still around 16.0 percent.

Sulfides and n-hexane are also decreasing, indicating improvement of the bottom sediment quality. COD, however, shown fluctuations, and future measures for bottom sediment quality improvement will require examination.

Water Quality Improvement

Figure 16 shows the annual changes in water quality in terms of BOD in the Shirinashi, Aji, and Kizu Rivers, in which organic sludge dredging and removal have been carried out.

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(Unit:mg/ℓ)
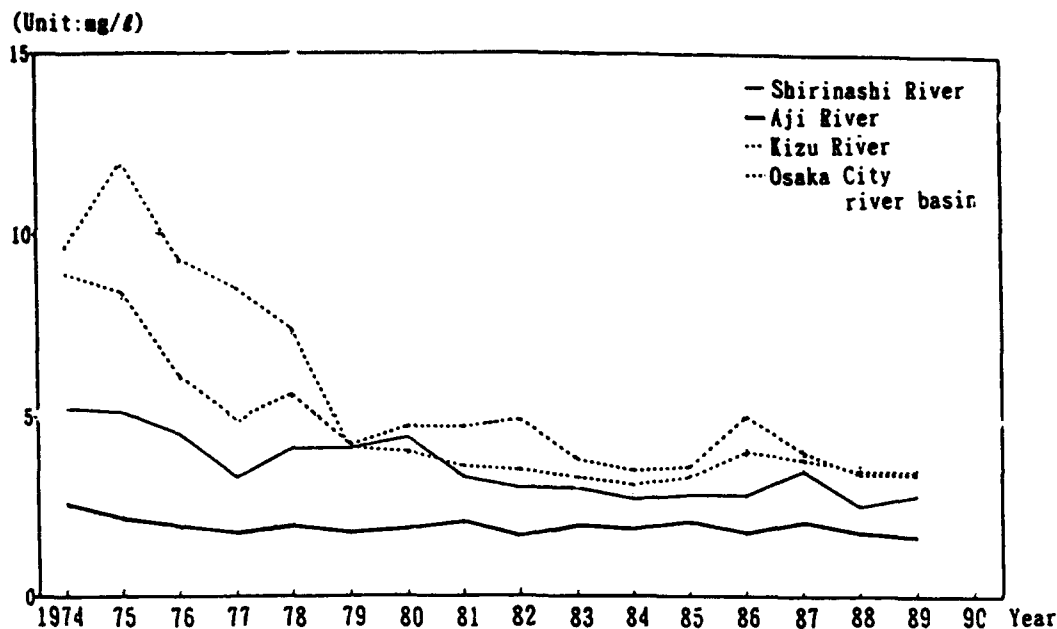
Figure 16. Annual changes in water quality
(in terms of BOD)

The Aji River shows the most favorable results, whose BOD figures have leveled off since 1976 and have registered below 2 mg/ℓ in recent years. The Shirinashi River has been registering below 4 mg/ℓ since 1976 and, in recent years, even below 3 mg/ℓ.

Meanwhile, the Kizu River, in which dredging work is still being continued, showed a drastic decrease of BOD up until 1979, which has then leveled off since 1980.

The annual changes in the Osaka City river basins (see Figure 17) indicate an overall tendency of decline in BOD because of the established water quality regulations: BOD decrease drastically until 1982 and has leveled off since 1983. The Kizu River shows a similar pattern to this tendency.

FUTURE CHALLENGES

In the Osaka Port area, the river water and bottom sediment quality have been improving, thanks to the positive effects of effluent restrictions made mandatory by laws and regulations, as well as the dredging and removal of organic sludge accumulated in rivers within the port area. For further improvement in the future, the following challenges will have to be faced.

A New Terminal Disposal Site

At present, the North Port disposal site serves as Osaka City's terminal disposal site for dredged earth and sand, waste, and other matter. However, the site is scheduled to discontinue accepting matter for disposal in 1995.

Thus, it is imminently necessary to secure a new terminal disposal site. Considerations are currently being made for an earliest possible realization of a new disposal site, while the construction period for seawalls is being taken into account.

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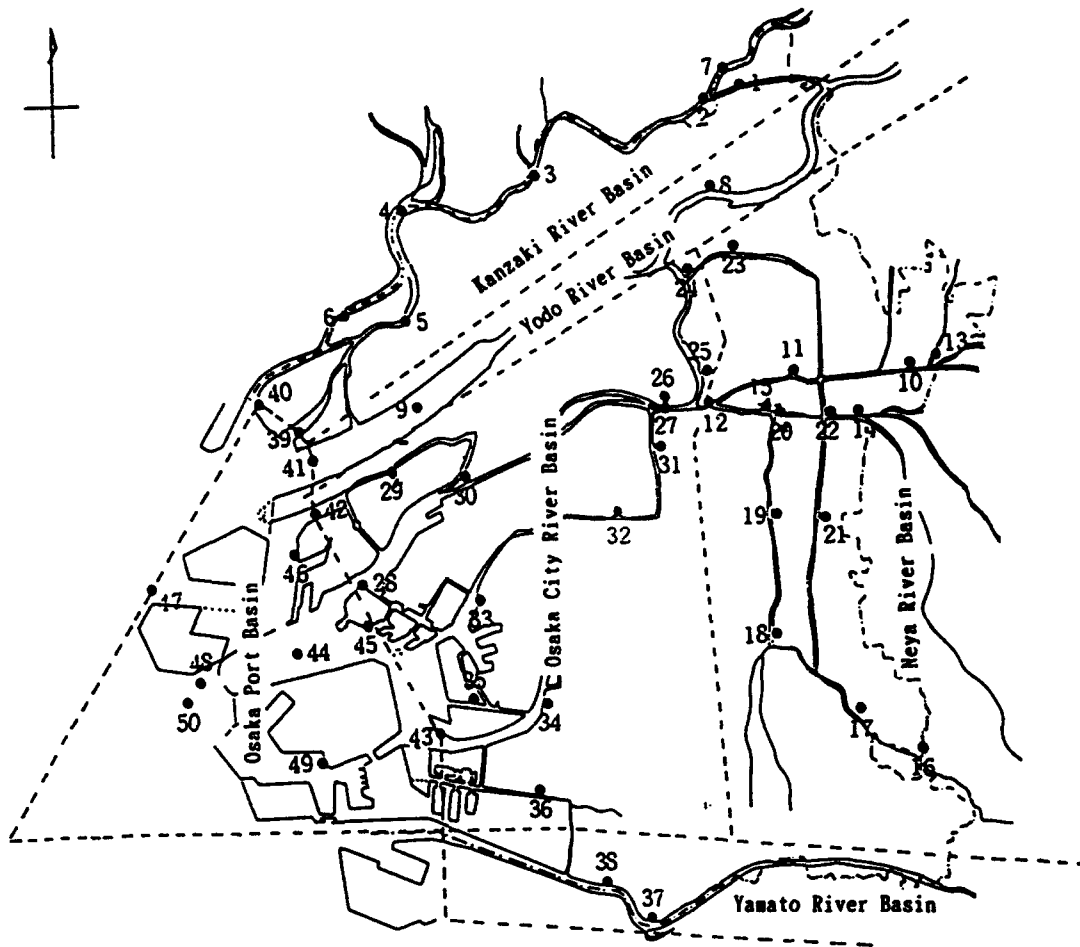
Note: Numbers indicate water quality survey spots.

Figure 17. River and port basins

For the construction of a new terminal disposal site, careful considera-
tion should be given to preservation of the surrounding sea environment.
Likewise, a scientific environmental assessment, including prior surveys on
water quality and tidal currents, will need to be made.

Consideration of
Organic Sludge Removal Standard

Ignition loss of 15 percent is set as the target standard for removal of
organic sludge accumulated in rivers in the Osaka Port area. Yet, as summa-
rized in this report, some items measuring bottom sediment quality have not
improved to achieve this target. For this reason, as well as to secure
improvement of the water quality of rivers and the Osaka Port area, it is
necessary to review the improvement measures, including this removal standard.
Accordingly, research and surveys should be continued in the future.

Water Quality Control at
the Upper Reaches of Rivers

To improve the water quality of Osaka Port, it is essential to control the water quality of rivers flowing into the Port area, especially at their upper reaches. While the sewerage system coverage is almost 100 percent in Osaka City, areas at the upper reaches of rivers are not yet fully covered by sewerage systems, thus hindering the improvement of water quality of the Neya and the Yamato Rivers.

It is expected that extensive water quality preservation measures, covering all the basins of rivers flowing into Osaka Port, will be required in the future. Thus, a major challenge for water pollution control will be the promotion of extensive measures involving both upper and lower reaches of rivers.

Moreover, marked tendencies of eutrophication found in the Osaka Port area, coupled with high pH values in the terminal disposal site, urgently call for effective countermeasures.

In consideration of these challenges, Osaka City is currently planning to introduce advanced water treatment systems to upgrade sewerage treatment and to combat eutrophication. It is expected that this plan will reduce the water pollution load (COD) released from the sewerage treatment plant and, when combined with effective countermeasures against phosphorus, will help prevent eutrophication.

The improvement of water and bottom sediment quality in the Osaka Port area accomplished by the dredging and removal of accumulated organic sludge has been described, along with measures for the discharge of excess water from the disposal site and for environmental monitoring in the areas surrounding the disposal site. It is hoped that this report will contribute in some way to the environmental improvement of port and harbor areas in Japan and the United States.

TECHNOLOGIES FOR REMEDIATION OF
CONTAMINATED SEDIMENTS IN THE GREAT LAKES

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ABSTRACT

Technologies that have been identified as feasible for
remediating contaminated sediment and being considered
for demonstration in the Great Lakes are presented in
this paper. The review encompasses the components
required for removal of highly contaminated sediment.
Technologies reviewed concentrate on those involving
treatment of the contaminated sediment. Approximately
200 technology process options were reviewed for
effectiveness, implementability, and costs. However,
few of these processes have been applied to contami-
nated sediment on a full scale. Most of the technol-
ogy evaluations have been on the bench scale with
limited pilot testing results available for
assessment. Therefore, further testing and evaluation
of the most promising technologies is being conducted
under the ARCS program at the Buffalo River, Ashtabula
River, Saginaw River, Sheboygan River, and Grand
Calumet River/Indiana Harbor areas of concern.

INTRODUCTION

Thank you, Co-Chairmen Bates for the gracious introduction. Co-Chairman
Kawashima and our distinguished delegates from Japan and the United States, it
is my distinct pleasure and honor to be here today to attend my fourth meeting
of Experts on the Management of Highly Contaminated Toxic Bottom Sediments. I
have many fond memories of the 10th meeting which was held in Kyoto in 1985.
At that meeting, I discussed some of the promising technologies we were
assessing for the management of contaminated dredged material in the United
States. Since that time, there has been considerable emphasis placed on the
identification, assessment, and remediation of highly contaminated toxic bot-
tom sediments in the U.S. and around the world. To address this problem, a
number of major Federal and state laws, regulations, and programs have
evolved.

ARCS PROGRAM

Prominent among the new programs is the Assessment and Remediation of
Contaminated Sediments (ARCS) program which is managed by the U.S. Environ-
mental Protection Agency (EPA). For the past two to three years, the
U.S. Army Corps of Engineers (CE) has been working with EPA's Great Lakes

National Program Office (GLNPO) to implement the requirements of Section 118(c)(3) of our Federal Water Quality Act of 1987. This Section specifically directs the EPA to "carry out a five-year study and demonstration projects relating to the control and removal of toxic pollutants in the Great Lakes, with emphasis on the removal of toxic pollutants from bottom sediments" (Horvatin 1989). The Act specified that priority Areas of Concern for implementation of demonstration projects were Saginaw Bay, Michigan; Sheboygan Harbor, Wisconsin; Grand Calumet River, Indiana; Ashtabula River, Ohio; and Buffalo River, New York.

Major Study Participants

The EPA operating through its GLNPO is responsible for the ARCS program in the Great Lakes. The Department of Army operating through its CE has entered into an agreement to provide technical assistance to EPA and GLNPO to carry out the study and demonstration program. The CE's North Central Division and Districts with technical assistance from the U.S. Army Engineer Waterways Experiment Station (WES), Vicksburg, Mississippi, is responsible for assessing the engineering feasibility of a variety of contaminated sediment remediation alternatives and technologies. As part of this effort, my co-author, Dan Averett, and others at WES, completed a review of technologies for the containment and treatment of contaminated sediments either in place or after removal.

Purpose of Technology Review

The purpose of the technology review was to identify technologies and process options that may be feasible for remediating Great Lakes contaminated sediment and that may be considered for demonstration under the ARCS program. Over 300 process options were reviewed which resulted in approximately 40 processes having potential for bench and pilot testing. The technologies reviewed included those involving removal of contaminated sediment with subsequent transport, treatment, containment, or disposal, and those for nonremoval alternatives, such as in situ treatment or containment of contaminated sediment. A report (Averett et al. 1990) of this review of technologies was prepared and I have provided Co-Chairman Mr. Kawashima with a copy.

Purpose of Presentation

To prepare for this meeting, I have summarized our review of technologies study and will present only a brief description of a variety of technologies and basic alternatives for managing contaminated sediments in the Great Lakes and elsewhere in the U.S. Due to the limited time for this presentation, my verbal remarks will be restricted to only a few of the technology types and processes that have been evaluated or are being demonstrated in the Great Lakes.

COMPONENTS OF REMOVAL

The components for alternatives that require removal of contaminated sediments are: (a) excavation of sediment, (b) transport of dredged sediment, (c) pretreatment of dredged sediment, (d) treatment of dredged sediment, (e) disposal of dredged materials, and (f) water (effluent and leachate) treatment. A variety of technologies are potentially available for each

component; however, only a limited number have actually been applied on a pilot scale or full scale.

Factors that need to be considered when evaluating removal alternative technologies include the following: (a) state of technology, (b) availability, (c) effectiveness, (d) implementability, and (e) cost.

Excavation Component

Principal concerns during excavation operations are the prevention of contaminant releases from the sediment being removed with subsequent transport of contaminants to a previously uncontaminated area and efficient removal of contaminated sediment without excessive overcutting. If an unavoidable release occurs, undesirable consequences could result in regards to the environment, costs, and public relations. Overcutting increases the volume of material for treatment or disposal and increases costs. Technologies for the excavation of contaminated sediment include the following:

  <u>a</u>. Selection of appropriate mechanical or hydraulic dredges

  <u>b</u>. Use of operational controls during excavation activities

  <u>c</u>. Deployment of barriers during sediment removal

Transport Component

Primary transportation methods used to move contaminated dredged sediment include pipelines, barges or scows, and hopper dredges. Overland transport could also include railways and trucks.

Pretreatment Component

Pretreatment technologies are defined for the purpose of this talk as technologies that prepare dredged sediment for additional treatment or disposal. These technologies are designed to accelerate treatment in a disposal site, to reduce the water content of the dredged material, or to separate fractions of the sediment by particle size. Pretreatment technology process options are dewatering, particle classification, and slurry injection. These processes are primarily applicable to hydraulically dredged sediment. Physical separation or particle classification is being demonstrated on a pilot scale on sediments from the Saginaw River. Approximately 300 tons of PCB-contaminated sediment will undergo soil washing and hydrocycloning to separate 80 percent sand from the remaining silt fraction. The pretreatment will prepare the silt for further treatment using bioremediation technology being demonstrated at the Sheboygan Harbor, Wisconsin site.

Treatment Component

Many of the process options are not stand alone processes but are components of a system that may involve multiple treatment processes to address multiple contaminant problems. Most of these processes also require one or more of the pretreatment processes discussed above. Technology types for the treatment component are: (a) biological, (b) chemical, (c) extraction, (d) immobilization, and (e) thermal.

Biological Processes

Biological degradation technologies use bacteria, fungi, or enzymes to break down polychlorinated biphenyls (PCBs), pesticides, and other organic constituents into innocuous or less toxic compounds. The microorganisms may be indigenous microbes, conventional mutants, or recombinant DNA products. Biodegradation processes have not been applied and evaluated for contaminated dredged material other than on a bench scale. Several of the conceptual processes are proprietary processes that may be available on a pilot scale, and new vendors continue to enter this market. The Bio-Clean process, being considered for the Hudson River, is estimated to cost $130 to $270 per cubic yard. A potentially lower cost would be incurred if biodegradation can be conducted in a confined disposal facility (CDF).

Because of the dependence of biological processes on carefully maintained environmental conditions, reliability of these processes is questionable. Implementability for most of these processes is difficult because of the developmental nature of these processes for contaminated sediment and because of long time periods and large systems that will likely be required for treatment of contaminated sediment.

Enhanced natural biodegradation of PCB's in sediments is being evaluated in a pilot contained treatment facility (CTF) at the Sheboygan River Superfund remediation project. The CTF was designed to accommodate approximately 3,000 cu yd of sediments dredged from the upper Sheboygan River. The CTF is divided into two treatment sections with controls to allow for regulation of nutrient and oxygen conditions for the bacteria. The control sections will not receive added nutrients to enhance biodegradation. Both anaerobic and aerobic biodegradation conditions are being assessed in the study.

Chemical Processes

Chemical treatment technologies use chelating agents, bond cleavage, acid or base addition, chlorine displacement, oxidation, or reduction in the destruction, detoxification, or removal of contaminants found in the contaminated media. Few of these technologies have been used for treatment of organic and heavy metal contaminants in sediment. Chemical treatment technologies considered include chelation, chemical hydrolysis, and detoxification.

Implementability for chemical processes is difficult because of materials handling and process control requirements that have not been fully demonstrated for application to dredged sediment. Costs for these processes have not been reported and are difficult to quantify, but they are expected to exceed $100 per cubic yard.

Extraction Processes

Extraction is the removal of contaminants from a medium by dissolution in a fluid that is later recovered and treated. Soil flushing and soil washing are other terms that are used to describe extraction processes. A key element of an extraction process is the ability to separate the contaminant from the solvent so that the solvent can be recovered for reuse in the process. Also important is the toxicity of the solvent. Most processes require multiple extraction cycles to achieve high removal efficiencies. Follow-on

treatment processes are required to treat or dispose of the concentrated contaminant stream.

Implementability for most of these processes is difficult because of the lack of full-scale development for handling sediment and the problems of solvent recovery and potential toxicity of residual solvents. Costs are not well documented but are expected to exceed $100 per cubic yard.

Solvent extraction will be demonstrated for highly contaminated sediments from the Grand Calumet and Indiana Harbor Canal. A pilot study of the triethylamine (TEA) extraction process will be evaluated for removal of poly-aromatic hydrocarbons (PAHs) and PCBs from the sediment.

This technology has been evaluated previously on sediments contaminated with PCBs from the New Bedford Harbor Superfund Site and on sediments/soils contaminated with creosote from the Bayou Bonfouca Superfund Site in Slidell, Louisiana.

Immobilization Processes

Immobilization processes are defined as technologies that limit the mobility of contaminants for sediment placed in a confined site or disposal area. The environmental pathway most affected by these processes is transport of contaminants to the ground water or surface water. Most of the immobilization processes fall into the category of solidification/stabilization (S/S) processes. Objectives of S/S are generally to improve the handling and physical characteristics of the material, decrease the surface area of the sediment mass across which transfer or loss of contaminants can occur, and/or limit the solubility of contaminants by pH adjustment or sorption phenomena.

Effectiveness of S/S processes is usually evaluated in terms of reduction of leaching potential. Reductions are process and contaminant specific with immobilization of some contaminants accompanied by increased mobility of other contaminants. Implementability for most of these processes is better than chemical or extraction processes because they are not as sensitive to process control conditions. The opportunity for in situ S/S within a CDF is also an advantage. Costs for these processes are generally less than $100 per cubic yard.

The immobilization of residual wastes from the thermal desorption demonstration project at the Buffalo River Site will be evaluated. Previous bench scale studies of S/S processes have been conducted for the Indiana Harbor and Buffalo River sediments.

Thermal Processes

The thermal type technologies are incineration processes, pyrolytic processes, vitrification processes, supercritical and wet air oxidation, and other processes that require heating the sediment several hundred or thousands of degrees above ambient. Thermal desorption or extraction of low level PAHs in sediments is being demonstrated for the Buffalo River and Astabula River demonstration projects. Low temperature thermal desorption does not destroy the organics. Instead, it removes the low temperature volatile compounds (VOCs) through the vaporization of the organics and water from the sediment. The VOCs and water vapor are collected for further treatment and disposal.

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Thermal processes are generally the more effective options for destroying organic contaminants, but they are also the more expensive. Costs for thermal processes range from several hundred dollars to over a thousand dollars per cubic yard.

SUMMARY

The technologies available for managing contaminated sediment can be categorized as either nonremoval or removal. The removal technologies reviewed for this paper have been assessed for their effectiveness, implementability and costs, and a brief description of the treatment technologies being demonstrated in the Great Lakes ARCS program is provided. Approximately 30 technology categories and over 200 process options were reviewed as a basis for this presentation. These pilot projects will provide a basis for advancing the technology gaps that now exist for incorporation of these technologies into remedial action plans for contaminated sediments.

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DEVELOPMENT OF A LEACHING PROTOCOL FOR EVALUATING GROUND WATER IMPACT FROM CONTAMINATED SEDIMENT

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ABSTRACT

The U.S. Army Engineer Waterways Experiment Station is developing laboratory tests and data interpretation algorithms for predicting leachate quality in confined dredged material disposal facilities (CDFs). Leachate quality predictions are needed for evaluation of potential impacts of leachate seepage on foundation soils and ground water. Both batch and column laboratory leach tests are under investigation. A sequential batch leach test is being developed to provide a short-term laboratory test that describes the distribution of contaminants between aqueous and solid phases. Column leach tests are being developed as laboratory-scale physical models of contaminant leaching in a CDF. Current studies show that sediment salinity and oxidation status significantly affect contaminant leaching. Sediments from freshwater environments generally behave according to classical desorption theory. However, leaching of sediments from estuarine environments with freshwater results in nonideal behavior that significantly complicates prediction of long-term leaching trends. Nonideal behavior is due to release of sediment organic colloids as ionic strength is decreased through salt wash out. Data from sequential batch leach tests clearly indicate that elution of several pore volumes through estuarine dredged material is necessary to produce maximum concentrations of contaminants in leachate.

INTRODUCTION

When contaminated dredged material is placed in a CDF, contaminants may be mobilized and transported to the site boundaries by leachate generation and seepage. Subsurface drainage and seepage through foundation soils and dikes may then reach adjacent surface and ground waters and act as sources of contamination (Figure 1). Therefore, techniques for predicting leachate quality in CDFs are needed to establish sound engineering and environmental data for the selection, design, and management of CDF's.

The U.S. Army Corps of Engineers (CE) has initiated CDF leachate investigations and has developed a theoretical framework for prediction of leachate quality based on mass transport theory. The theoretical framework includes
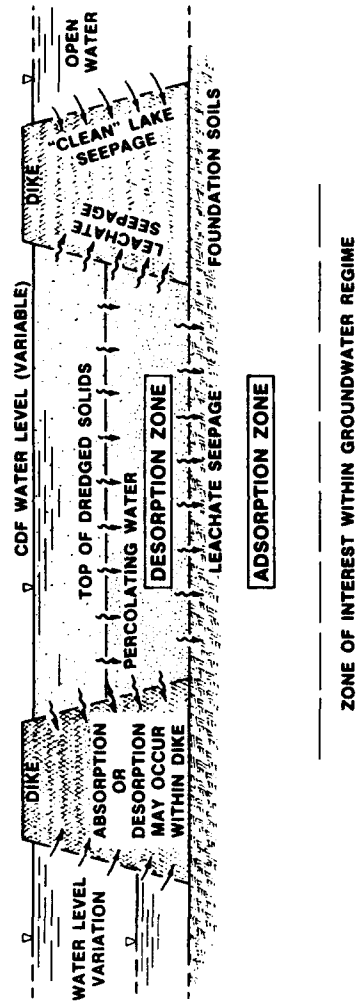
Figure 1. Contaminant migration pathway: leachate seepage

both batch and column testing. Batch testing provides a quick, relatively easy method for determining the distribution of contaminants between dredged material and leachate, while column testing more closely approximates contaminant losses from a CDF under field conditions. Batch and column results are integrated by using distribution coefficients derived from batch testing in conjunction with column operating parameters and mass transport theory to compare predicted results with those observed from column leaching experiments.
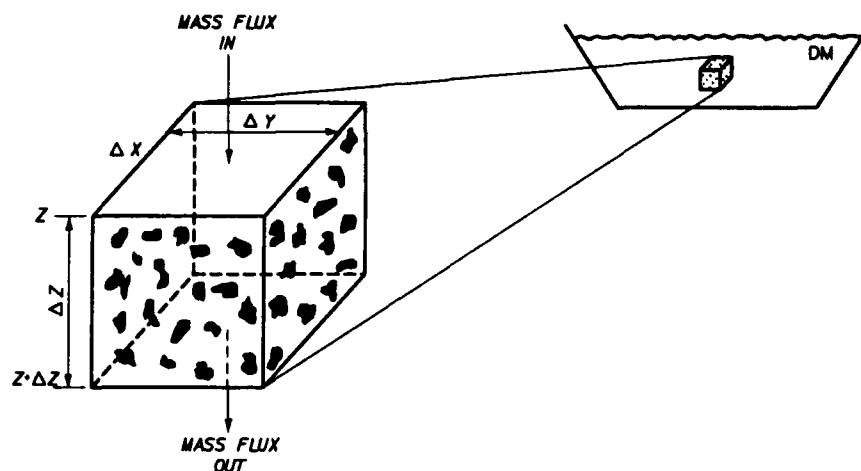
We report here results of batch and column tests conducted with dredged material. Comparability of batch and column data and directions for further research are also discussed.

BACKGROUND

Contaminant migration via leachate seepage is a porous-media contaminant transport problem (Figure 2). Leaching is defined as interphase transfer of contaminants from dredged material solids to the pore water surrounding the solids and the subsequent transport of these contaminants by pore water seepage. Thus, leaching is interphase mass transfer (Equation 2, Figure 2) coupled with porous-media fluid mechanics (Equation 1, Figure 2). Interphase mass transfer during dredged material leaching is a complicated interaction of many elementary processes and factors such as adsorption, desorption, precipitation, dissolution, surface complexation, redox potential, ionic strength, and pH. A complete description of all these processes, their interactions, and factors affecting these processes is not presently possible. Instead, a lumped parameter, the distribution coefficient (K_d), is used to describe the distribution of contaminant between aqueous and solid phases.

To simplify predictive laboratory tests and mathematical models for routine use, local equilibrium conditions are assumed between the dredged material and leachate. When the rate at which water moves is slow relative to the rate at which equilibrium is approached, a local chemical equilibrium exists between the pore water and the sediment solids. The local equilibrium assumption implies that as a parcel of water passes a parcel of dredged material solids, the water and solids come to chemical equilibrium before the parcel of water moves to contact the next parcel of dredged material solids. Leachate quality at the surface and at the bottom of a CDF may differ, while both are in equilibrium with the dredged material solids. Some soil column studies have indicated that the local equilibrium assumption is valid for pore water velocities as high as 10^{-5} cm/sec (Valocchi 1985). In reality, equilibrium controlled desorption requires an infinitely fast desorption rate. However, if the critical interphase transfer rates are sufficiently fast, the equilibrium assumption can yield results indistinguishable from those obtained by full kinetic modeling (Jennings and Kirkner 1984, Valocchi 1985, Bahr and Rubin 1987).

In addition to being a good approximation, the assumption of equilibrium controlled desorption is conservative; that is, predictions based on the equilibrium assumption will overestimate leachate contaminant concentrations for dredged material. The equilibrium assumption is conservative because interphase transfer is from the dredged material solids to the pore water, and equilibrium means that all of the desorption that can occur has occurred. Thus, for clean water entering the dredged material, pore water contaminant concentrations cannot be higher than the equilibrium value.

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$$D_p \frac{\partial^2 C_i}{\partial z^2} - V \frac{\partial C_i}{\partial z} + S = \frac{\partial C_i}{\partial t} \qquad (1)$$

$$S = \frac{\rho_b}{n} \frac{\partial q_i}{\partial t} \qquad (2)$$

where

D_p — dispersion coefficient for ith contaminant, m^2/sec

C_i — pore water concentration of ith contaminant, mg/ℓ

z — space dimension, m

V — average pore water velocity, m/sec

t — time, sec

S — interphase contaminant transfer, mg/ℓ sec

ρ_b — bulk density, kg/ℓ

n — porosity, dimensionless

q_i — solid phase concentration of ith contaminant, mg/kg

Figure 2. Mathematical model of dredged material leaching
(from Hill, Myers, and Brannon 1988)

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METHODS

Oxidized Sediment Preparation

Sediment used in aerobic testing was first placed into 38-1 glass aquarium to a depth of approximately 6 cm. The sediment was allowed to oxidize at ambient temperature. Each week the sediment was thoroughly mixed to expose fresh sediment surfaces to the air. When necessary, distilled-deionized (DDI) water was added to the sediment to maintain the original moisture condition. At the end of six months, the sediment was again thoroughly mixed before being used in testing.

Anaerobic Sediment Preparation

Anaerobic sediments were maintained in sealed containers under refrigeration at 4 °C. All sample handling and manipulation was conducted in a glove box under a nitrogen atmosphere to preclude sediment oxidation.

Batch Testing

A 4:1 water-to-sediment ratio and a shaking time of 24 hr were used in the sequential batch leach tests. General test procedures for assessing steady-state leachate and sediment metal and organic contaminant concentrations are detailed in Table 1. Sequential batch tests for metals under anaerobic conditions were conducted in triplicate 250-ml polycarbonate centrifuge bottles with leakproof caps. Each centrifuge bottle was loaded under a nitrogen atmosphere with anaerobic sediment and deoxygenated DDI water. Tubes were mechanically shaken, then centrifuged at 13,000 x g for 30 min. Most of the leachate from each 250-ml centrifuge bottle was filtered through a 0.45-μm membrane filter. The unfiltered leachate was analyzed for pH using a combination electrode and a millivolt meter, and for conductivity using a Yellow Springs Instrument Company conductivity meter and cell. Fresh deoxygenated DDI water was added to replace the leachate removed for analysis. The procedure described above for sequentially contacting anaerobic sediment with clean water was repeated seven times. The same general procedure was repeated for aerobic batch leach tests for metals, except that anaerobic conditions were not maintained.

Testing of sediment for organic compounds was conducted as described for metals except that 450-ml stainless steel centrifuge tubes double-rinsed with acetone were used. Also, the total mass (approximately 350 g) of sediment and water was adjusted to allow the tube to be safely centrifuged at 6,200 rpm (6,500 x g). Following shaking, samples were removed from the tumbler and centrifuged for 30 min. Resulting supernatants were filtered through a Whatman GF/D prefilter and a Gelman AE filter with a nominal pore size of 1.0 μm. The filters (Whatman GF/D prefilters and Gelman AE filters) are binderless, glass-fiber containing no detectable organic contaminants. As a further precaution against contamination, the filters were combusted at 400 °C prior to use. Filtration was conducted under a nitrogen atmosphere and samples for organic contaminants were acidified with a few drops of Ultrex nitric acid and refrigerated at 4 °C in acetone-rinsed 2-ℓ glass bottles until analyzed. A subsample of filtered leachate was set aside from both the anaerobic and aerobic tests for analysis of total organic carbon. After each cycle, the sediment was remixed with DDI water, shaken for 24 hr, and then processed as

TABLE 1. TEST SEQUENCE FOR SEQUENTIAL BATCH LEACHING OF ANAEROBIC SEDIMENT FOR ORGANIC CONTAMINANTS AND METALS

Step 1.   Load sediment into appropriate centrifuge tubes; 250-ml polycarbonate for metals and 450-ml stainless steel for organic contaminants. Add sufficient water to each tube to bring final water-to-sediment ratio to 4:1. Load sufficient number of stainless steel tubes to obtain sufficient leachate for analysis.

Step 2.   Place centrifuge tubes for metals on reciprocating shaker and shake at 160 cycles per minute. Place centrifuge tubes for tributyl TIN and PAHs in rotary mixer and turn at 40 revolutions per minute.

Step 3.   Centrifuge for 30 min at 6,500 × g for organic contaminants and 13,000 × g for metals.

Step 4.   Filter leachate through 0.45-μm membrane filters for metals or through WHATMAN GD/F glass-fiber prefilters followed by GELMAN AE glass-fiber filters of 1.0-μm nominal pore size for organic contaminants. Set aside a small amount of leachate prior to acidification for analysis of pH, conductivity, and TOC.

Step 5.   Return to Step 2 after replacing leachate with deoxygenated-distilled water. Repeat the entire procedure the desired number or times.

Notes: Testing sequence is the same for aerobic sediments except that anaerobic integrity is not maintained.

previously described. Three replicates were taken through six leach cycles for the anaerobic and aerobic testing.

Column Leach Testing

Column leaching tests were conducted in divided-flow permeameters designed to minimize wall effects and provide for pressurized operation (Figure 3). The inner permeameter ring divides flow, separating the leachate flowing through the center of the column from that flowing down the walls, thereby minimizing wall effects on leachate quality. The applied pressure forces water through the sediment at rates sufficient to allow sample collection in a reasonable period of time.

Sediment was loaded into the permeameters in several lifts having an average thickness of 5 cm, the number of lifts added depend on the total sediment thickness desired. As each lift of water-saturated sediment was added, the permeameter was vigorously agitated on a vibrating table to remove trapped air. The weight and height of each lift were measured and recorded following vibration. Sediment height averaged 18 cm for metal and 36 cm for organic
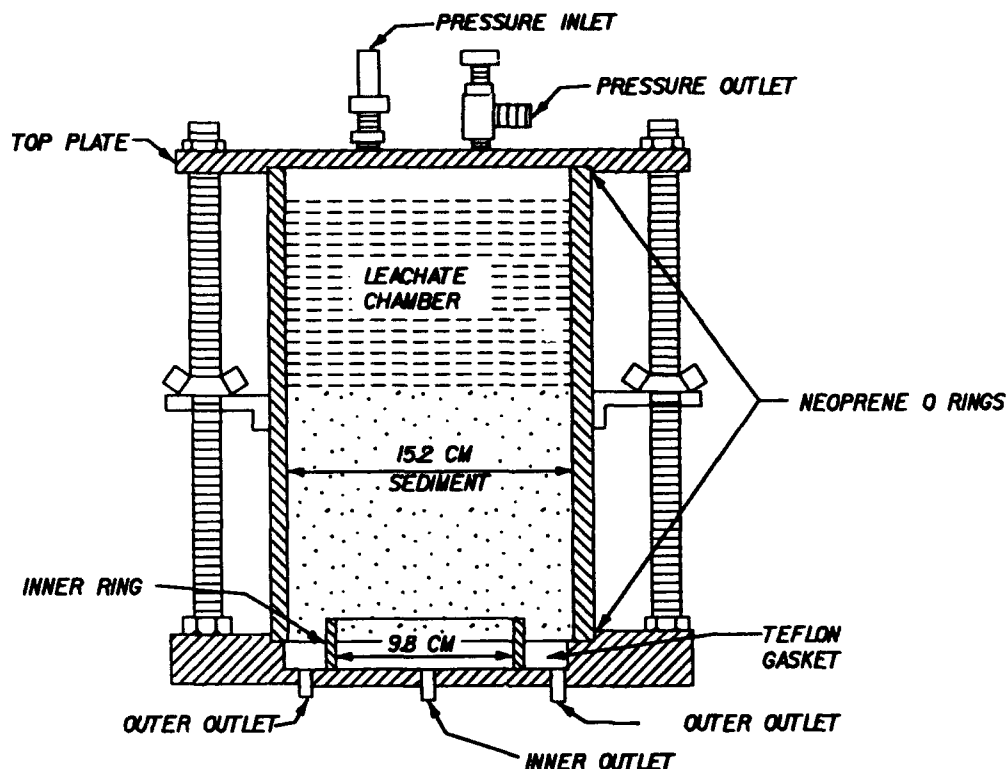
Figure 3. Divided-flow leaching column

contaminant analysis. A greater depth of sediment was needed for organic analysis because a greater sample volume was needed for chemical analyses. Sediment pore volume was determined by measuring the total weight and volume of sediment added to the permeameter and then the weight and volume of sediment samples before and following oven drying at 105° C; weight loss upon drying was then equated to the volume of water in the permeable voids. Next, the void volume for the sediment column above the inner ring of each permeameter was determined. Therefore, pore volumes eluted refer to the column of water filled voids above the permeameter inner ring.

Following sediment addition, distilled, deionized water was added to the permeameters; the apparatus was sealed and pressurized with either nitrogen or air depending on whether the test was conducted on anaerobic or aerobic sediment, respectively. Periodic addition of water was necessary during the course of a test. Effluent from the inner and outer permeameter rings was drained through teflon tubing into 1,000-ml graduated cylinders. The cylinder, receiving flow from the inner outlet of each permeameter, was isolated from the atmosphere by a water trap that allowed gas used to pressurize the permeameters to escape without exposing the leachate to the atmosphere. The collection cylinder head-space was purged with nitrogen prior to testing anaerobic sediment.

Effluent flow from the permeameters was regulated by adjusting the operating pressure. The permeability of sediments generally decreased for the first 2 weeks of operation. As permeability decreased, operating pressure was increased to maintain a constant flow. Permeameter flow generally stabilized

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after 2 weeks of operation. A daily record was maintained of operating pressure and flow from both the inner and outer rings of the permeameter. Leachate samples for metals and organic contaminants from anaerobic sediment were filtered under nitrogen using procedures previously described for batch testing.

Data and Statistical Analysis

All statistical analyses were conducted using methods developed by the Statistical Analysis Systems Institute (Barr et al. 1976). To test for differences between means, analysis of variance procedures were used.

RESULTS AND DISCUSSION

Sequential batch tests have been applied to estuarine and freshwater sediments (Environmental Laboratory 1987; Myers and Brannon 1988b; Brannon et al. 1989; Palermo et al. 1989; Brannon, Myers, and Price 1990). Results of sequential batch leaching of contaminants are strongly affected by the salinity of the sediment being tested. Sediments from saline environments possess high pore water concentrations of anions and cations such as sodium, chloride, potassium, and sulfate that increase the ionic strength of pore waters and leachate. As sequential batch leaching with fresh water proceeds, the ionic strength of the freshwater leachate remains relatively constant, but the ionic strength of leachate from saline sediments decreases (Brannon et al. 1991). In the following paragraphs, typical results from estuarine (saline) and freshwater sediments are presented.

Freshwater Sediments

Cadmium and zinc (Zn) desorption isotherms (sediment concentration (q) versus leachate concentration (C)) prepared from anaerobic sequential batch leach tests conducted on freshwater sediment from Indiana Harbor, Indiana (Environmental Laboratory 1987) are shown in Figure 4. These desorption isotherms are well defined and follow the theory for constant K_d, where K_d is the slope of the isotherm.

Anaerobic sequential batch leaching for polychlorinated biphenyls (PCBs) in Indiana Harbor sediment produced clustered desorption isotherms that did not show in Figure 5 a well-defined trend (Environmental Laboratory 1987). The insert in the upper right-hand corner of Figure 5 shows that when plotted with the graph origin at the point 0,0 the data reduce to a dot. For clustered desorption isotherms, K_d is the single point distribution coefficient with the centroid of the cluster as the point q,C. Although the desorption isotherm is clustered, the distribution coefficient is interpreted as a constant.

Results of other sequential batch leach tests on anaerobic freshwater sediments have shown the classical desorption indicated in Figures 4 and 5 (Brannon et al. 1989; Brannon, Myers, and Price 1990; Myers 1991). In general, distribution coefficients for metals are small, usually less than 10 ℓ/kg, and the fraction of metal resistant to aqueous leaching is large, usually greater than 99 percent of the bulk metal concentration. The distribution coefficient for PCBs in freshwater sediments is constant and usually greater than 1,000 ℓ/kg, and the fraction resistant to leaching is usually assumed to be zero.
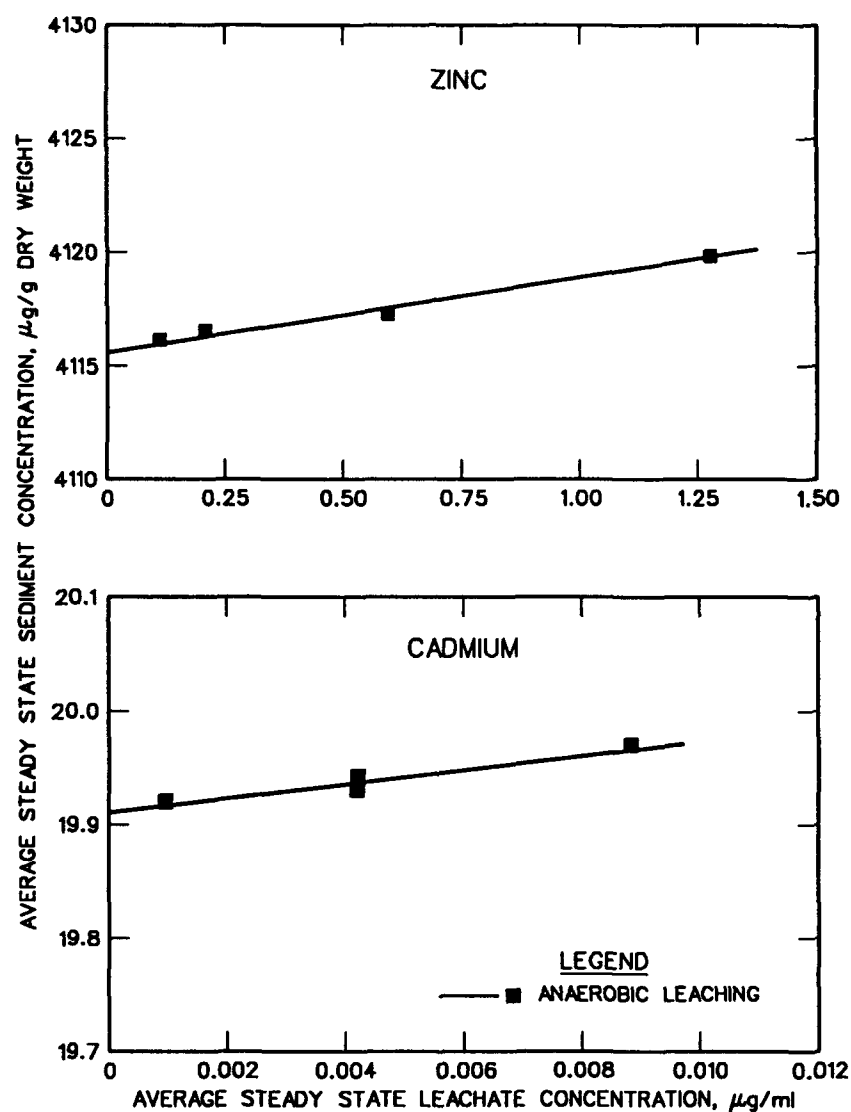
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Figure 4. Desorption isotherms for zinc and cadmium
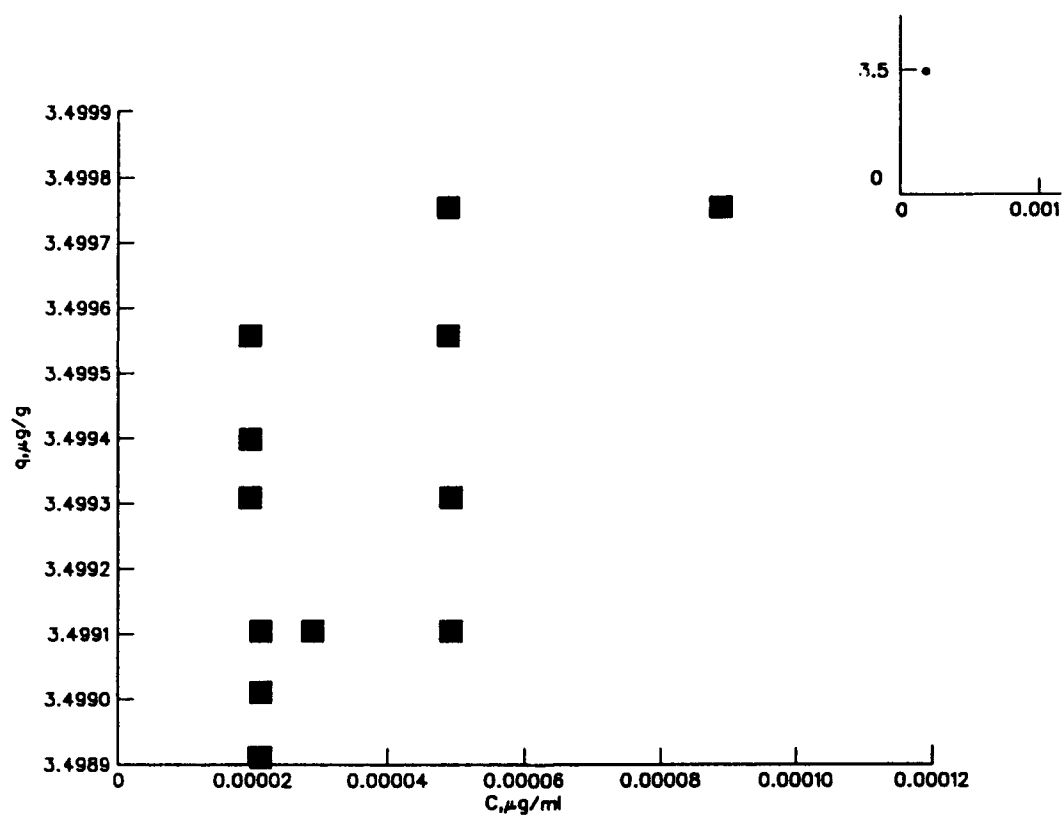in Indiana Harbor sediment

Figure 5.   Desorption isotherm for 2,2',4,4'-tetrachlorobiphenyl
for anaerobic leaching of Indiana Harbor sediment

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Estuarine Sediment

Arsenic and nickel concentrations in anaerobic sequential batch leachate from Everett Bay, Washington, sediments as a function of sequential leach cycle number are shown in Figure 6. Arsenic and nickel concentrations were low initially, peaked at either the third or fourth leach cycle, then declined. The arsenic and nickel desorption isotherms prepared from the data in Figure 6 are shown in Figure 7. Initially, the isotherm slopes for these elements were negative; that is, leachate metal concentrations increased as the bulk sediment metal concentrations decreased. After, the third or fourth leaching cycle, the isotherms form changed to a classical form.
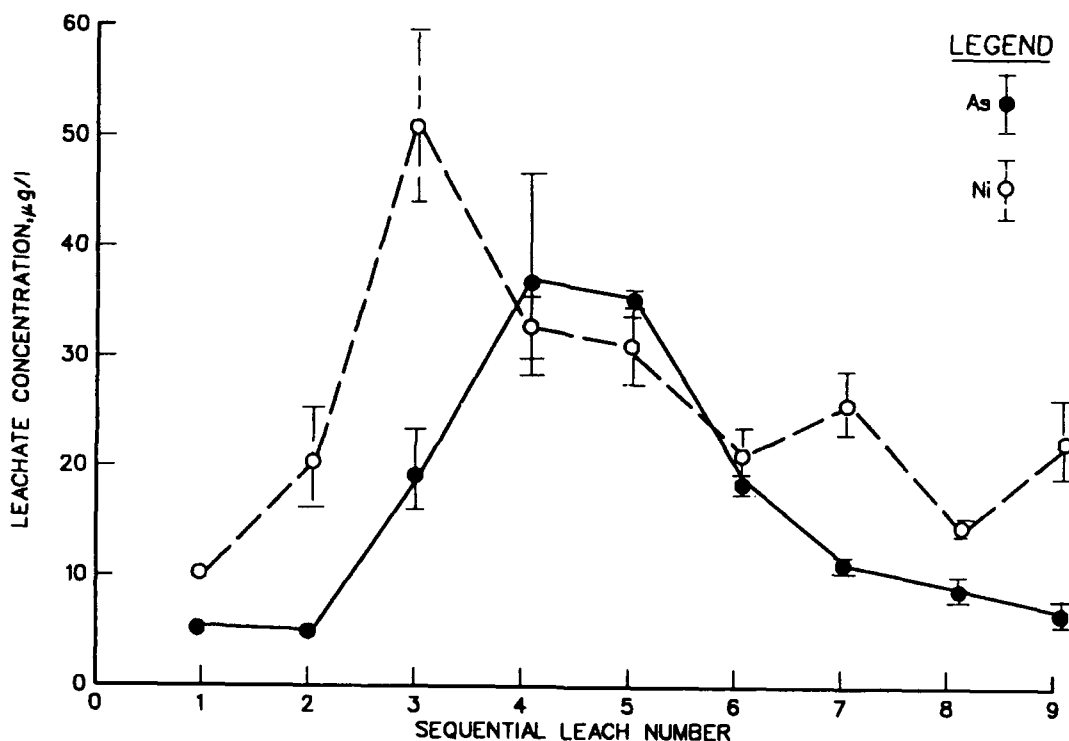
Figure 6. Arsenic and nickel concentrations in anaerobic sequential batch leachate for Everett Harbor sediment

In some studies of estuarine sediments, slopes of metal desorption isotherms have been negative through the entire leaching sequence (Figure 8). A turning point was never reached, although a turning point must exist; otherwise, the desorption isotherm will intersect the abscissa. This result is a physical impossibility because it implies that a clean sediment can leach contaminant. In the limited testing conducted thus far, these types of desorption isotherms have been found only for estuarine sediments.

Figure 9 shows a PCB desorption isotherm prepared from anaerobic sequential batch leach tests conducted on sediment from the New Bedford Harbor Superfund Site, New Bedford, Massachusetts, (Myers and Brannon 1988b). This desorption isotherm indicates nonconstant K_d during sequential leaching. Nonconstant PCB partitioning during sequential leaching has recently been related

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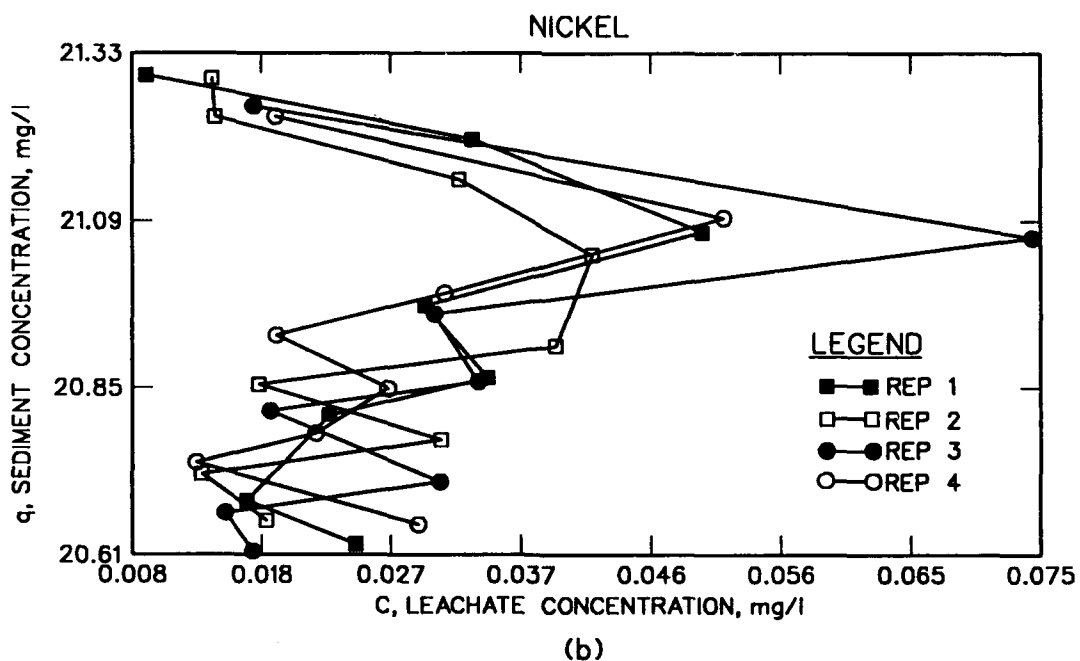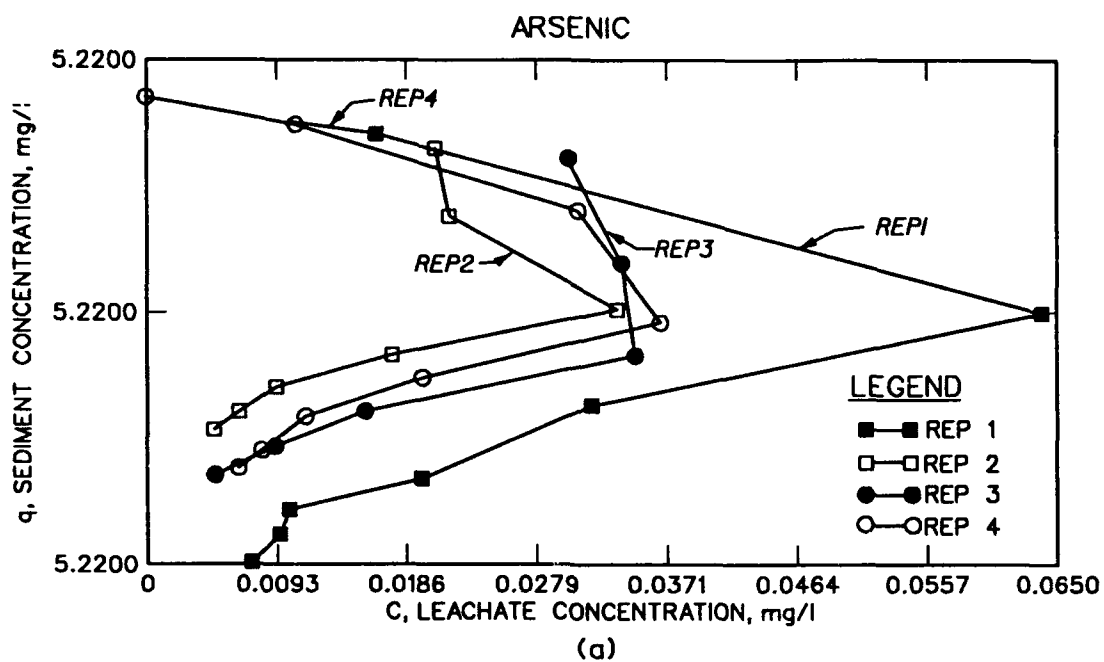
Figure 7. Arsenic (a) and nickel (b) desorption isotherms for Everett Harbor sediment

Figure 8.   Desorption plot for Zn from anaerobic sequential
batch testing of New Bedford Harbor sediment

Figure 9.   Desorption isotherm for PCB congener 118 from sequential
batch leaching of New Bedford harbor sediment

to salt washout and subsequent deflocculation of colloidal sediment organic carbon containing PCBs (Brannon et al. 1991). As previously discussed, deflocculation of colloidal sediment organic carbon refers to release of organic carbon associated with sediment. The overall result is an elution curve that has a distinct peak in leachate 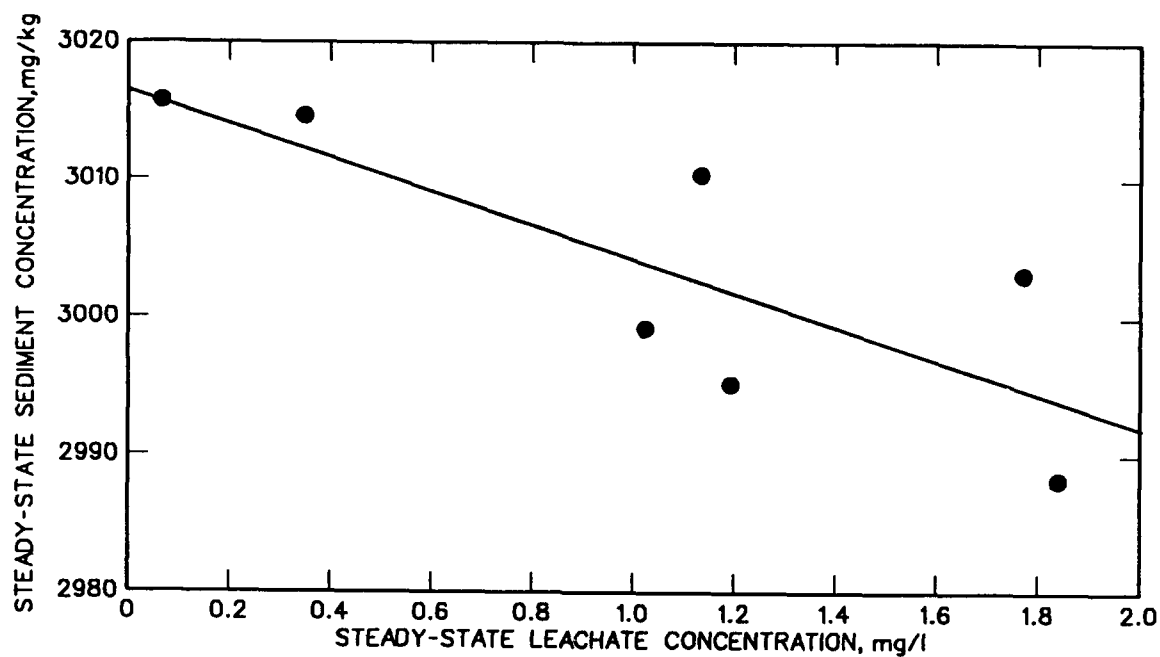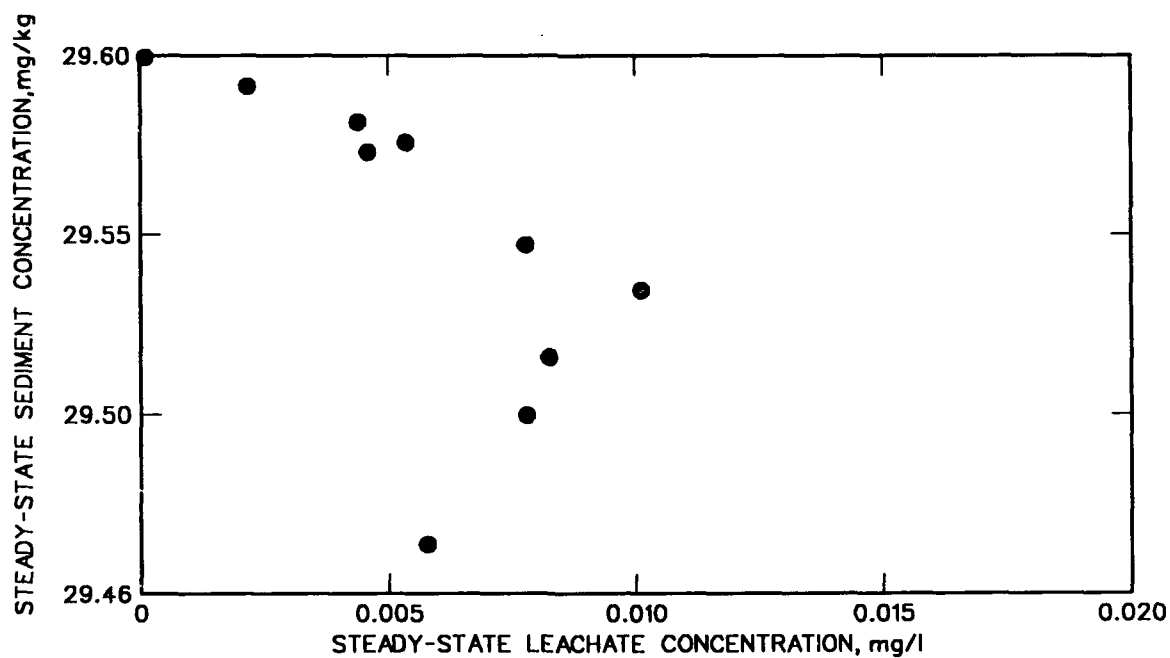PCB concentrations that occurs after the first four leaching cycles. This same effect has been observed in other studies (Brannon et al. 1989).

Sediment Oxidation Status

Sediment oxidation status exerts pronounced effects on metals leaching from most saline sediments, e.g., Baltimore Harbor sediment (Figure 10). In saline sediments high in sulfur and low in carbonate, leachate pH generally shows a marked decrease following 6 months of oxidation (Figure 10a). In addition to the drop in pH brought about by sediment oxidation, leachate sulfate concentration increased by an order of magnitude because of oxidation of sulfur and sulfide compounds in the anaerobic sediment (Figure 10b). As sequential batch leaching progressed, leachate pH increased and sulfate concentrations decreased in the aerobic leachate. Aerobic conditions resulted in much higher concentrations of Zn in the leachate than anaerobic conditions (Figure 10c). During the course of sequential batch testing, 7.7 percent of sediment Zn was lost under aerobic conditions compared to 0.4 percent under anaerobic conditions. These results are illustrative of the effects that sediment oxidation can exert on metal leachate concentrations.

Column Testing

Sequential batch leach tests, useful for determining desorption kinetics, equilibrium distribution coefficients, and long-term leaching characteristics, cannot simulate advective-dispersive and other mass transfer effects occurring in CDF's. Column leach tests are used as laboratory scale physical models of contaminant elution from dredged material that include advective-dispersive and other mass transfer effects. An integrated approach is used to examine the applicability of source terms formulated on the basis of sequential batch leach data to contaminant transport in porous media. In the integrated approach, parameters from sequential batch leach tests, soils tests, and column operating records are used in a contaminant transport equation to predict column elution histories. Predictions are then compared to observed elution behavior. If predicted and observed behavior agree, the conclusion may be reached that the processes governing transfer of contaminants from dredged material solids to water have been adequately described. If not, other source term formulations may be needed. Once interphase transfer has been adequately described, contaminant migration by leaching can be evaluated for the flow conditions that apply in the field.

To date, column leaching studies have been conducted on sediments from Indiana Harbor, Indiana (Environmental Laboratory 1987), New Bedford Harbor, Massachusetts (Myers and Brannon 1988a), and Everett Harbor, Washington (Palermo et al. 1989). The major problems encountered in using the divided-flow column leaching apparatus were the number of pore volumes that could be eluted and the potential for sample deterioration during collection.
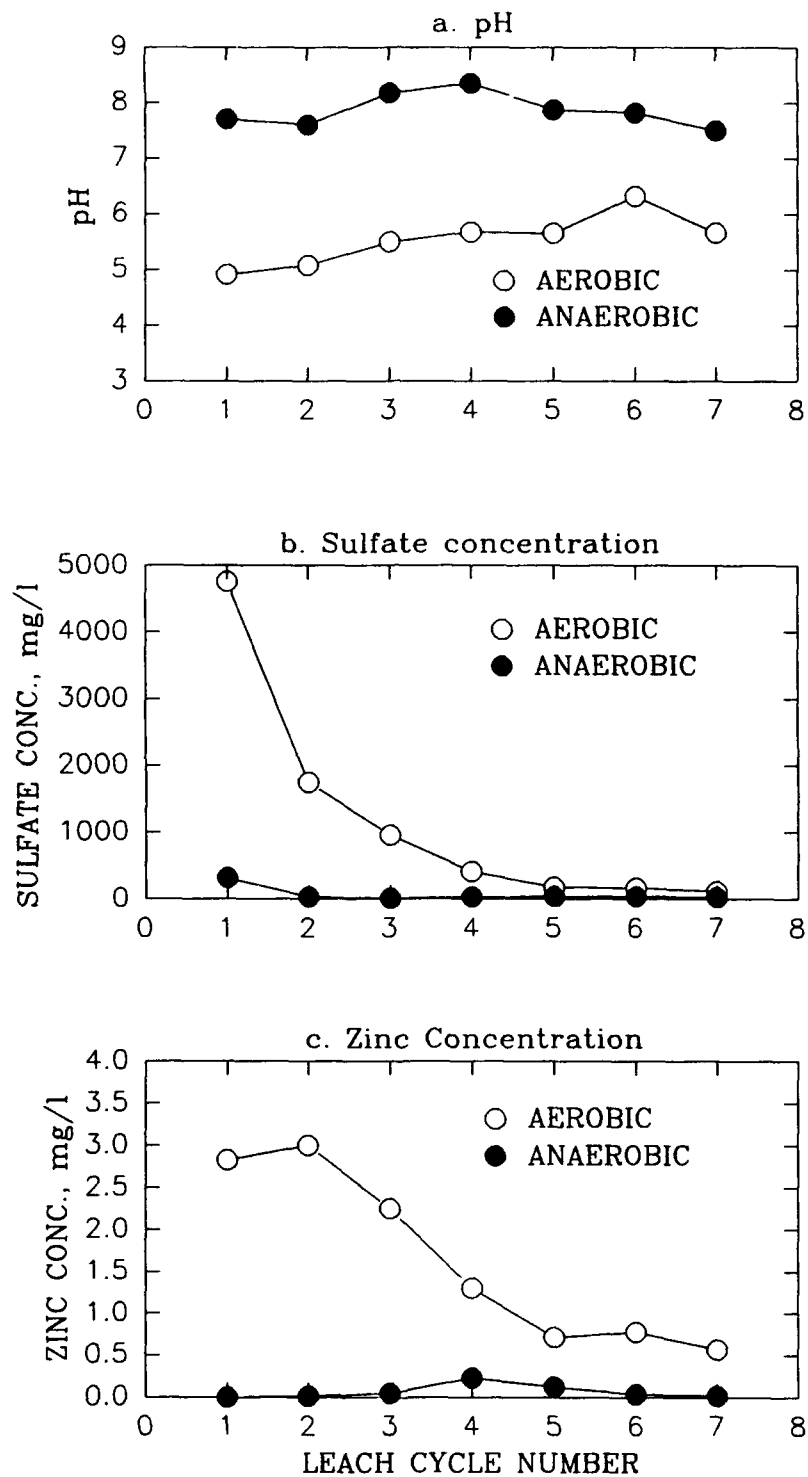
Figure 10.   Relationship between oxidation state in
Baltimore sediment and leachate

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Freshwater

Anaerobic column leach tests conducted on Indiana Harbor sediment indicated that a source term based on contaminant specific constant K_d adequately described observed elution curves for metals and PCB's (Environmental Laboratory 1987). Figure 11 shows predicted and observed column elution curves for PCBs from Indiana Harbor sediment. The column leach tests also showed that the sequential batch leach test overestimated metals and PCB concentrations in column leachates and was, therefore, a conservative estimator of leachate quality for Indiana Harbor dredged material.
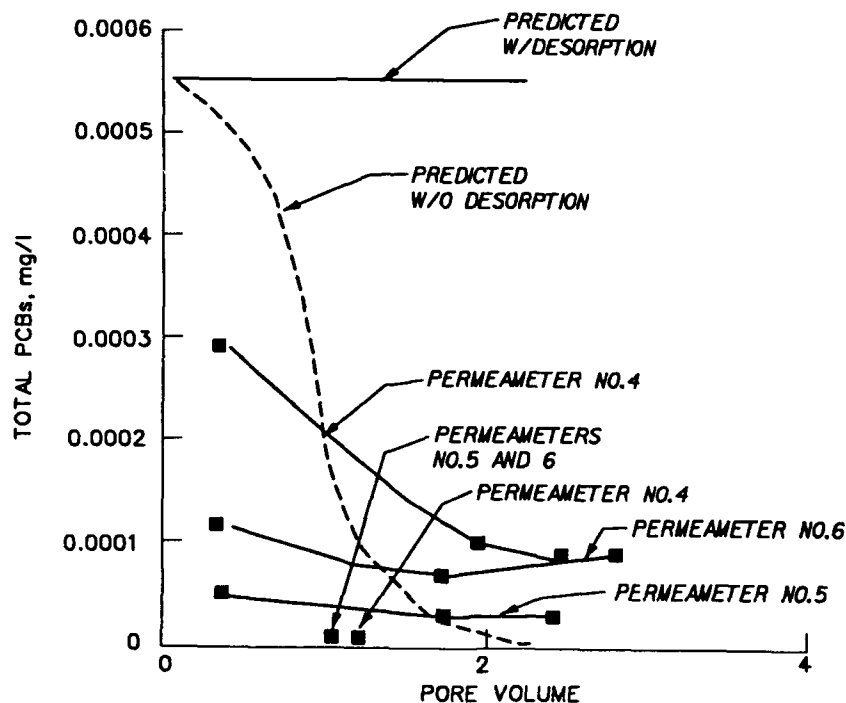
Figure 11. Total PCB concentrations in anaerobic column leachate for Indiana Harbor sediment

The prediction shown in Figure 11 was developed using a semi-infinite analytical solution to Equation 1 (see Figure 2) with constant K_d. Sequential batch leach tests on other freshwater sediments indicate that source term formulations based on constant K_d will probably describe contaminant leaching for fresh water sediments (Brannon et al. 1989, Myers 1991). However, Indiana Harbor sediment is the only freshwater sediment that has been investigated in column leaching studies. Furthermore, only four pore volumes were eluted. Operational limitations of the columns prevented collection of more data. Elution of the volume of sample needed for PCB analysis required several months, and elution of additional pore volumes would have extended the period of data collection to beyond the scope of the study. An improved column design that overcomes these limitations is currently being evaluated.

Aerobic column leaching studies were also conducted on aged Indiana Harbor sediment. These studies were largely unsuccessful because the residual oxygen demand in the sediment converted "aerobic" columns to anaerobic columns

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shortly after they were flooded (Environmental Laboratory 1987). Since aerobic batch and column leach tests were not conducted under equivalent redox conditions, source term formulations developed from aerobic batch tests were not applicable to "aerobic" columns. Application of the integrated approach to partially oxidized sediment was, therefore, inappropriate because the assumption of equivalent redox conditions could not be maintained.

Estuarine Sediment

Everett Harbor

Results of sequential batch leaching of Everett Harbor sediment differed sharply from results for Indiana Harbor sediment. Leachate contaminant concentrations were lower and release of contaminants during anaerobic sequential batch leach testing did not follow the classical desorption behavior observed for Indiana Harbor sediment. Column leaching studies on Everett Harbor sediment could not confirm or refute the trends observed in sequential batch leach tests because column operational limitations prevented elution of a sufficient number of pore volumes.

The permeameter elution curve for cadmium in leachate for anaerobic Everett Harbor sediment was not carried far enough to compare to elution trends observed in the sequential batch leach test (Figure 12). The number of pore volumes needed for comparison were not eluted because, as previously discussed for Indiana Harbor sediment, to do so would have extended the period of data collection beyond the scope of the study. Furthermore, the predicted curve in Figure 12 is based on equating each cycle in the sequential batch test to elution of an equivalent number of pore volumes; that is, Equation 2 with a source term was not used. To predict column leachate concentrations using Equation 2 was impossible because the desorption isotherms from the sequential batch leach tests showed nonconstant partitioning and source term formations for this type of partitioning are not available.

Aerobic column leaching studies were also conducted on aged Everett Harbor sediment. Residual sediment oxygen demand, as previously discussed for Indiana Harbor sediment, made application of the integrated approach inappropriate (Palermo et al. 1989).

New Bedford Harbor

Leach tests conducted on anaerobic New Bedford Harbor sediment showed that desorption theory based on contaminant specific constant K_d did not adequately described leaching of metals or PCB's in either batch or column leach tests (Myers and Brannon 1988b). Desorption isotherms showed the nonconstant partitioning previously observed for Everett Harbor sediment. Sequential batch leach data indicated that maximum leachate contaminant concentrations would not occur until after several pore volumes were eluted. Therefore, the time period for data collection from column leach tests was extended for New Bedford Harbor sediment relative to the data collection periods used for Indiana Harbor and Everett Harbor sediments.

Column leachate PCB data for anaerobic New Bedford Harbor sediment showed complicated elution curves in which concentrations first tended to decrease and then increase to peak values after about three pore volumes had

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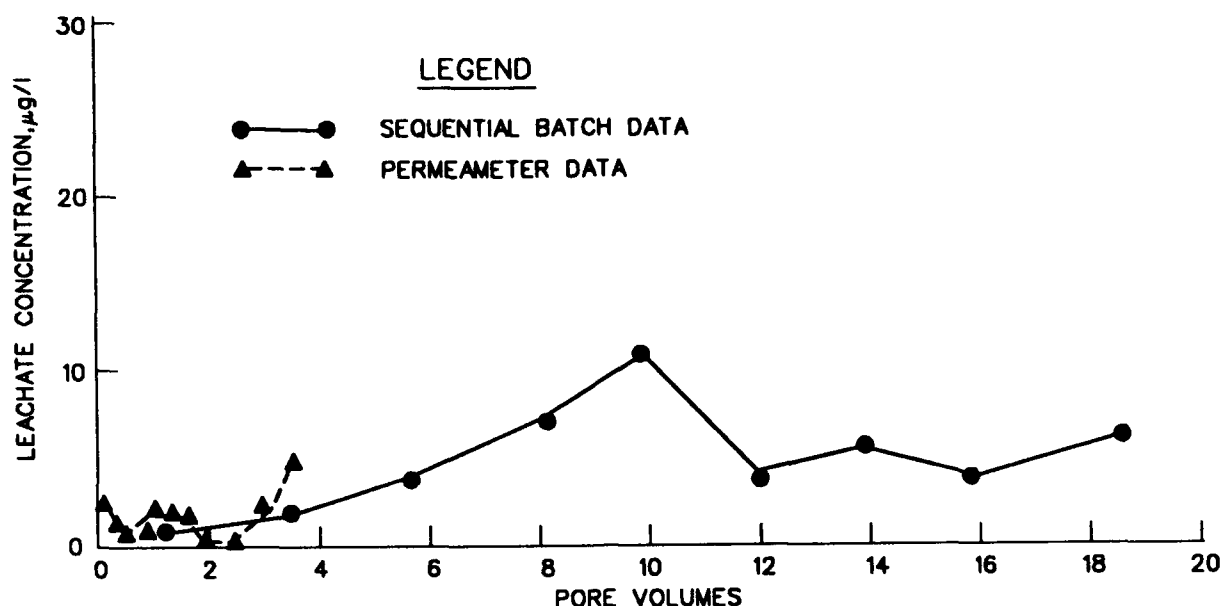
Figure 12.   Comparison of observed and predicted cadmium
concentrations in leachate from anaerobic
permeameters for Everett Harbor sediment

been eluted.   These trends are illustrated for aroclor 1242 in Figure 13.   The
decrease in concentrations from initial values corresponded to the period in
which electrical conductivity rapidly decreased, and the increase to peak
concentrations corresponded to the period following development of lower,
relatively constant electrical conductivity in column leachate.   More than a
year was required to elute the six pore volumes shown in Figure 13.

Although predicted and observed curves are not shown in Figure 13, the
shape of the observed PCB elution curve is in agreement with the shape pre-
dicted from sequential batch leach tests (Myers and Brannon 1988b).   The PCB
concentrations in column leachate, however, were significantly lower than in
the batch leachates.   Several explanations for concentration differences
include loss of contaminants by sorption to collection vessels during extended
periods of leachate collection, particle disaggregation effects related to
differences in hydraulic regimes in batch and column leach tests, and the
inability to elute more pore volumes. Any of these factors may have precluded
covery of true peak concentrations at higher pore volumes.   An improved
lumn design that overcomes some of these problems is currently being evalu-
ated (Myers, Gambrell, and Tittlebaum 1991).   Additional column leaching
studies on estuarine sediments with elution of more than six pore volumes is
needed to verify the correlation of contaminant elution curves with changes in
electrical conductivity observed in the New Bedford Harbor study.

Aerobic column leaching studies were also conducted on aged New Bedford
Harbor sediment.   Residual sediment oxygen demand, as previously discussed for
Indiana and Everett Harbor sediments, made application of the integrated
approach inappropriate.

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Figure 13. Aroclor 1242 concentration in column leachate from anaerobic New Bedford Harbor Sediment

SUMMARY AND CONCLUSIONS

In the leaching studies conducted to date, each sediment has provided unique leachate quality data. A source term based on contaminant specific constant K_d adequately described observed elution curves for metals and PCB's in freshwater Indiana Harbor sediment. Sequential batch leach tests in Ind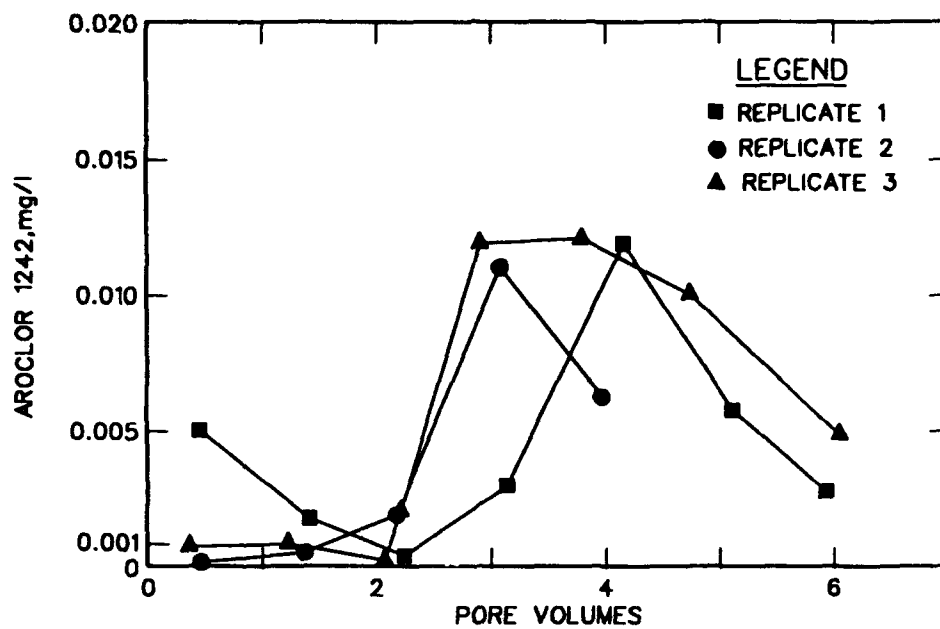iana Harbor sediment overestimated metals and PCB concentrations in column leachates and was, therefore, a conservative estimator of leachate quality for Indiana Harbor dredged material.

Sequential batch leaching of saline Everett Harbor sediment did not follow the classical desorption behavior observed for freshwater Indiana Harbor sediment. Desorption isotherms showed nonconstant partitioning for which source term formulations are not available. Similar nonconstant partitioning was observed in saline New Bedford Harbor sediments. Batch leaching curves could not be validated for either saline sediment because of the limited number of pore volumes (4-6) that could be eluted from the columns.

Changes in sediment redox conditions and sediment initial salinity have been shown to strongly influence leachate quality. Sediment aged to simulate development of an aerobic crust tends to release metals, whereas anaerobic sediments tend to retain metals. The pH changes associated with oxidation of sediments are believed to be the underlying cause of increases in metals mobility. Furthermore, estuarine and freshwater sediments behave differently. Desorption isotherms for contaminants in freshwater sediments tend to follow classical sorption theory, whereas, isotherms for estuarine sediments are unlike any previously reported. Sediment organic matter and the tendency to release sediment organic matter as salts are leached are believed to be the underlying factors causing differences in results between freshwater and estuarine sediment.

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PREDICTION OF SURPLUS WATER DENSITY
AT RECLAMATION SITE

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ABSTRACT

When a land is reclaimed using pump-dredging soils, fluid is poured into the landfill site together with earth and sand, giving rise to the problem of surplus water. When land reclamation works approach their end, muddy water overflows the site because of its limitation of volume. In recent years, regulations have been enforced to control effluent from reclaimed lands to prevent water pollution and protect environments, and such surplus water should be disposed properly, according to established standards. In order to work out an effective plan for surplus water disposal, it is necessary to know the behavior of surplus water, especially the changes in its density that take place in accordance with the progress in reclamation works. No noticeable researches have been done on this subject, and there is no established method to work out a disposal plan. With the purpose of casting a light on this problem, a reclamation site related to an actual engineering work was surveyed to study to behavior of surplus water; on the basis of findings on the spot, tests using a water tank model were conducted top examine the accuracy of reproducibility of onsite conditions.

During the on-the-spot survey, the emphasis of study was placed on the relations between residence time and density of slurry inflow and the grading of turbidity components. for model tests, survey results were taken as the prototype and conformity with the prototype regarding the Frouds Law, and water area load was considered as basic law of similarity. The size of the model was set in a scale of 1 to 30 in horizontal length (Lr - 1/30) and 1 to 10 in vertical length (Hr - 1/10). The following findings were made as the result of the survey and model tests:

<u>a</u>. On-the-spot survey

    (1) Under the conditions of landfill-site area of 27,600 m^2, resident volume of 1-m water depth and inflow of 760 m^3/hr, the shortest resident flow distance stood at 226 m and resident time at 51 min. The water depth was

measured by depth sounding. The water content ratio of soils at the position was 300 to 350 percent.

(2) Average suspended solids (SS) of slurry inflow at the site stood at 115,500 mg/ℓ (70,000-200,000 mg/ℓ), that of slurry at the point 30 m from the sludge outlet at 20,000 mg/ℓ (8,000-41,000 mg/ℓ) and that of surplus water outflow at the spillway was 50 mg/ℓ (13-181 mg/ℓ). The removal rate of slurry inflow near the sludge outlet was 82.8 percent against 99.96 percent at the spillage outlet, indicating that the most of soil grains settle down near the sludge outlet.

(3) As to the grading, slurry inflow contained 8 percent of sand, 89 percent of silt, and 3 percent of clay (of which colloids accounted for 2.7 percent). Particles of less that 20 μm amounted to 90 percent of all particles contained in the slurry near the sludge outlet, with the average of 4 to 5 μm. Similarly, 90 percent of particles contained in surplus water outflow were less than 20 μm with the average standing at 3 to 4 μm, showing that these particles were a little finer than those near the sludge outlet.

b. Model tests

(1) The tests indicated an average surplus water SS density of 173 mg/ℓ (136-218 mg/ℓ) against the prototype's average of 50 mg/ℓ (14-18 mg/ℓ), showing a difference of about 120 mg/ℓ.

(2) Particles of more than 10 μm accounted for 20 percent of all particles contained in the surplus water of the prototype, while the model tests showed the size group occupied only 5 percent. The probable reason was the refloating of soil particles at the spillway of the prototype. Model tests in general showed greater distribution of finer grains than in the prototype.

(3) As to the sedimentation removal rate by particle size, the prototype showed no remarkable changes for size groups, indicating the rate of more than 99 percent for all groups. In the model tests, the size group of more than 10 μm showed a rate of nearly 100 percent , but finer size groups indicated various trends, the 2-to 10-m group showing a

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gradual decrease, the 0.8- to 2-μm group a
gradual increase, and the 0.4- to 0.8-μm
group a gradual decrease. Overall, the
removal rates in model tests were lower by
2 to 5 percent than those of the prototype.

PREFACE

It is often the case with a land reclamation using pimp-dredged soils
that the quality of surplus water deteriorates as the reclamation works pro-
gress and on the final stage of reclamation, muddy water of high density flows
out of the reclamation site because of its limited volume. The emphasis of
study on the volume of a landfill site is usually placed on the rate of change
in the volume of disposed soils. When the quality of surplus water is taken
into consideration, however, it is necessary to give a free volume to the
site. It is also important to grasp and predict the relationship of accumula-
tion of soils with the quality of surplus water, especially its density of SS,
in order to make timely treatment of the surplus water to meet the discharge
standards.

Analysis of the numerical model and model tests are considered to be
useful for prediction of surplus water density at a reclamation site. In
either case, it is necessary to compare the results with the results of on-
the-spot investigation and to examine their reproducibility. Data concerning
this subject are insufficient at present; therefore, a reclamation site
related to an actual engineering work was surveyed to collect data on changes
in water quality. On the basis of the findings, tests using a water tank
model were conducted to grasp the accuracy of reproducibility of onsite
conditions.

During the survey, the relationship between the residence time of slurry
inflow and the density of outflow and the grading of turbidity components were
taken up for probing. In model tests, survey results were takes as the proto-
type, and conformity with the prototype regarding the Frouds Law and water
area load was considered as basic law of similarity; a model of a scale of
horizontal length (1/30) and vertical length (1/10) was used, and the accuracy
of reproducibility of surplus water was confirmed. This report introduces the
results of the survey and model tests.

ON-THE-SPOT SURVEY

This survey was conducted to grasp the relationship between the resi-
dence time of slurry inflow and density of surplus water outflow and the grad-
ing of turbidity components at a reclamation site. The reclamation site was
created for disposal of dredged soils coming from dredging works in Hakata
Port, Kyushu District, to develop a channel and a berth.

Subject Engineering Work

The subject of this survey was the dredging work aimed at the develop-
ment of a channel extension and a berth, which was intended to be one of the
two berths planned at the public wharf (-12 m), shown in Figure 1, but was to
be opened for the time being as a wharf of 9 m in depth.
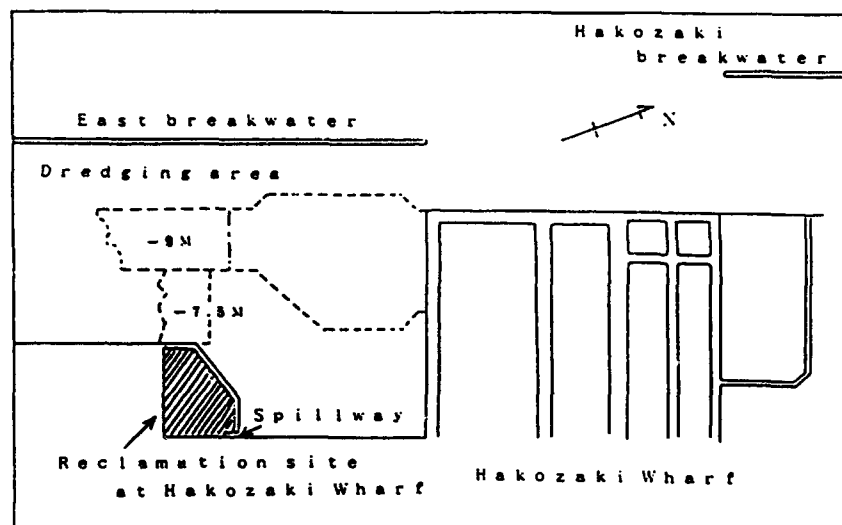
Figure 1. Plotting of reclamation site

The planned volume of dredged soils was 129,500 m^3, and dredging was being done by a special pump (oozer pump) dredge. Dredged soils were disposed of at a landfill site near the dredging area.

As shown in Figure 2, a part of the existing wharf was partitioned by a steel pipe sheet pile, and an embankment 2.5 m high was raised along the edge of the partitioned wharf apron. The area of the reclamation site was 27,600 m^2 with the volume of 237,000 m^3. Figure 3 gives a complete view of a disposal area.

The spillway consisted of a weir with stop log, a sedimentation basin, and an outlet basin. Surplus water was sent out of the outlet basin by four discharge pipes (ϕ610 m/m) into the open sea. For the treatment of surplus water, equipment was set up near the stop log weir to add inorganic or organic coagulant to surplus water. The outlets of the discharge pipes in the open sea were encircled by two nets of pollution prevention membrane. The ceiling of surplus water density was set at SS 60 mg/ℓ at points near the outside net of pollution prevention membrane.

At the time of the survey, a sand pipe (ϕ560 m/m) was set up on land extending from the fixed point to the sludge outlet located on the west side of the reclamation site. Coagulant was not added to surplus water at that time.

Outline of Survey

Cases of Survey

The survey was conducted four times, as shown in Table 1.

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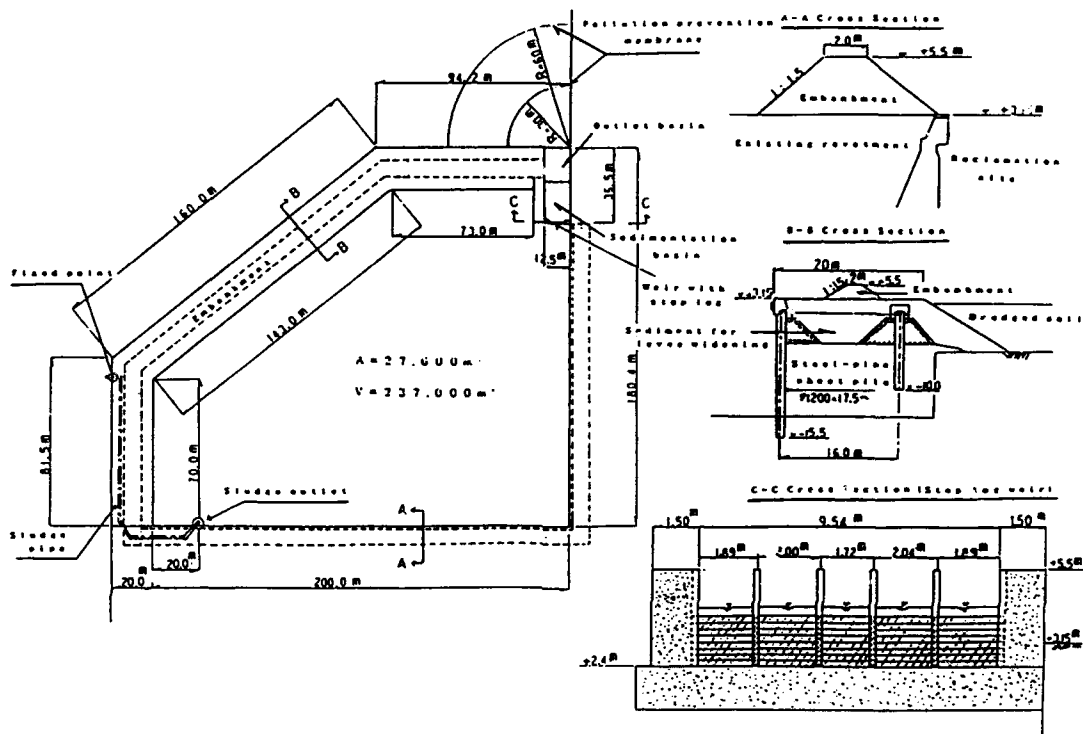
Figure 2. Plan of reclamation site
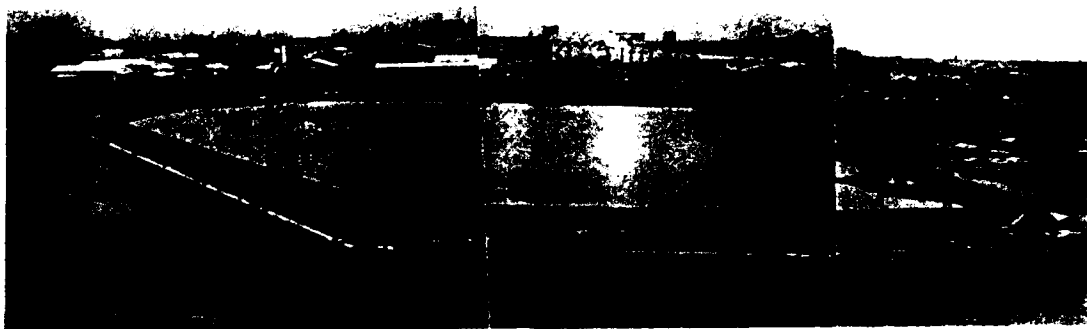
Figure 3. Complete view of disposal area

TABLE 1. CASES OF SURVEY

Case	Accumulated Volume of Dredged Soil at the Time of Survey
Case-A	90,500 m^3
Case-B	97,150 m^3
Case-C	99,658 m^3
Case-D	105,233 m^3

Items of Survey

Soils dredged up with water are carried by a sand pipe to the sludge outlet and discharged in to the landfill site. Of the earth and sand discharged into the site, most of the crude particles settle down around the sludge outlet together with some of finer particles forced to settle through hindered settling or other phenomena. Particles unable to settle down here spread out throughout the site and flow through resident channels toward the spillway, some of them going out of it with surplus water.

Efforts were made during this survey to grasp turbidity not only in degrees or as total SS volume but as SS grading of muddy surplus water at the following three different points. The points are also shown in Table 2 with the items of survey.

TABLE 2. ITEMS OF SURVEY

Point of Survey	Items of Survey	
Inlet point (Sludge outlet)	Time of inlet	
	Inflow	
	Slurry inflow	Water content, grading
Resident flow (Within landfill site)	Soil accumulation	Depth, water content
	Slurry near inlet	Turbidity, SS, grading
Outflow point (Spillway)	Time of outflow	
	Outflow	
	Spillway	Turbidity, SS, grading

a. Grading of slurry inflow. This effort examined whether dredged earth and sand are divided into particles and mixed up completely before being discharged into the reclamation site. when

considerably clayey earth and sand are dredged by cutter pump dredge, the slurry often contains lumps of soils, which may not be divided into particles. Such lumps may not contribute to turbidity when discharged into a landfill site. In order to confirm if such conditions existed, slurry samples obtained near the sludge outlet were examined by two methods. One of the methods was JISA1204 test method (names "Shape" method) retained the original conditions of slurry samples and examined the grading. The results of the two ways of examination were then compared.

b. Grading of slurry near the sludge outlet. Rates of settling of floating particles near the sludge outlet or within the radius of about 30 m from it were examined on the basis of samples of slurry in this scope and those of slurry inflow, both taken in the same period.

c. Grading of surplus water outflow. Grading was confirmed of surplus water overflowing the weir with stop log of the spillway.

Results of Survey

Confirmation of Stability

Adjustment of the Stop log weir was done in the morning and in the evening. Logs were added in the morning and withdrawn or added in the evening. Therefore, the outflow of surplus water stopped early in the morning, started again after 3 to 4 hr, and reached a stable state after an additional 2 to 3 hr, maintaining the stability up to the time of adjustment in the evening.

On the other hand, turbidity of the outflow was low for about an hour after the start of outflow but tended to become high as the volume of outflow increased. Later on, turbidity moved downward in Case-A, leveled off in Case-B, and increased further in Case-C. In Case-D, the survey was conducted for two day s and the turbidimeter's automatic recording indicated a trend of low to high, then to low, reaching a stable state of quality after 10 hr since the start of outflow.

On the basis of above data, it was hedged that stability of outflow volume and water quality was not reached in Cases A, B, and C, and only the data in Case-D could be utilized as materials for prediction. Samples in Case-D were taken during the period of *:00 to 15:00 on February 17, and the resulting values were considered to be representative. Therefore, only the results of Case-D will be reported below.

Results of the survey on inlet time, the width and height of the weir with stop log, overflow depth and turbidity in Case-D are shown in Figure 4.

Slurry inflow

The fo'lowing findings were made:

a. Examination. Slurry inflow samples indicated a water content of 420 to 2,320 percent and soil grain specific gravity of 7,607 to 2,651.

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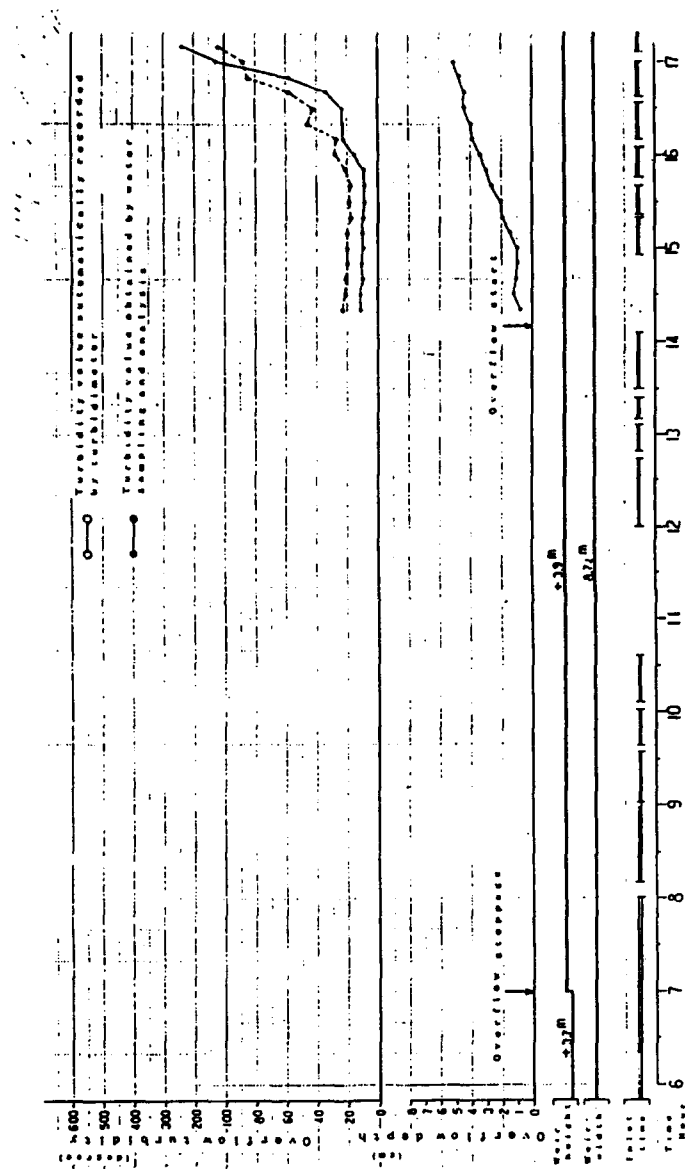
Figure 4. Results of examination of Case-D on 2/16-17 (Sheet 1 of 3)
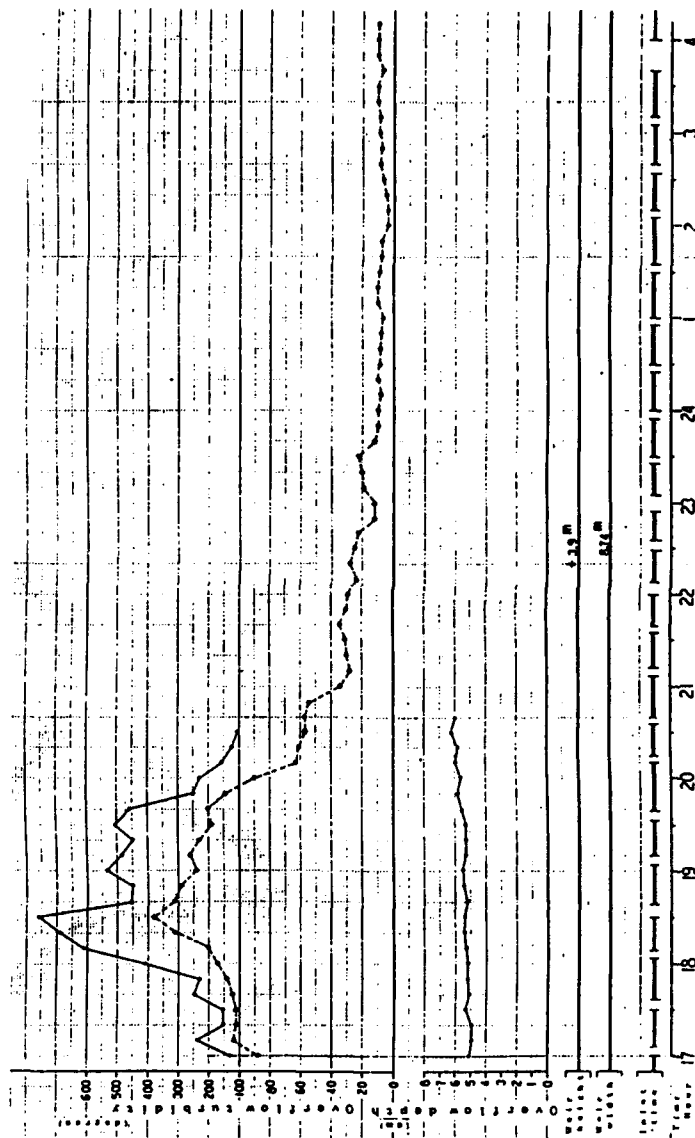
Figure 4.   (Sheet 2 of 3)
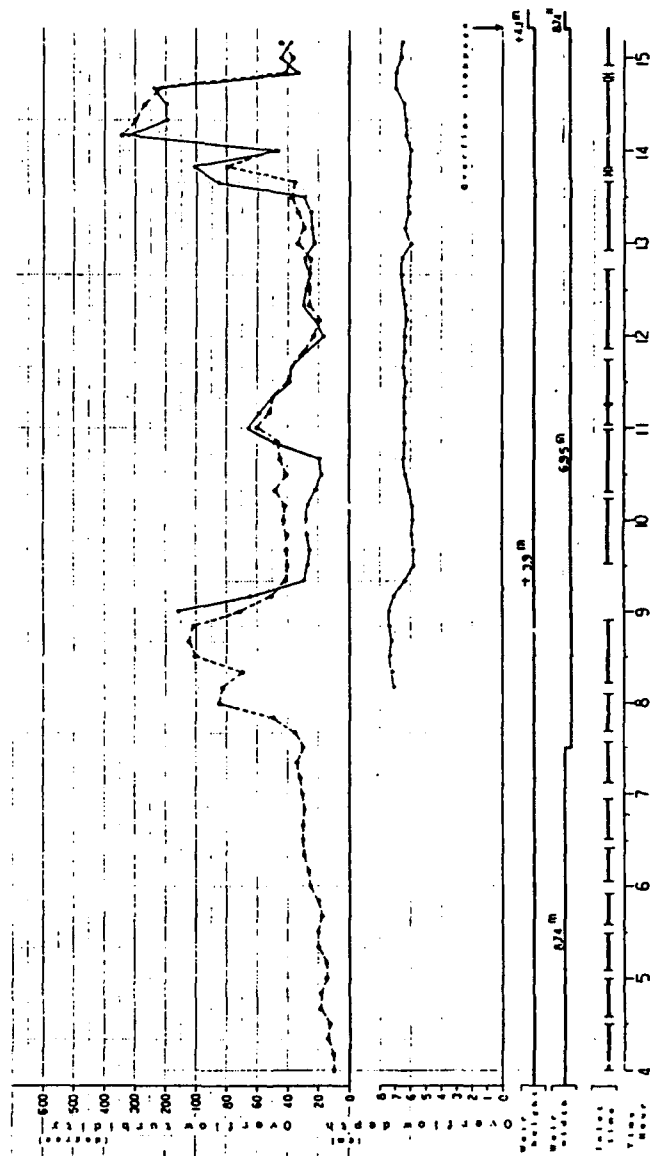
Figure 4. (Sheet 3 of 3)

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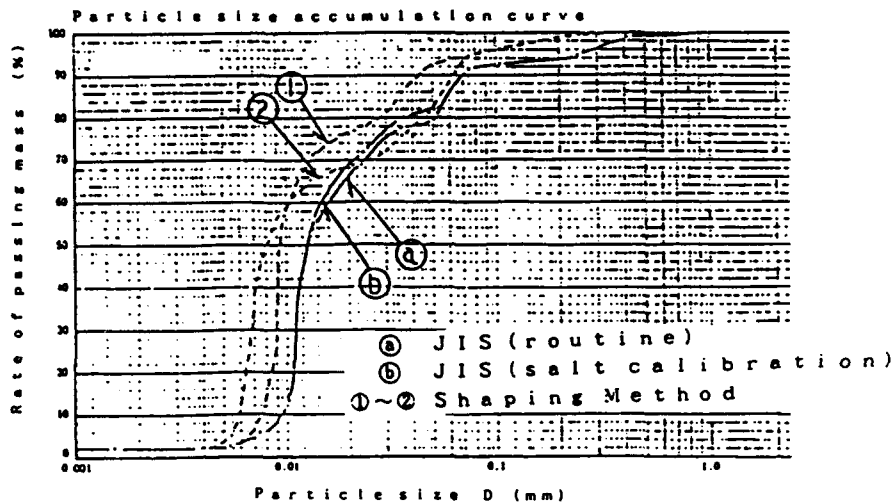
Figure 5. Particle size of slurry inflow

When converted to SS, they showed the value to 43,520 to 224,540 mg/ℓ.

b. **Grading.** Results of analysis by different methods are shown in Figure 5.

Examination

(1) The presupposed phenomenon of clay lumps was not confirmed by screening using a 2,000 μ sieve.

(2) When   ne and salt calibration of "JIS method" are compared, part   are finer in the latter case.

(3) Central size group (D_{50}) in the case of "JIS method" was 9-13 μ. In the case of "Shaping method," it was 7-12 μ, and the greater the volume of soils to be analyzed, the finer becomes the particles.

(4) The larger size of particles in "JIS method" than in "Shaping method" is attributable to the secondary cohesion of particles caused by air drying of samples.

(5) Different methods of analysis showed delicately different compositions of grading, but the average grade distribution of the slurry inflow was 8 percent of sand, 89 percent of silt, and 3 percent of clay. The "shaping method" used to test this should be tested under various conditions.

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Slurry near Sludge Outlet

Additional findings on the slurry follow.

a. <u>Density and grading.</u> The SS of slurry sample was 7,800-40,900 mg/ℓ. As to the grading, analysis by "Coal-tar counter method" indicated there was no noticeable difference of particle sizes. There was no noticeable difference among the cases either, as shown in Figure 6 of each case's particle size accumulation curve.
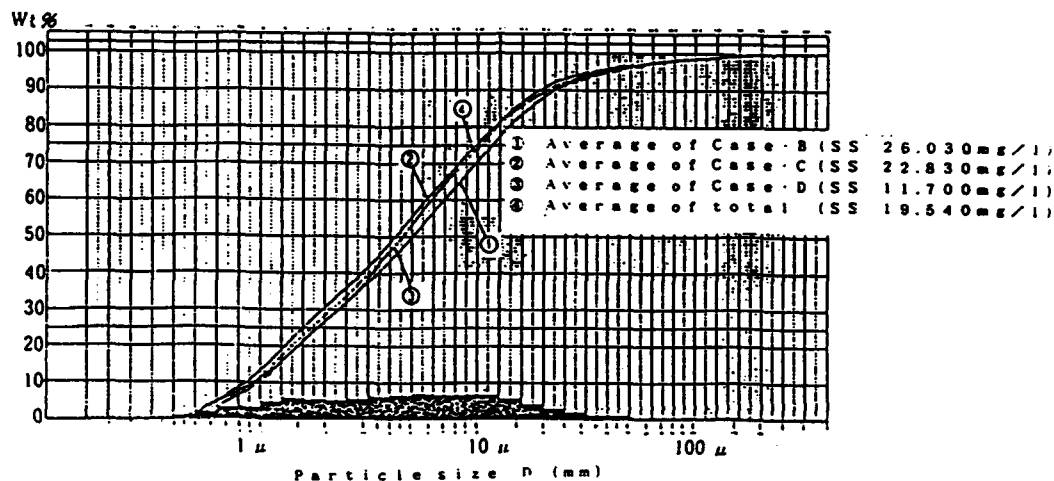
Figure 6. Average particle size of slurry near sludge outlet of reclamation site

b. <u>Removal rate and flotation rate.</u> The rate of settling soil particles around the sludge outlet was sought through comparison with slurry inflow. Figure 7 shows an example of grading curves. On the basis of these curves and other data concerning density and weight of various samples, the removal rate of total SS volume around the sludge outlet was calculated at an average of 86.2 percent (74.7-92.7) and the flotation rate at an average of 13.8 percent (7.3-25.3). By size of particle, the percentage of clay around the sludge outlet was greater than in the slurry inflow, and Figure 7 shows considerable difference in grading characteristics. Even considering the possibility of errors due to differences in analytical methods, this phenomenon is difficult to understand. Although the problem of clay remained unsolved, understandable results were obtained concerning sand, silt, and colloid, with higher removal rates for greater particle sizes.
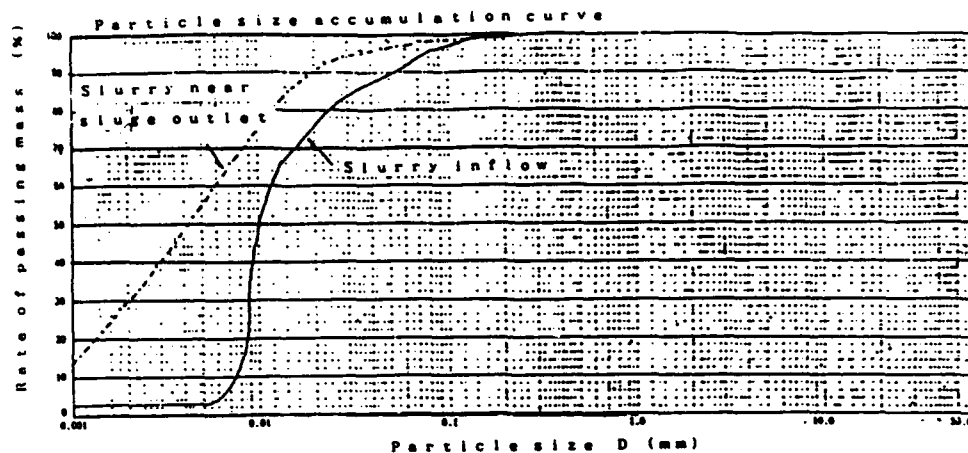
Figure 7. Comparison of particle sizes of slurry inflow
and slurry near sludge outlet

Surplus Water Outflow

Changes with time in outflow and density in Case-D are shown in
Figure 8.

a. **Density and grading.** The SS of surplus water sample was calculated
at 13-181 181 mg/ℓ. Grading (obtained by Coal-tar counter method)
is shown in Figure 9. There was no noticeable difference of
particle size rates regardless of SS sizes. With the peak at 4 to
5 μ, normal distribution was seen in the scope of 1.5 to 20 μ.
There was a trend that the component ratio of 0.5 to 0.6 μ was a
little higher than normal.

b. **Removal rate and outflow rate.**

(1) The ratio of settling soil particles in the resident flow
course was calculated through comparison with the slurry around
the sludge outlet, and on the basis of this calculation and
other data concerning weight and density of samples, the ratio
of removal and the ratio of outflow were calculated as shown in
Table 3. A comparison of particle sizes of slurry near sludge
outlet and surplus water outflow is illustrated in Figure 10.

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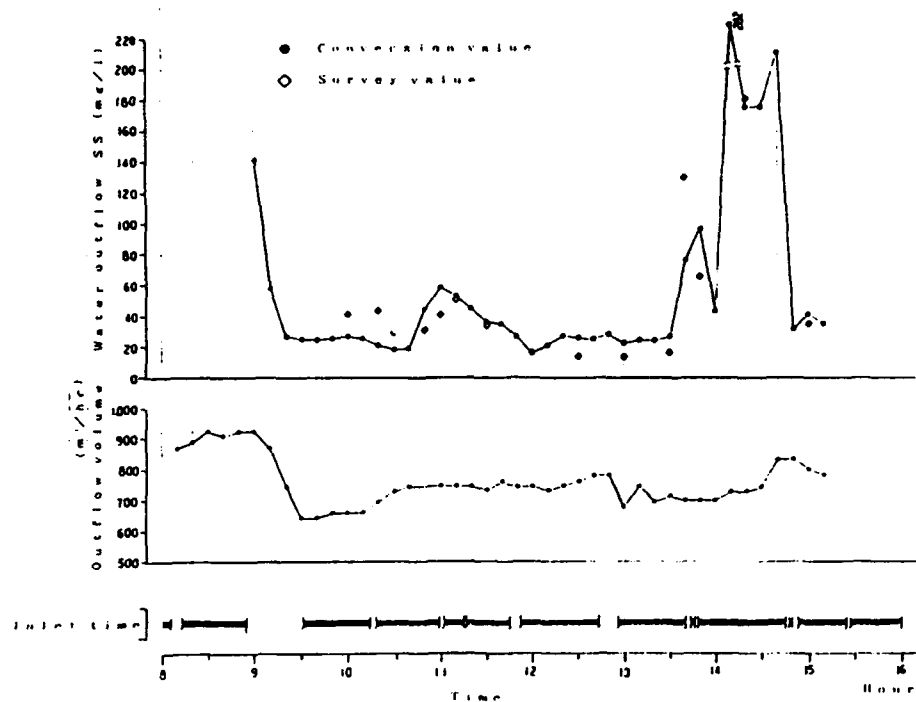
Figure 8. Outflow volume and SS of water outflow in Case D
(2.17, 0800-1600 hr)
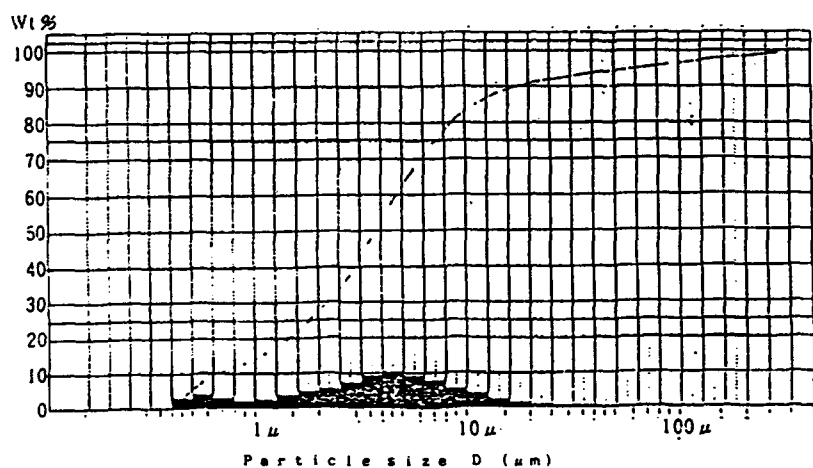
Figure 9. Average particle size of surplus water outflow

TABLE 3. RATES OF REMOVAL AND OUTFLOW IN RESIDENT FLOW COURSE

Particle Size (μm)	Slurry Near Sludge Outlet		Spillway		Removal Rate (%)		Outflow Rate (%)	
	SS (mg/ℓ)	Grading rate (%)	SS (mg/ℓ)	Grading rate (%)	SS	Grading	SS	Grading
406-74		3.1		5.3		99.56		0.44
74-5	19.540	47.5	50	47.6	99.74	99.77	0.26	0.23
5-1		40.1		34.4		99.74		0.26
less than 1		9.3		12.7		99.66		0.34

(2) The removal rate of total SS volume in the resident flow course
was calculated at 99.74 percent and the outflow rate at
0.26 percent. By size of particle, silt nd smaller particles
showed a tendency of higher outflow rates. Sand of larger size
showed a higher rate of outflow despite its small absolute load
probably due to reflotation of particles in from of the weir.
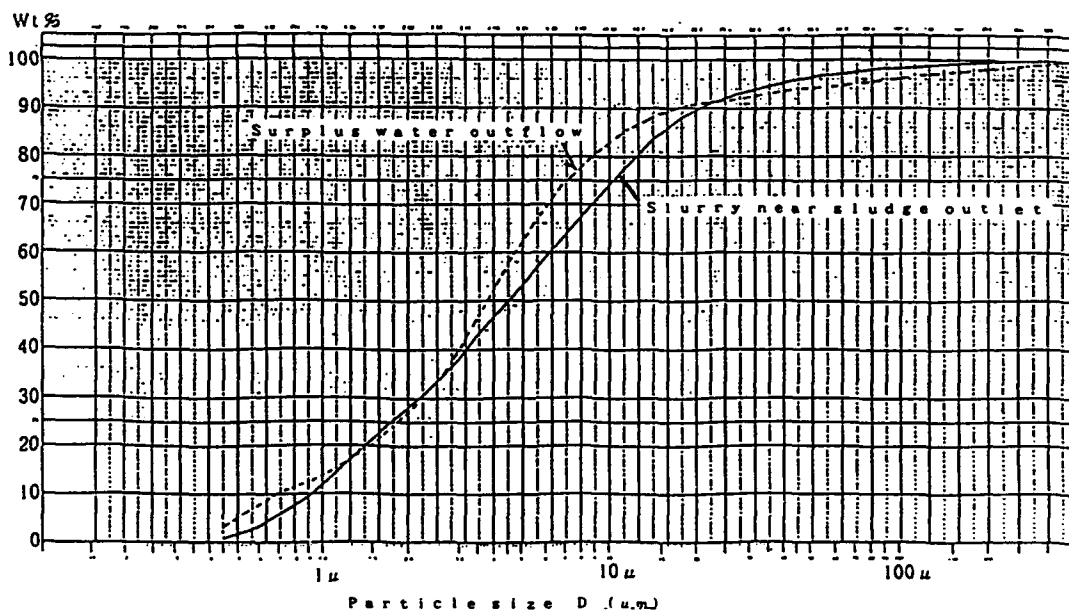
Figure 10. Average particle sizes of slurry near sludge
outlet and surplus water outflow

Summary

The original purpose of this survey was to obtain data on the resident
flow volume corresponding to the initial, middle, and final stages of reclama-
tion and on the relationship between the passage of time and surplus water

density. As a result, however, the survey was successful in gathering only such data as correspond to the final state of reclamation. A summary of the survey's findings follow:

a. Under the conditions of the reclamation site's water area of 27,600 m^2, resident flow volume of 1-m water depth, and inflow of 760 m^3/hr, the shortest resident flow distance stood at 226 m and the shortest resident time was 51 min. The water depth was obtained by depth sounding under the earth pressure of 1.8 g/cm red. The water content of soils at the point was 300 to 350 percent.

b. The SS of slurry inflow into the reclamation site was 115,500 mg/ℓ (70,000 - 200,000 mg/ℓ); that of the slurry at the point 30 m from the sludge outlet was 20,000 mg/ℓ (8,000 - 41,000 mg/ℓ); and that of surplus water outflow at the surplus water outlet was 50 mg/ℓ 13-18 mg/ℓ. The removal rate of slurry inflow near the sludge outlet was 82.8 percent against 99.96 percent at the surplus water outlet, indicating that the most of soil grains settle down near the sludge outlet.

c. As to grading, slurry inflow contained 8 percent of sand, 89 percent of silt, and 3 percent of clay (of which 2.7 percent was colloids). Particles of less than 20 μm amounted to 90 percent of all particles contained in the slurry near the sludge outlet, with the average size (D_{50}) of 4 to 5 μm. Similarly, particles of less than 20 μm accounted for 90 percent in surplus water outflow, with the average standing at 3 to 4 μm. Generally, particles in surplus water outflow were finer than those of the slurry near the sludge outlet.

WATER TANK MODEL TESTS

For these model tests, the results of the on-the-spot survey introduced in previous discussions were taken as the prototype, and the accuracy of reproducibility was confirmed (Case-A). Also, of the various factors of land reclamation, water depth, density of inflow, and the partition weir and other devices used to promote settling of particles were taken as parameters to confirm their qualitative effects on surplus water using a model based on the reclamation site surveyed (Case-B).

Outline of Tests

Similarity Law of Model

The establishment of a law of similitude between the prototype and its model is a prerequisite of a successful model test. In handling fluid like water, the similarity law of Reynolds (R similarity) is applied to the cases of no free surface as inside a pipe, but the similarity law of Frouds (F similarity) is mainly used for such cases where the influence of free surface is great as in the cases of harbors. Application of either of the two is problematic in the case of a reclamation site. The use of R similarity will pose a difficulty concerning the gradient of water surface caused by gravity, while reproduction of flow regime such as vortex caused by viscosity poses a difficulty for F similarity. In addition to the hydromechanical difficulties of similarity, modeling of settling matters poses a problem for model tests of sedimentation of matters in a model sedimentation basin. In the models of

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harbors, specific gravity is adjusted to fit F similarity. A simple solution for model tests of sedimentation in the model. In this case, however, the behavior of the settling matters will be distorted under either of the similarity laws, if the model of a reclamation site, for instance, is constructed in geometrical similarity to the prototype. Therefore, an ideal, vertical, and two-dimensional sedimentation basin is considered to realize similarity of sedimentation phenomena. This method is called similarity of water area load and used widely for works related to water treatment. In this case, sedimentation is idealized to lessen hydromechanical value. However, the item of speed will become closer to that of the prototype, slower than R similarity, but greater than F similarity. In these tests introduced here, emphasis was placed on conformity with the prototype regarding water area load on the basis of the similarity law of Frouds. The scales of the model are shown in Table 4.

Conditions of Tests

These conditions consider test cases such as A and B as well as test equipment and method of test.

    a. Case-A. The outline of the findings of the survey, which were made to develop the prototype for this case, is shown in Table 5.

TABLE 4. RELATION OF SCALE

Item		Frouds Similarity	Similarity of Water Area Load
Horizontal length scale	Lr		
Vertical length scale	Hr		$H_r - L_r^{2/3}$
Horizontal flow rate	Vr	$V_r - H_r^{1/2}$	$V_r - L_r^{1/3}$
Flow rate	Qr	$Q_r - L_r \cdot H_r^{3/2}$	$Q_r - L_r^2$
Residence time	tr	$t_r - L_r \cdot H_r^{-1/2}$	$t_r - L_r^{2/3}$
Soil particle	dr	$d_r = L_r^{-\frac{1}{4}} \cdot H_r^{3/4}$	$d_r - 1$
Water area load	Vor	$V_{or} - L_r^{-1} \cdot H_r^{1/2}$	$V_{or} - 1$

On the basis of above findings, the horizontal length scale of the model was made 1/30, and "Kasaoka clay" was adopted as sample soil as its composition resembles that of soils around the sludge outlet of the prototype. Specifications of the prototype and the model are shown in Table 6.

    b. Case-B. Conditions of reclamation are numerous, including the plane shape of the landfill site, water depth, inflow, density of inflow and grading of inflow. This case was considered as an extension of CASE-A and a prototype having the same plane shape, inflow and

TABLE 5. RESULTS OF ON-THE-SPOT SURVEY

Position	Item	Result
Inlet point (Sludge outlet)	Sludge inflow SS	70,000-200,000 mg/ℓ Average 115,500 mg/ℓ
	Sludge inflow grading	Particle size accumulation curve (Fig. 2-6)
Landfill site	Water depth at landfill site	0.3-3.4 m Average 1.0 m
	Slurry SS near sludge outlet	8,000-41,000 mg/ℓ Average 20,000 mg/ℓ
	Slurry grading near sludge outlet	Particle size accumulation curve (Fig. 2-9)
Outlet point (Spillway)	Rate of outflow	760 m^3/h
	Surplus water outflow SS	13-181 mg/ℓ Average 50 mg/ℓ
	Surplus water outflow grading	Particle size accumulation curve (Fig. 2-9)

inflow grading as the model was presumed and such test parameters as water depth, inflow density and devices for promotion of settling within the reclamation site like a partition weir were selected. The parameters are shown in Table 7.

c. **Test cases.** Test cases are shown in Table 8.

d. **Test equipment.** The flow chart of test equipment is shown in Figure 11. The positioning of precipitation devices and their cross section are given in Figures 12 and 13. The test water tank is shown in Figure 14.

e. **Method of test.** Appropriate amounts of seawater and sample soil were put into the raw water production tank so that raw water of desired density could be obtained. They were mixed up using the agitator and circulating pump. Raw water was then poured into the dry test tank up to the level 1 or 2 cm below the surplus water overflow line by a fully opened pump (more than 200 ℓ/min). Then the flow was adjusted to a set volume. For each test case, raw water was poured for 2 or 3 hr after confirming the state of stability by the oscilloscope of the turbidimeter. Water samples were taken at 15-min intervals and were measured and analyzed regarding each one of the items.

TABLE 6. SPECIFICATIONS OF MODEL AND PROTOTYPE

Item	Prototype	Model	Note
Horizontal length scale		Lr - 1/30 - 0.033	
Vertical length scale		Hr - 0.104	
Landfill site water depth	0.3-3.4 m Average 1.0 m	3.1 - 35.4 cm Average 10.4 cm	
Overflow width at spillway	6.95 m	23 cm	
Rate of inflow	760 m³/hr	14.1 ℓ/min	
Raw water inflow SS	20,000 mg/ℓ	20,000 mg/ℓ	Subject: Slurry near sludge outlet
Water area	27,600 m	30.7 m	
Water area load	7.65 × 10 -- m/sec	7.65 × 10 -- m/sec	

TABLE 7. TEST PARAMETERS

Item	Prototype (Assumption)
Landfill site water depth	(Average) 2m · 3m
Raw water inflow SS	10,000 mg/ℓ · 20,000 mg/ℓ
Devices for precipitation	Partition weir · submerged dike · Protector

Results of tests

Case-A

An example of sequential measuring of SS and outflow of raw water and surplus water is shown in Figure 15. Additional findings follow.

a. Confirmation of set conditions. Conditions set for tests such as the rate of flow, raw water density, and grading and test results are shown in Table 9 and Figure 16.

b. Surplus water and grading. The results of tests on surplus water density and grading are shown in Table 10 and Figure 17.

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TABLE 8. TEST CASES

	Case	Reclamation site	Spillway weir width	Inflow	Soil Sample	Water depth at site	Raw water inflow	Precipitation measures
					Test Condition			
A	Case-1·①	Hakozaki Wharf reclamation site	6.95 m	760 m /hr	Kasaoka Clay	1m	20,000 mg/ℓ	
	Case-1·②							
	Case-1·③							
	Case-1·④							
	Case-2·①					2	20,000 "	
	Case-2·②					"		
B	Case-3					3	20,000	
	Case-4					1	10,000	
	Case-5					1	20,000	Partition weir
	Case-6					1	20,000	Partition weir · Submerged dike
	Case-7					1	20,000	Partition weir · Submerged dike Protector
	Case-8					1	20,000	Protector

① Seawater tank
② Raw water production tank
③ Test water tank (landfill site model)
④ Catch basin
⑤ Sedimentation basin
⑥ Drain ditch
⑦ Coagulant adding equipment
⑧⑨ Flowmeter
⑩ Turbidimeter

Figure 11. Flow chart of test equipment

Figure 12. Positioning of precipitation devices

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Partition weir	Submersed dike	Protector

Figure 13. Cross section of precipitation devices
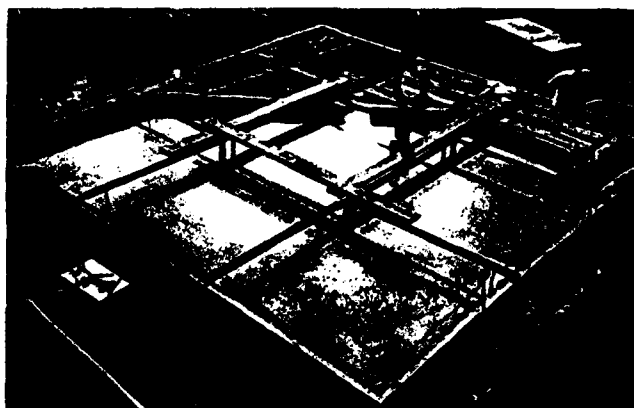
Figure 14. Test water tank (landfill site model)

c. **The SS weight by particle size.** The SS weight by particle size per unit volume of water as calculated from the test results on density of raw water and surplus water and on grading are shown in Figures 18 and 19. The difference of surplus water SS weights in the prototype and the model is calculated and shown in Figure 20. Test results regarding the removal rate by sedimentation are shown in Figure 21.

Case-B

The following figures and tables illustrate test results of Case-B.

a. **Confirmation of set conditions.** Test conditions set for flow rate, raw water density and grading, and test results are shown in Table 11 and Figures 22 and 23.

74
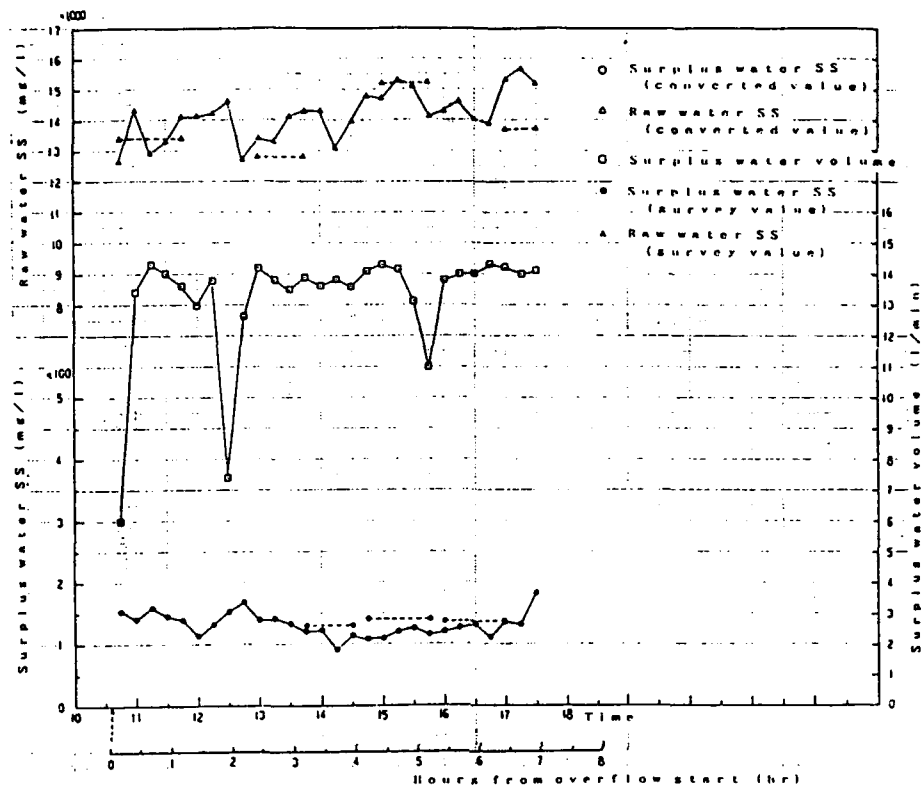
Figure 15. Test result (example) case 1-1(2)

TABLE 9. DISCHARGE AND RAW WATER DENSITY

Case	Flow Rate (ℓ/min)		Raw water density (mg/ℓ)	
	Set value	Survey value (av.)	Set value	Survey value (av.)
Case-1 · ①		13.8		11.400
Case-1 · ②		13.9		13,800
Case-1 · ③	14.1	13.7	20,000	13.200
Case-1 · ④		14.0		12,900

b. Surplus water and grading. The results of tests on surplus water density and grading are shown in Table 12 and Figure 24 and 25.

c. Rate of removal by sedimentation by particle size. Rates of removal by sedimentation were calculated from test results on density of raw water and surplus water and on grading (Figures 26 and 27).
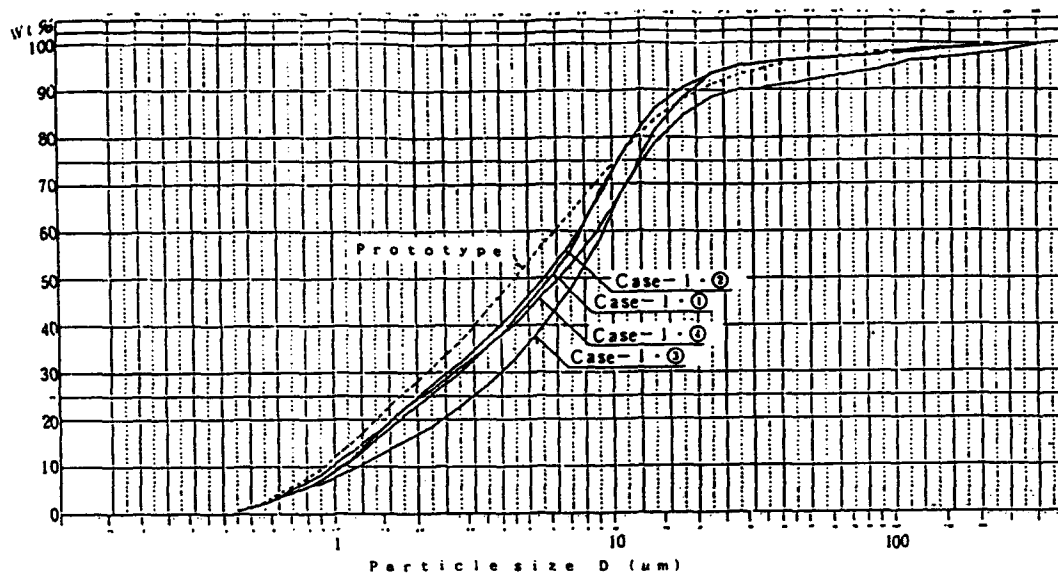
Figure 16. Particle size of raw water

TABLE 10. SURPLUS WATER DENSITY

Case	Prototype (Average)	Survey Value			
		Sample-1	Sample-2	Sample-3	Sample-4
Case-1 · ①		190 mg/ℓ	140 mg/ℓ	181 mg/ℓ	174 mg/ℓ
Case-1 · ②		132	139	137	136
Case-1 · ③	50 mg/ℓ	221	228	204	218
Case-1 · ④		167	124	193	162

Consideration

Case-A

For this case, survey results were taken as the prototype and conformity with the prototype regarding the Frouds Law, and the water area load was considered as basic law of similarity; the size of the model was set in a scale of 1 to 30 in horizontal length and 1 to 30 in vertical length, all to seek reproducibility of surplus water density.
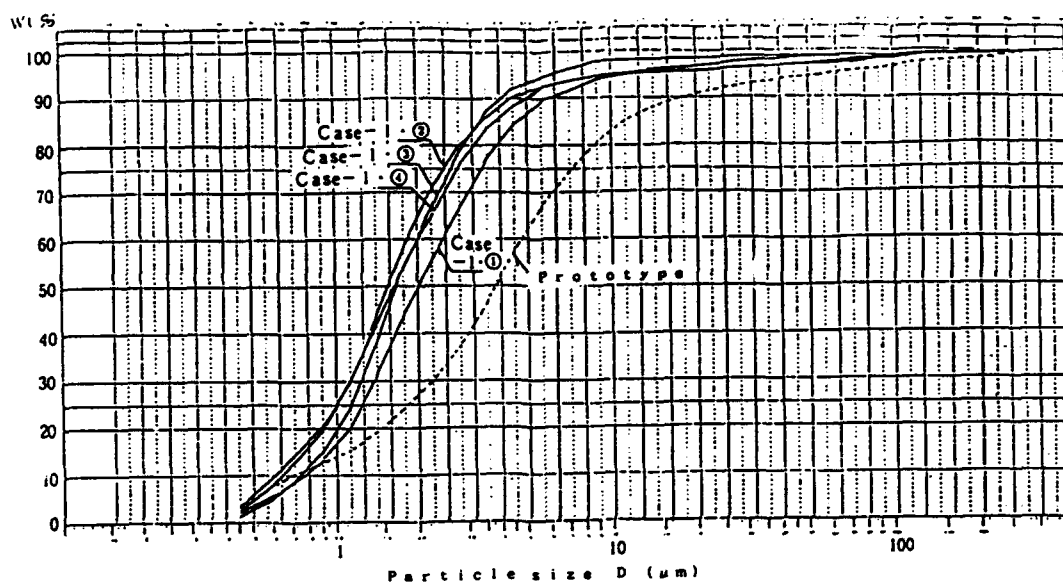
Figure 17. Particle size of surplus water
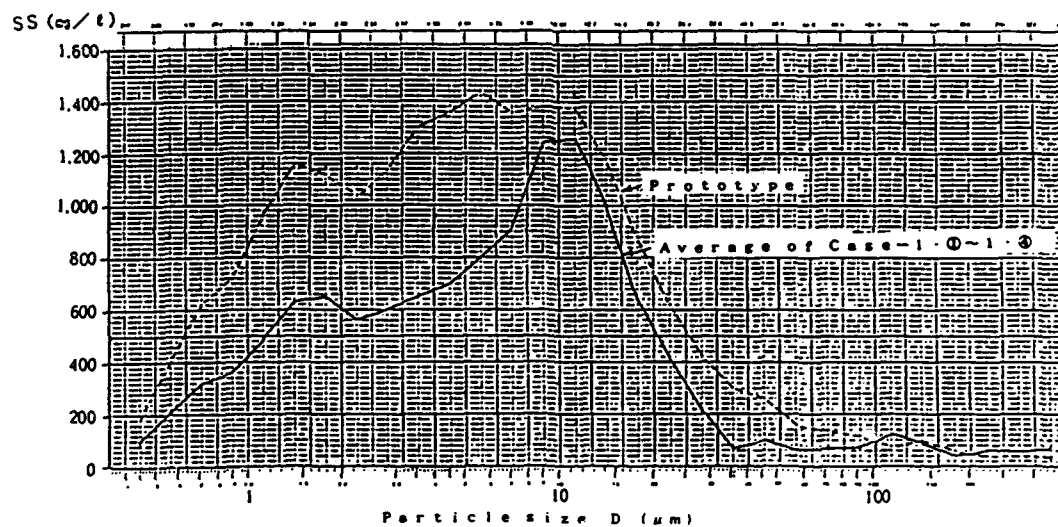
Figure 18. SS weight of raw water per unit volume

77
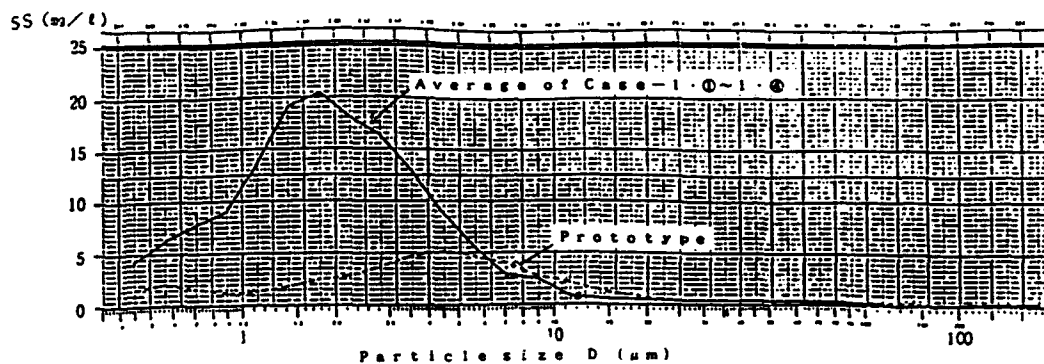
Figure 19. SS weight of surplus water per unit volume
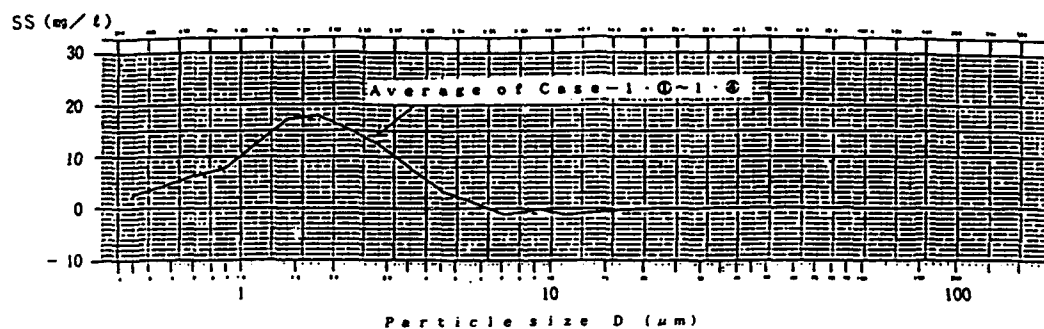
Figure 20. Surplus water SS weight differential
between prototype and test
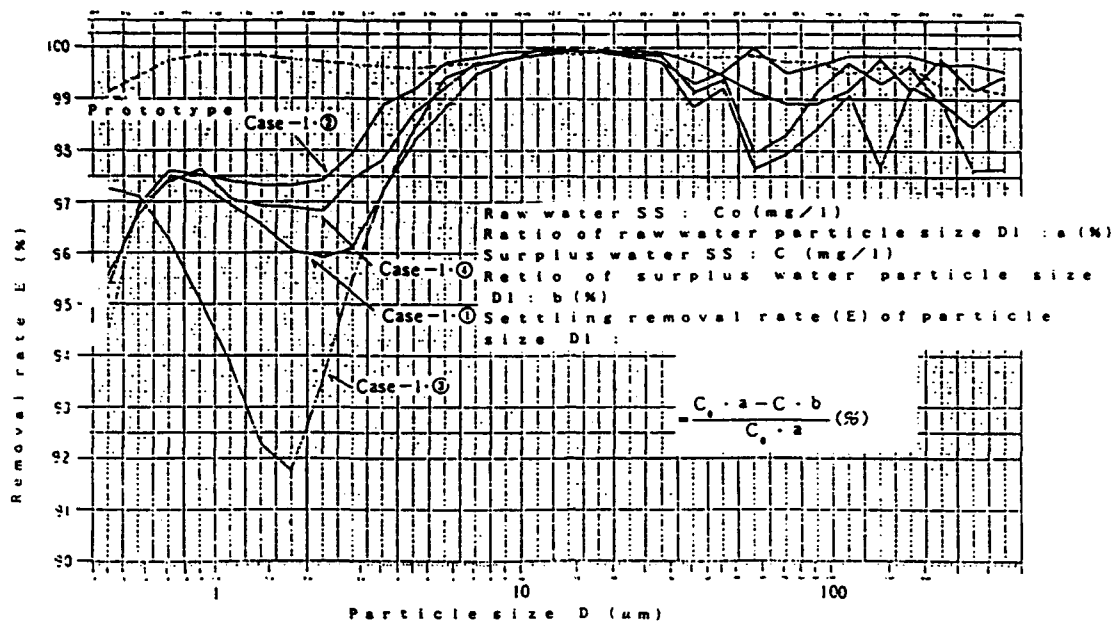
Figure 21. Rate of removal by sedimentation
by particle size

TABLE 11. DISCHARGE AND RAW WATER DENSITY

Case	Flow Rate (ℓ/min)		Raw water density (mg/ℓ)	
	Set value	Survey value (av.)	Set value	Survey value (av.)
Case-2 · ①		13.6		14,200
Case-2 · ②		13.6	20,000	12,000
Case-3		13.6		12,700
Case-4	14.1	14.0	10,000	6,470
Case-5		14.0		11,500
Case-6		13.9	20,000	13,200
Case-7		13.6		11,700
Case-8		13.9		13,200

Figure 22. Raw water particle size (case of change
in depth and raw water density
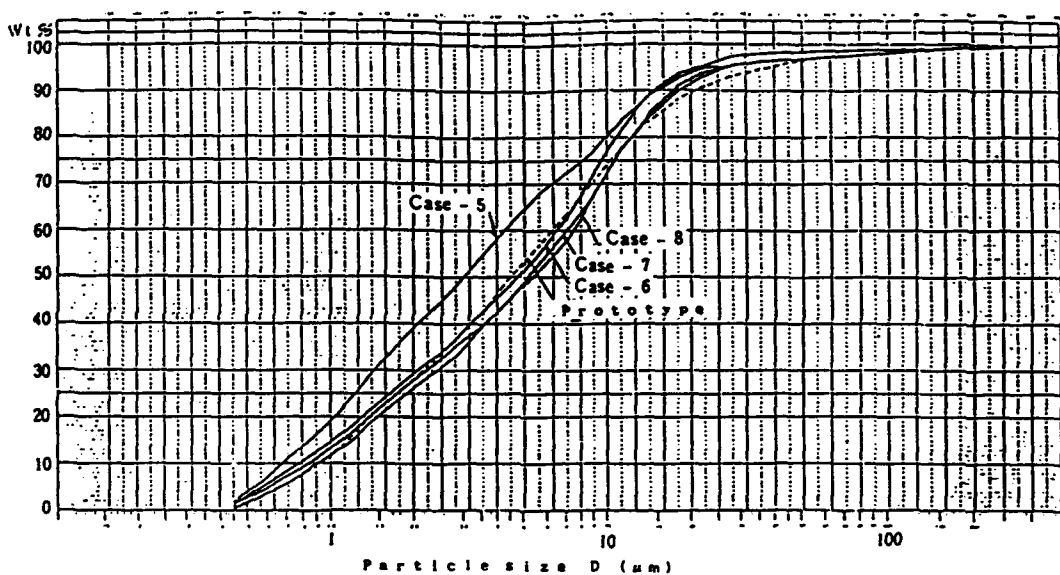
Figure 23. Raw water particle size (case where
precipitation devices are set up)

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TABLE 12. SURPLUS WATER DENSITY

Case	Survey Value				
	Sample-1	Sample-2	Sample-3	Sample-4	Average
Case-2 · ①	248 mg/ℓ	326 mg/ℓ	331 mg/ℓ	340 mg/ℓ	312 mg/ℓ
Case-1 · ②	214	154	150		173
Case-3	256	254			255
Case-4	193	191	239		208
Case-5	62	73	91		76
Case-6	51	57	52		54
Case-7	68	60	41		57
Case-8	91	66	67		75

a. On quality of surplus water. Regarding the quality of surplus
    water, following assertions can be made on the basis of comparison
    of test results with the prototype.

(1) Four model tests indicated an average surplus water SS density
     of 173 mg/ℓ (136 - 181 mg/ℓ) against the prototype's average of
     50 mg/ℓ (14 - 181 mg/ℓ), indicating a difference of about
     120 mg/ℓ.

(2) Regarding SS grading (Figure 17), particles or more than 10 μm
     accounted for 20 percent of all particles in the prototype,
     while the model tests showed the size group occupied only
     5 percent. This difference was considered because of refloat-
     ing of particles in the prototype at the surplus water outlet.
     Model tests in general showed greater distribution of finer
     grains than in the prototype.

(3) As to the sedimentation removal rate by particle size, the pro-
     totype showed no remarkable changes for size groups, indicating
     the rate of more than 99 percent for all size groups. In the
     model tests, the size group of more than 10 μm showed a rate of
     nearly 100 percent, but finer size groups indicated various
     trends: the 2- to 10-μm group showing a gradual decrease, the
     0.8- to 2-μm group a gradual increase, and the 0.4- to 0.8-μm
     group a gradual decrease. Overall, the removal rates in model
     tests were lower by 2 to 5 percent than those of the prototype.

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Figure 24.   Surplus water particle size (case of change
in depth and raw water density)
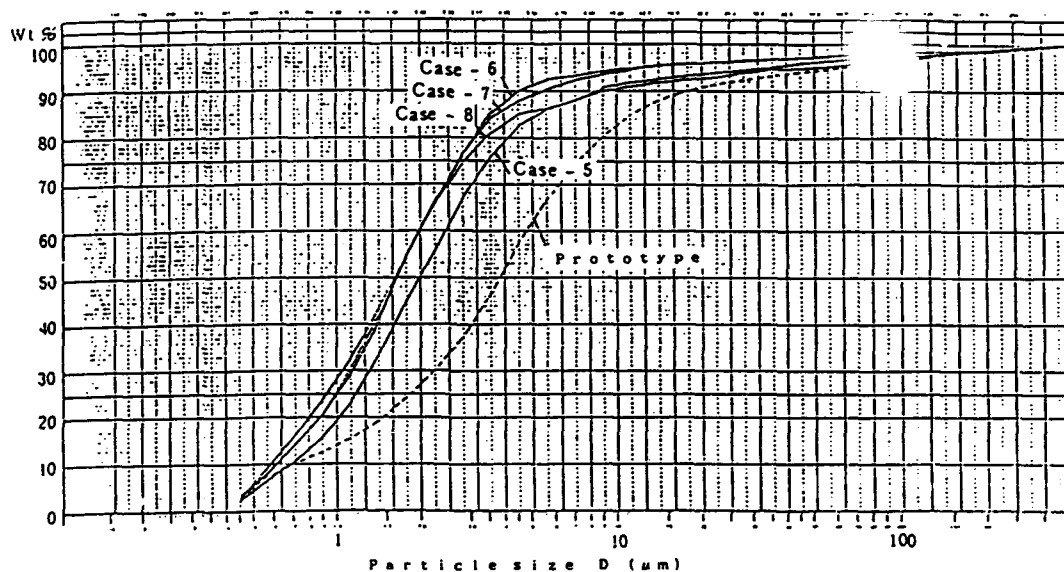
Figure 25.   Surplus water particle size (case where
precipitation devices are set up)
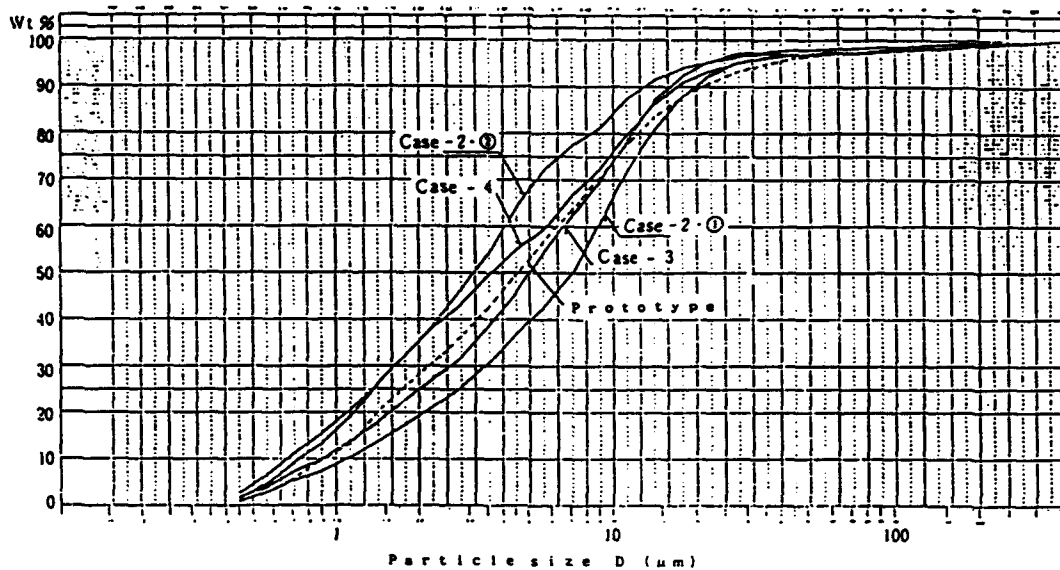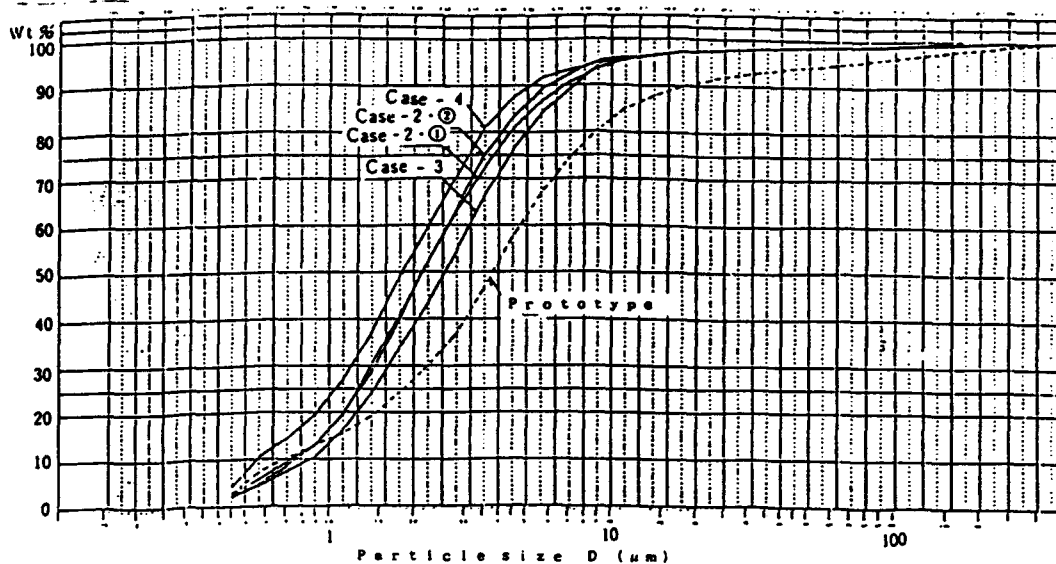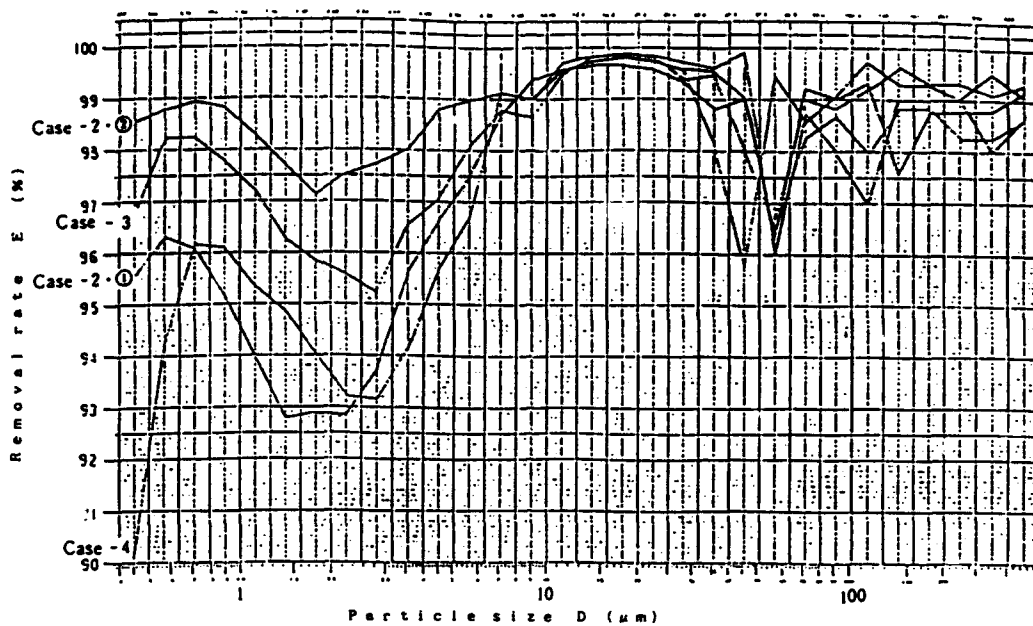
Figure 26. Rate of removal by sedimentation by particle size
(case of change in depth and raw water density)
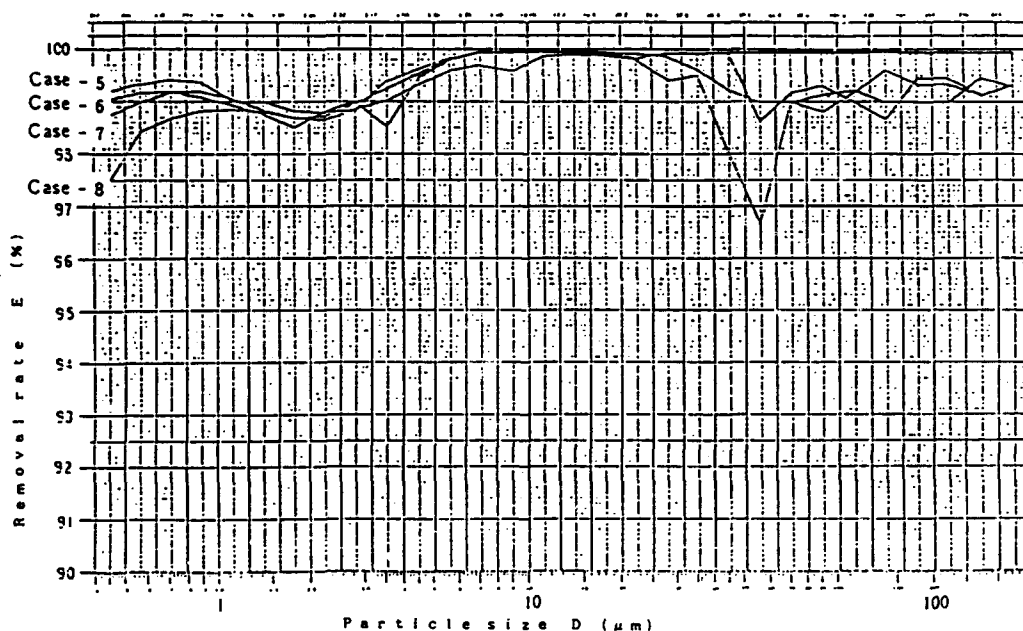
Figure 27. Rate of removal by sedimentation by particle size
(case where precipitation devices are set up)

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b. **On test conditions.** Regarding the difference of surplus water density, the following assertions can be made in view of the test conditions:

   (1) Test condition of inflow was set at 14.1 ℓ/min but the test results were a little smaller, showing the averages of 13.7 to 14.0 ℓ/min. Though there were changes during the passage of time, they are not considered as commanding factors, judging from the reaction of surplus water density in a state of stability.

   (2) Raw water density stood at an average of 12,800 mg/ℓ (11,400-13,800 mg/ℓ) against the test condition of 20,000 mg/ℓ. This considerably lower density was caused by the sand sedimentation in the raw water supply pipe. Raw water density can be a factor to force sedimentation of finer particles near the sludge outlet as in hindered settling and thus can have strong influences on the quality of surplus water. Their relationship must be grasped more accurately.

   (3) Raw water grading (Figure 16) was a little coarser than that of the prototype but both can be said to be very close in composition. However, in view of the results concerning the raw water SS weight (Figure 18), absolute load of the SS components of less than 10 μm of surplus water was small by the difference of raw water SS densities. The influence of this difference on the removal rate, together with the relation with raw water density, should be made clear in the future.

c. **Summary.** The results of model rests indicated a surplus water density higher than the prototype by about 120 mg/ℓ because of the outflow of finer particles of less than 6 μm with the peak of 2 μm from the surplus water outlet. Their failure in settling was a tendency observed in all four tests regardless of the changes in surplus water density, showing a remarkable difference from the prototype. Causes are complex including the problems of condensation, hindered settling, difference of characteristics between sea clay and sample soil used in model tests, and so on, all very difficult to clarify. Collection of more data and supplementary experiments are needed for prediction of quantitative surplus water density.

Case-B

For this case, survey results show the influence of water depth, raw water density, and precipitation devices on surplus water density.

a. **Influence of water depth of reclamation site.** Surplus water density was indicated at 173 mg/ℓ (136-218 mg/ℓ), at 243 mg/ℓ (173-312 mg/ℓ) and at 255 mg/ℓ, corresponding to water depth of 0.1, 0.2, and 0.3 m, respectively. So far as the averages are concerned, the deeper the depth, the greater the density, but the differences are not great at all. It is difficult, therefore, to assert that water depth has a clear-cut impact on density. When water area loads are made similar, water depth has nothing to do with the density in an

ideal sedimentation basin. barring the possibility of refloating of soil particles, and the test results indicated this trend. It is considered because of the existence of marginal water depth contributing to the resident flow inside the landfill site.

b. <u>Influence of raw water density.</u> Regarding the five cases where the average model water depth was 0.1 m and raw water density was measured at 6,470 to 13,800 mg/ℓ, it can be said that surplus water density tended to decrease as raw water density increased. High density raw water is said to contain less soil particles and to tend to lower the density of surplus water. The tests proved this tendency.

c. <u>Effects of precipitation devices.</u> A partition weir, submerged dike, and protector were set up in the model with an average depth of 0.1 m and compared the effects with the case of no such devices. It is generally said that the partition weir is effective in streamlining the flow and in prolonging the residence time to promote settling; the submerged dike is helpful in shortening the distance for soil particles to reach the bottom and in controlling a flow of high density; and a protector is said to be effective in forging the settling of soil particles. Test results showed that the partition weir and the protector, each used alone, were effective in cutting surplus water density to 75 to 76 mg/ℓ from 173 mg/ℓ in the case of no such device. When the submerged dike was used with either one of them, the density further went down to 54 from 57 mg/ℓ.

POSTSCRIPT

Analysis of the numerical model and model tests are considered to be useful for prediction of surplus water density at a reclamation site. In any case, it is necessary to compare the results with the results of on-the-spot survey and to examine their reproducibility. This time, the differences between the onsite conditions and model tests results have been made clear regarding the particle size distribution in sedimentation, using the model made on the basis of on-the-spot findings taken as the prototype. From now on, research activities will be continued on the difference of sample soils used for model tests and on characteristics of surplus water near the sludge outlet and at the surplus water outlet, in order to make prediction accurate with supplementary data. Efforts will be made further to make this study helpful for the solution of the water pollution problem involving landfill sites in general.

A SUMMARY OF RECENT CAPPING INVESTIGATIONS WITH DREDGED SEDIMENT* IN NEW ENGLAND

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ABSTRACT

Capping of contaminated dredged sediments in mounds at shallow (20-60 m) offshore disposal sites with less contaminated sediments has been used as a management practice in New England since the early 1970's. Evaluation of the success of this technique and extension of its use at deepwater sites (60-100 m) have been the focus of several studies over the last several years. These studies have included assessment of physical mound stability, the long-term isolation of contaminants within the mounds, and surveys to determine the feasibility of creating sediment mounds at sites in the 100-m-depth range. The passage of Hurricane Gloria in 1985 was found to have limited erosion effects on capped disposal mounds at the Central Long Island Sound disposal site at 15-20 m-depth. This observation has also been supported by observations of mound stability at several sites for up to 15 years. Chemical profiles measured in cores taken in mounds in 1990, more than 10 years after contaminated and cap sediment placement, had undetectable contaminant migration. More recently, studies of mound formation with disposed sediments at the Massachusetts Bay disposal site, in 90-m depth, have begun to support the feasibility of capping sediments at this site and other similar depth sites.

INTRODUCTION

The management of contaminated dredged sediments in New England has relied heavily on the use of capping at offshore marine disposal sites. This dependence has been based on the lack of available upland sites due to protection of wetlands, intensive nearshore development, and the much greater economic costs required for upland disposal. Capping has been facilitated by the fact that the majority of dredging in New England is performed by clamshell dredges which keep sediments consolidated for subsequent disposal from bottom opening barges.

The first capping projects in New England were conducted in the early and mid 1970's. These projects (e.g., at Brenton Reef off Rhode Island) did not include monitoring to determine their level of success, rather it was

assumed that sequentially dredging to place the more contaminated sediments first and less contaminated sediments second would result in burial. Concerns about whether this approach actually accomplished the objective led in 1979 to the first carefully planned and monitored capping projects. Since that time, more than 10 capped disposal mounds have been created at New England sites and monitored using a variety of techniques to assess their short and longer term success (Figure 1) (Morton 1980; Brandes, Silva, and Fredette 1991; Sumeri et al. 1991; Fredette et al. 1992). These studies include several recent investigations which have examined physical stability, chemical isolation of contaminants within the mounds, and creation of mounds at sites up to 90 m in depth. Major findings of these recent studies are presented and discusses in the following sections. These monitoring surveys have been conducted as part of the U.S. Army Corps of Engineers, New England Division's Disposal Area Monitoring System (DAMOS).

CAPPING INVESTIGATIONS

Mound Creation and Physical Stability

Documentation of mound creation and determination of cap thickness has relied primarily on precision bathymetric and sediment profile camera surveys. Bathymetric surveys are usually conducted before and after contaminated material placement and following the placement of the cap. These surveys are then used to determine the lateral extent and thickness of the contaminated and cap layers as shown in Figure 2 (Morton 1980).

Use of a sediment profile camera (Figure 3) has been a more recent addition to the monitoring protocols for capping projects. The camera provides an excellent complement to bathymetry because it is capable of detecting the thinner deposits (0-20 cm) that exist around the central portion of the mound (Figure 4). Thus, managers can be provided with a much clearer indication of where sediments have been placed during either the contaminated or cap placement phases. Following contaminated material placement, this camera provides an ability to accurately plan coordinates where cap material is to be placed.

Once a capped disposal mound has been created, one of the primary concerns is the catastrophic failure by erosion of the cap during high bottom current conditions caused by storms. Again, a principal tool for assessing cap stability is the comparison of post-storm bathymetric surveys with those conducted following cap placement. However, caution needs to be used in interpreting differences to ensure that changes in mound height caused by consolidation are not misattributed to erosive losses. This interpretive difficulty was observed following Hurricane Gloria in 1985 which passed over New England (Figure 5) shortly after the completion of two capped disposal mounds at the Central Long Island Sound disposal site (Fredette et al. 1988).

Bathymetric surveys at five mounds, which were conducted following Hurricane Gloria, helped to strengthen support for the conclusion that caps were effective in protecting the contaminated sediments from erosion. Four of the five mounds surveyed showed only small changes in elevation, although one mound that had been completed just a few months before the storm showed a volume loss of up to 15,390 m^3. However, interpretation of the complementary sediment profile camera surveys did not support the erosion hypothesis. Sediment profile photographs from the crest and flanks of the mound showed evidence of near-surface features (wormtubes and oxidized sediment) that were

**US Army Corps
of Engineers**
New England Division

**Active Open Water
Dredged Material
Disposal Sites**

MAINE

VERMONT

●⌐ROCKLAND

NEW
HAMPSHIRE

●~PORTLAND*
●~CAPE ARUNDEL

ATLANTIC OCEAN

MASSACHUSETTS ●—MASS BAY

N

CONNECTICUT RI

●BUZZARDS BAY

~NEW LONDON *

~CORNFIELD SHOALS

~CENTRAL LONG ISLAND SOUND *

WESTERN LONG ISLAND SOUND
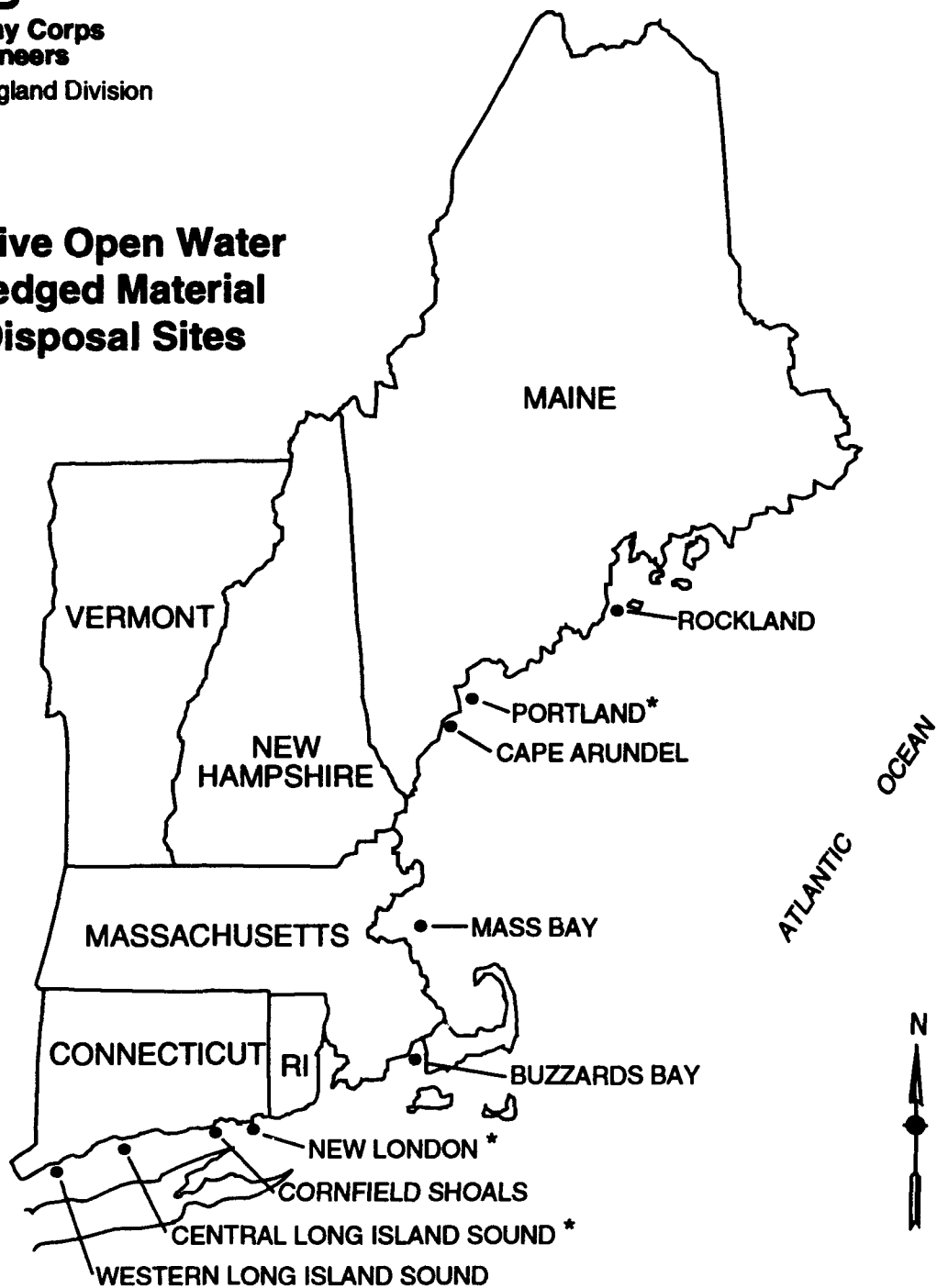
Figure 1.   New England disposal sites at which capping
has been conducted (indicated with asterisks)
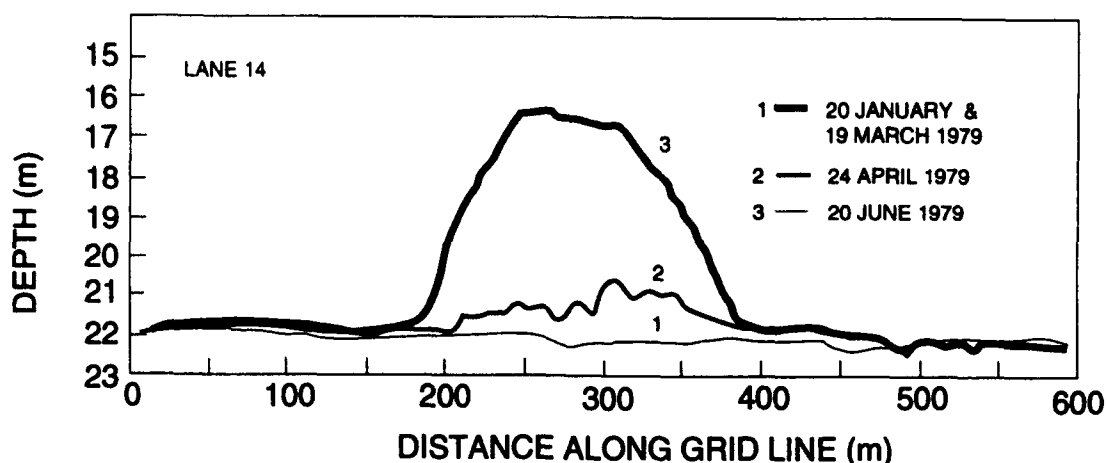
Figure 2. Three depth transects along one survey grid line at a
dredged-material mound before, during, and after
disposal operations. Vertical exaggeration is 25 times
the horizontal scale. The contaminated sediment was
deposited between surveys 1 and 2, and the silt cap
was added between surveys 2 and 3

still evident in photographs taken only a few days after the storm. The only
reasonable explanation was that the change in elevation was primarily
attributable to consolidation of the mound. Thus, the apparent lack of
effects following such storms and the observed stability of mounds for more
that 15 years supports the conclusion that these sites will perform as
expected.

Chemical Isolation

An often-cited concern with caps is whether they provide a long-term
barrier to release of contaminants to the environment. This concern centers
around the possibility that contaminated pore waters are released during con-
solidation, or in later years through either sediment pumping or diffusion.
If this possibility were true, then caps would, at best, serve only to slow
the eventual release of contaminants to the environment.

As part of the ongoing monitoring of cap sites in New England this ques-
tion has been partially addressed by taking cores on three disposal mounds at
the Central Long Island Sound disposal site (Sumeri et al. 1991, Fredette et
al. 1992). The mounds selected were sampled in 1990 and represented three of
the oldest mounds: two having been created in 1979 and one in 1983. Five
cores taken on each mound were sectioned in 20-cm increments for sediment
chemistry and grain size analyses. These results revealed very abrupt
increases in both organic and inorganic sediment chemistry at depths of 40 cm
or greater (Figure 6).

Capping at Water Depths of 90 m

While capping in water depths up to a 60-m depth has gained general
acceptance in New England, extending the use of this technique to sites in

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LIFTING BAR

END CAP
(HOUSING FOR
ELECTRONICS)

INNER FRAME

OUTER FRAME

WEIGHT

WEIGHT PACK

MUD DOOR
ELASTIC STRAP

MUD DOOR
HINGE

MUD DOOR

PRISM

FACE PLATE

BASE (SLED)

Front View
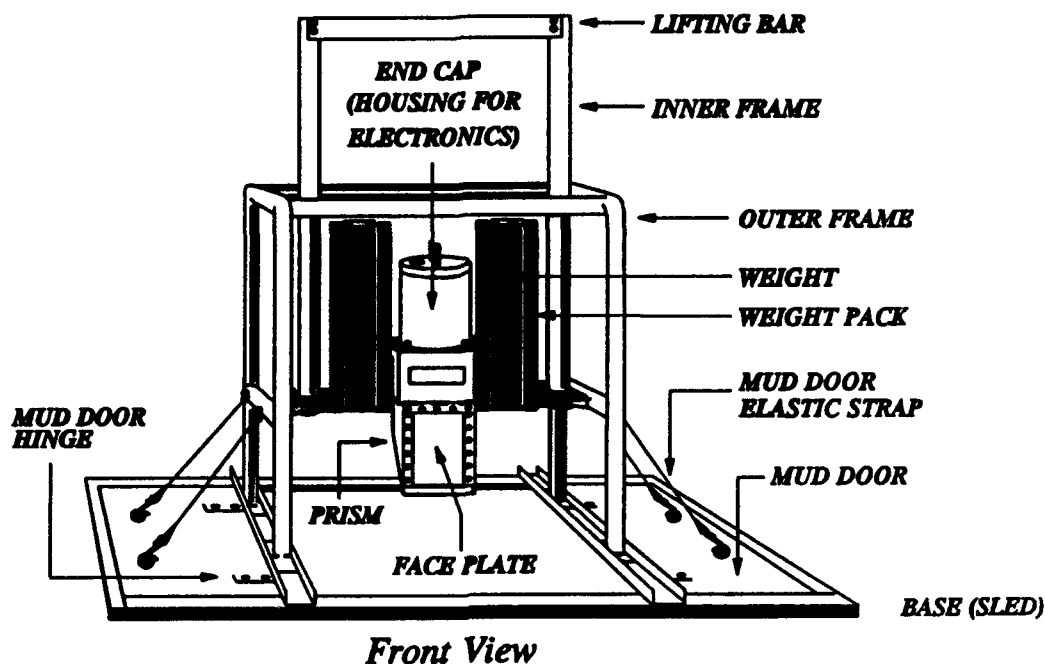
Figure 3.   Schematic diagram of the REMOTS® sediment
            profile camera

90-100-m depth remains very controversial. This controversy has been main-
tained because of a near absence of monitoring data on sites greater than a
20-m depth, earlier studies of disposal at New England's 90-m site (Massachu-
setts Bay Disposal Site) that failed to detect mound formation, and, in the
New England situation, the proximity of the proposed site to areas heavily
used by endangered and protected species of whales. Later analysis of the
study that failed to detect a mound concluded that lack of point disposal and
limitations of the detection limits of the surveys and equipment were likely
to be the principal reasons for lack of mound detection and not dispersion of
the material following disposal (Bajek et al. 1987).

Consequently, monitoring surveys at New England's deepest offshore dis-
posal site in Massachusetts Bay have focused on answering the basic question
about mound formation. This answer has been reached by disposing of all sedi-
ments since 1985 (7.2 million cubic meters) at a taut-wire moored buoy sta-
tioned within the site. Sequential bathymetric and sediment profile camera
surveys have been used to document the lateral and vertical distribution of
sediments through the most recent survey in 1991 (Science Applications Inter-
national Corporation 1990; In press).

In contrast to predictions based on the earlier study, the surveys have
documented the development of a mound 1.5 meters in height having a radius of
approximately 400 meters (Figure 7). Given the relatively low bottom currents
at this site (10-20 cm/sec) and the protection from wave effects that this
depth provides, this deposit is expected to remain stable.

90
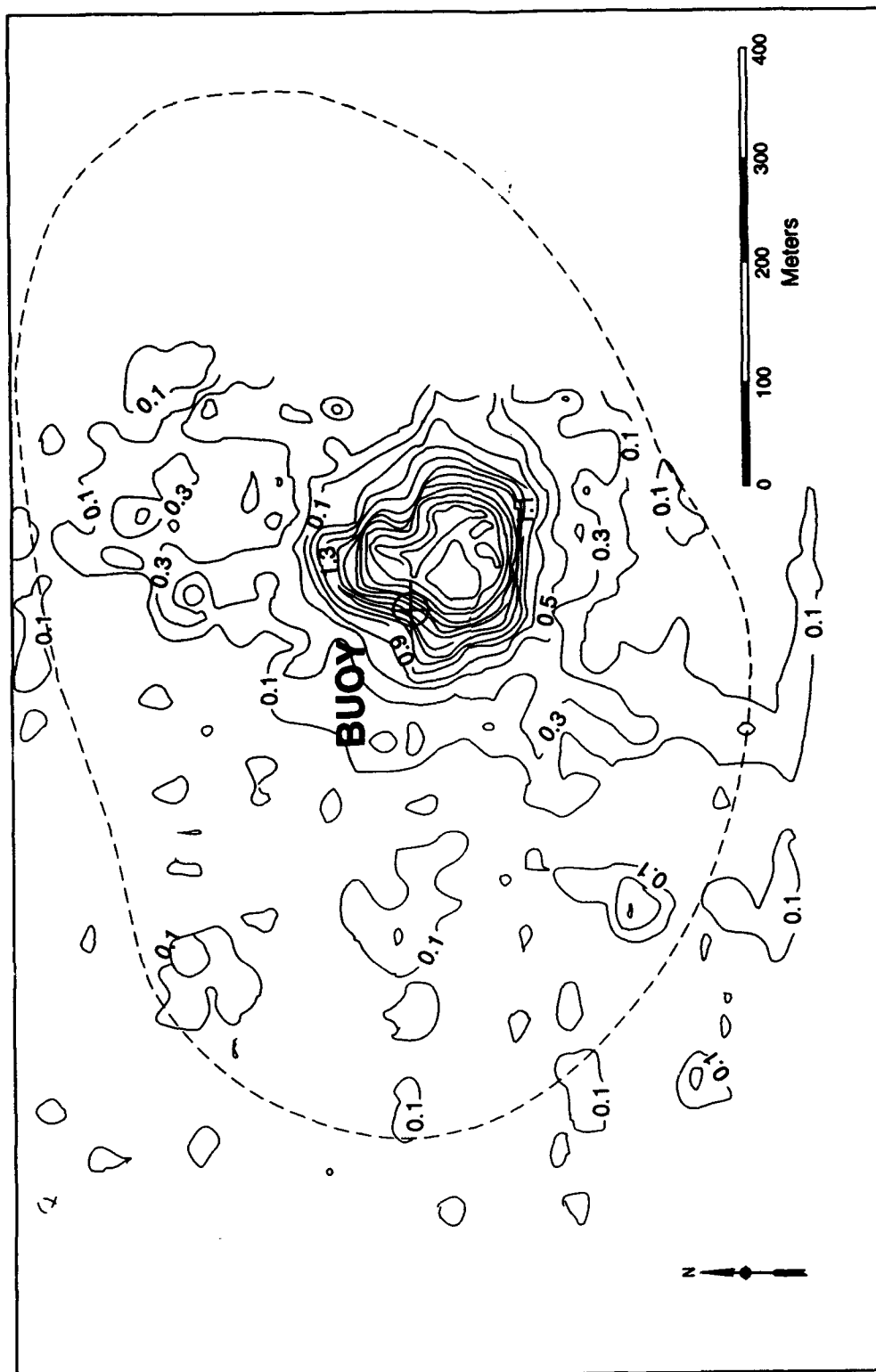
Figure 4. Depth difference contour map (contour interval = 0.2 m) showing the dredged material mound perimeter detected using a sediment profile camera (hatched line) and bathymetry
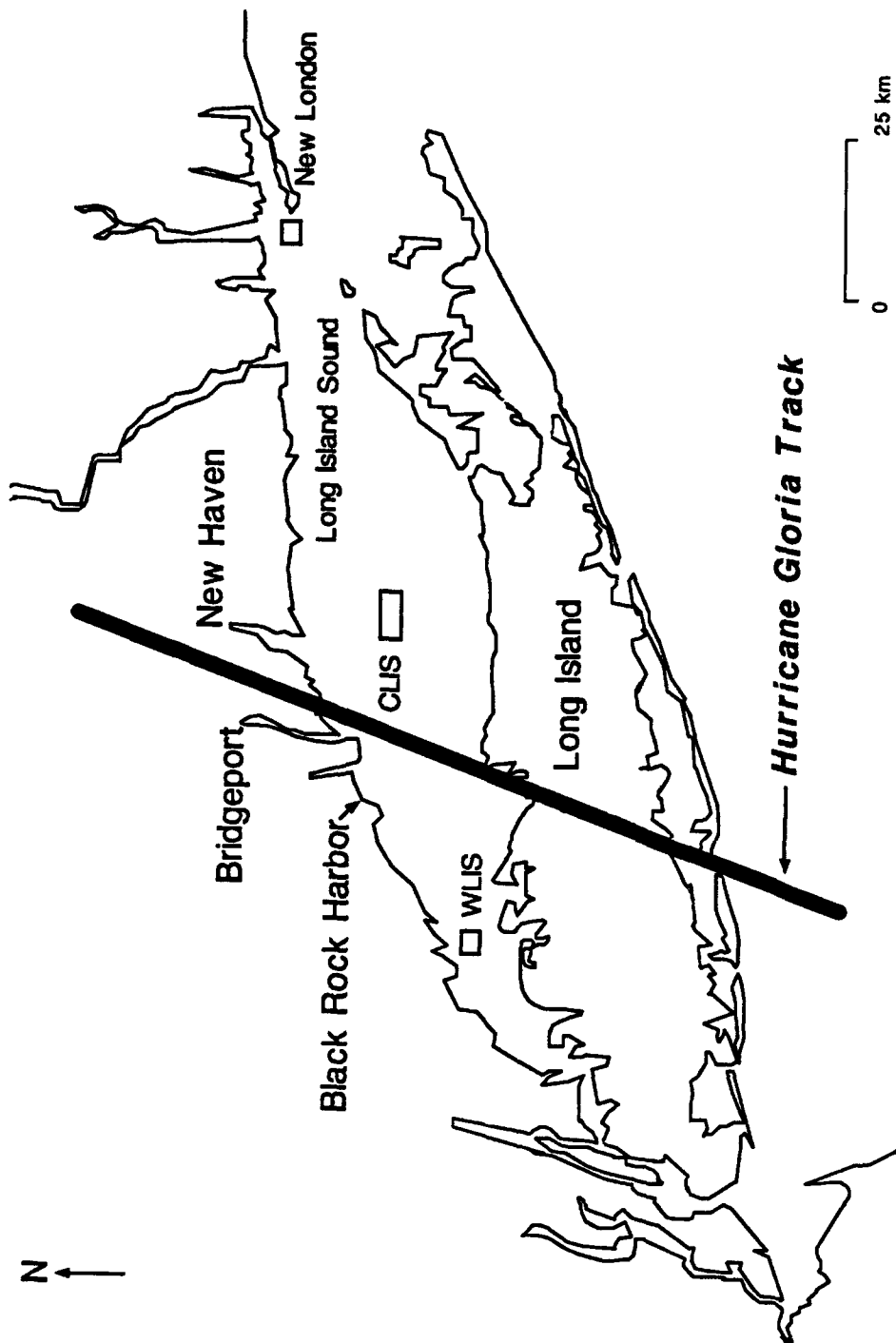
Figure 5. Location of the three disposal sites, Western Long Island Sound (WLIS), Central Long Island Sound (CLIS), and New London, in Long Island Sound and the track of Hurricane Gloria on 27 September 1985
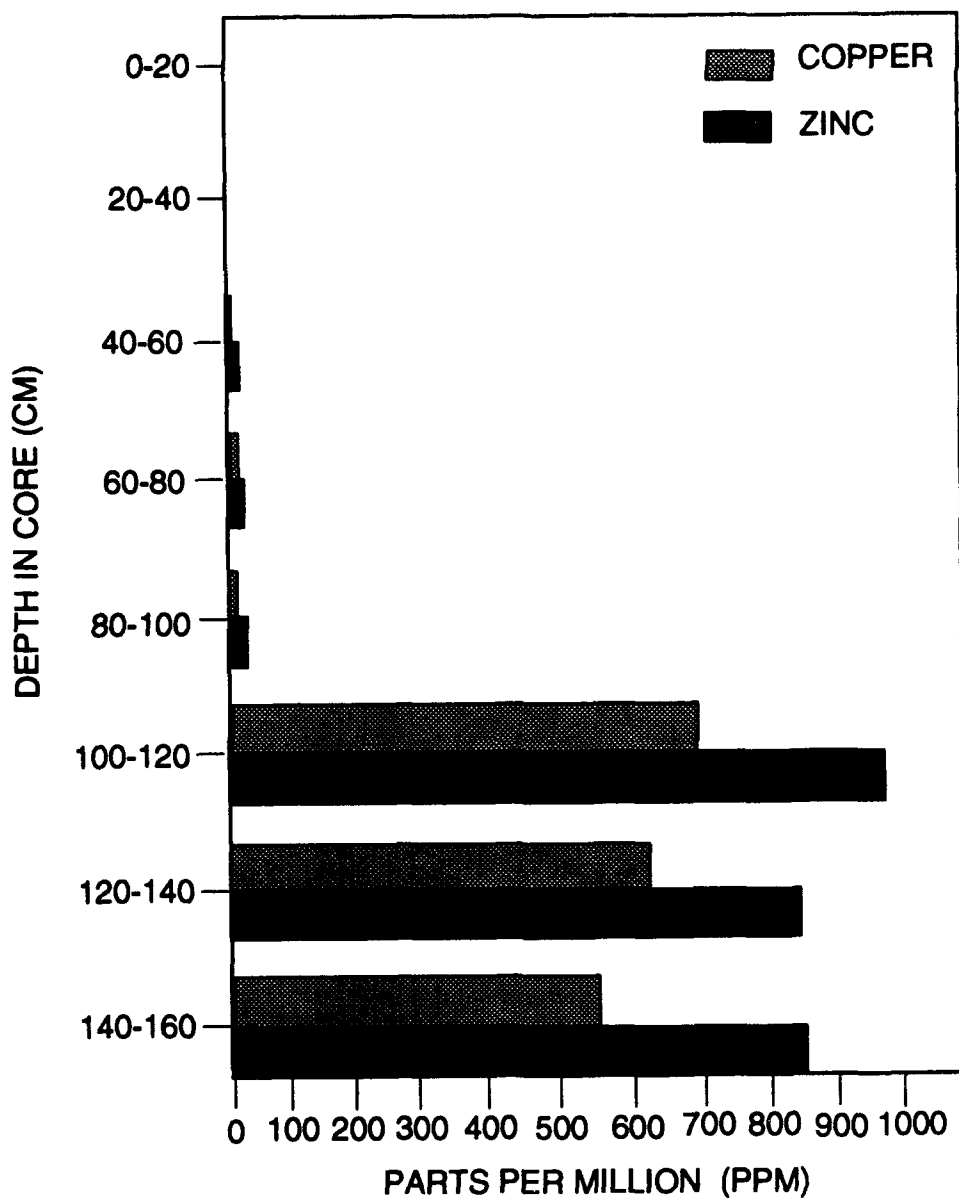
a. Copper and zinc concentrations

Figure 6.   Core sections of copper and zinc and four PAH
concentrations on a capped mound 11 years after
placement; cap/contaminated interface observed
in the 80- to 100-cm section   (Continued)
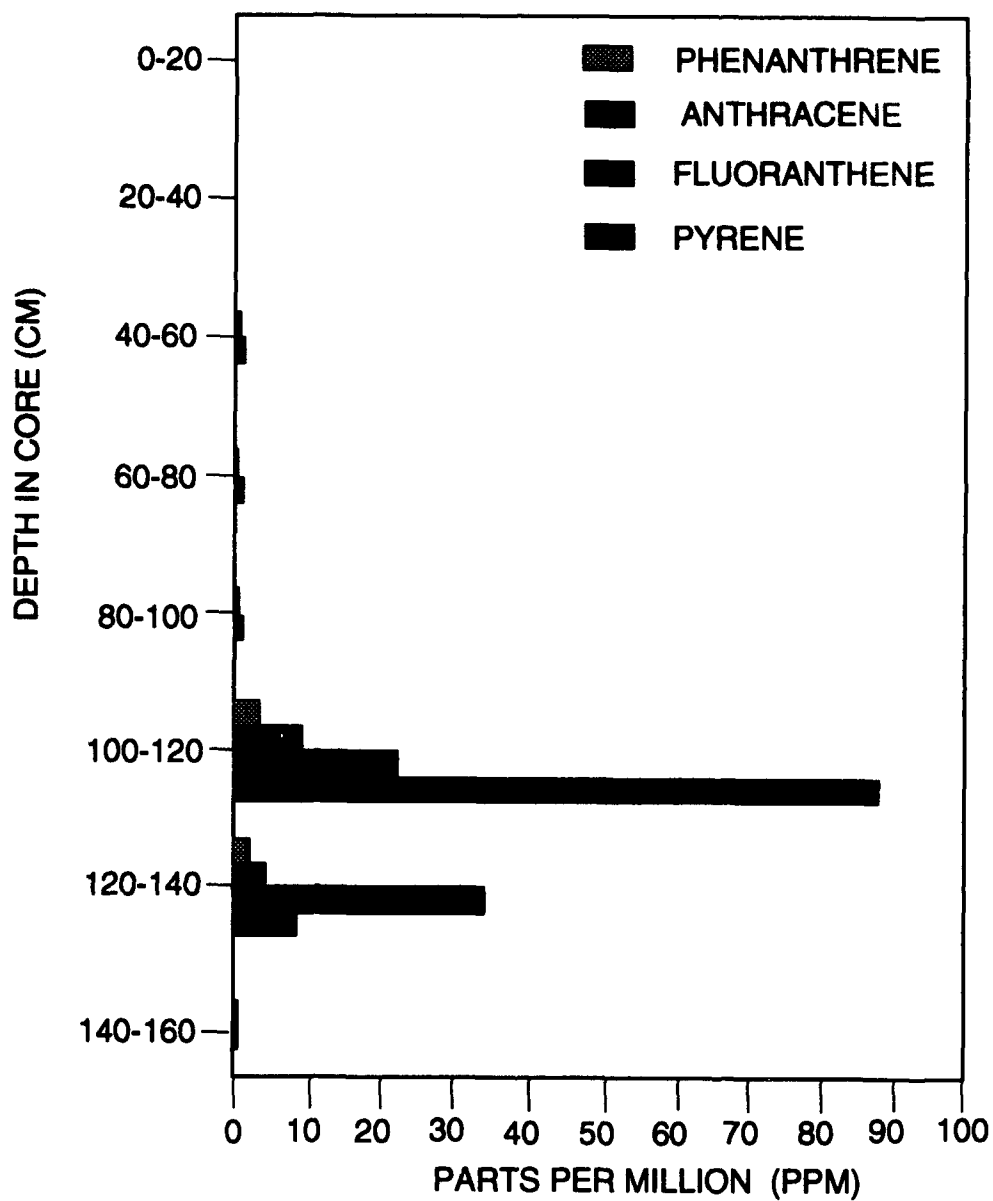
b. PAH concentrations

Figure 6. (Concluded)

DISCUSSION

Monitoring of capped disposal mounds and sediment behavior at sites of various depths has increased the confirmation of both the ability to cap contaminated sediments using conventional dredging equipment and predictions about cap performance in isolating contaminants from the environment. However, despite the large body of evidence supporting the success of capping, there remains a great deal of skepticism within the environmental community. Thus, there is still a need for continued monitoring and research to improve the information base on which to evaluate the capping alternative relative to other sediment management options.

The principal research need for the deeper water sites is a demonstration project to confirm the theoretical predictions about sediment behavior. Existing mathematical models (Brandsma and Divoky 1976, Johnson and Holliday 1978) and the empirical results from DAMOS monitoring surveys both support the prediction that contaminated sediments could be placed on the bottom in deposits similar in overall extent to those which have been capped in shallower sites. Confidence in the ability to then place cap sediments over the contaminated sediments and their long-term isolation of these contaminants should be directly transferable from our shallower water experience. Nonetheless, until a demonstration of these assumptions are made the most ardent of critics will remain unconvinced.

It is my belief that as we continue to study the long-term effectiveness of capping at offshore sites, we will find that this alternative, while not providing for 100 percent sequestration of contaminants, provides the most practical solution for the majority of contaminated sediments. Other remediation alternatives, such as diked containment areas, borrow pits, or treatment, will seldom be worth the incremental costs that such solutions demand when carefully evaluated relative to the incremental benefits.
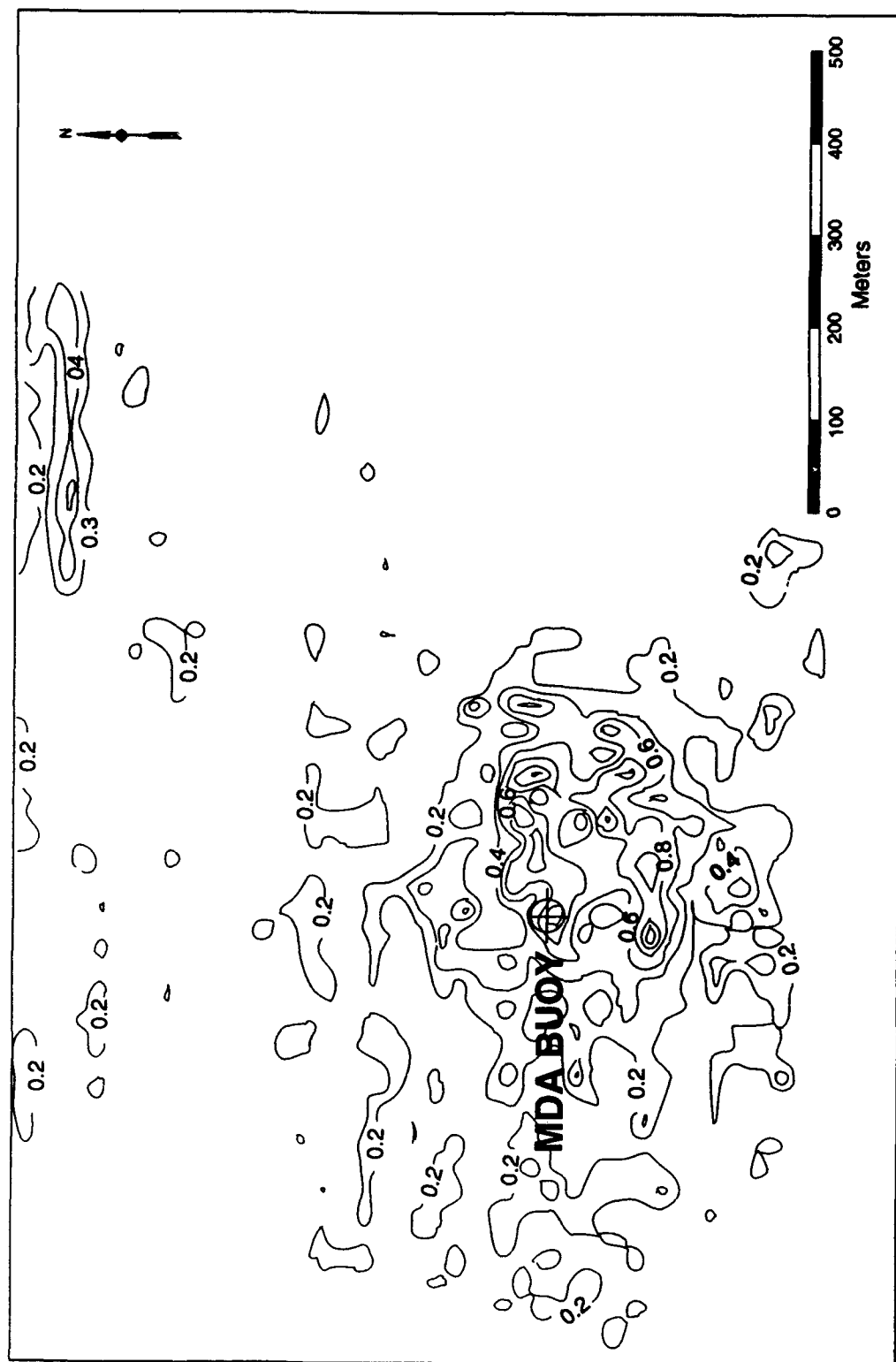
Figure 7. Depth difference (in meters) contour chart based on the comparison of 1990 and 1987 bathymetric data; ambient depth range is 85 to 90 m

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THE DEVELOPMENT OF CLEAN AND DENSE DREDGING SYSTEM

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ABSTRACT

A new clean and dense dredging method was developed that can dredge the bottom sediments found in rivers, lakes, and harbors without mixing with water. By using this method, only a small amount of water is dredged together with the bottom sediments, and the quality of environment is not deteriorated.

In the course of development, fundamental tests using a model were carried out in the laboratory basin to ascertain the effectiveness of this new dredging principle. The following points were confirmed at filed tests by using a small testing machine:

a. High density dredging/transportation with the solid concentration of over 80 percent obtainable.

b. The amount of turbidity caused by dredging operation is far less--1/5~1/10 of that caused by conventional methods (grab, cutter suction, etc.).

c. A flat finish is obtainable, with the accuracy of flatness between -1 to +5 cm where the dredged soil thickness is 30 cm.

This report summarizes the outline of the system and the development process form the fundamental model tests to the positive filed tests using the small testing machine and then to the execution of real dredging work.

INTRODUCTION

The waterfront development has progressed throughout Japan, and the creation of spaces where people feel closer to water, beneficial to both man and nature, are in urgent demand. Especially the improvement of water environment, to make it amenable to human beings, has gained in importance.

Usually the quality of water cannot be improved without improving the bottom quality, and one of the solutions is to remove the bottom sediments, thus the dredging is carried out. The conventional dredging methods generally use grab or cutter suction dredges. The cutter suction pump-type dredging is disadvantageous because it requires a large sedimentary area for the great volume of water sucked in with the bottom sediments, and such water is

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detrimental to the transportation efficiency. In the case of the grab-type dredger, the turbidity caused by the dredging operation and inability to dispose of the large volume are major drawbacks. Therefore, an improved dredging system was in keen demand.

This newly developed clean and dense dredging system should meet the demand. Rotating and advancing, the developed dredging equipment is partially inserted to the bottom sediments quietly, at a rotating speed simultaneous to its advancing speed to cut off and lift up the bottom sediments. This system can dredge bottom sediments just as the sediments accumulated, without disturbing the sediments. This system can dredge bottom sediments, not allowing extra water to enter, not causing environmental turbidity.

OUTLINE OF THE SYSTEM

Principle of Dredging

The basic principle of dredging is to rotate the dredging equipment having a plurality of bucket chamber formed by sequentially projected sliding blades, synchronously to its advancing speed, and to penetrate the bucket chambers into the bottom sediments to cut and lift up the bottom sediments gently.

Structure of Dredging Equipment

Broadly, the dredging equipment is made of three major components. It is structured as shown in Figure 1. The dredging drum (item 1, Figure 1) comprises two side
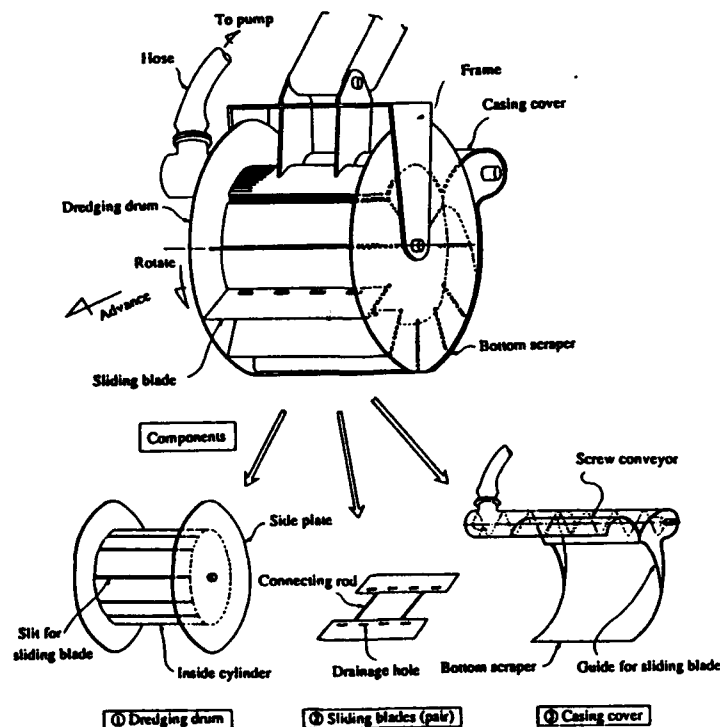
Figure 1. Structure of dredging equipment

plates and an inside cylinder, which is rotated by an oil hydraulic motor. The inside cylinder has 12 radial slits for the sliding blades (item 2) to slide in and out. The casing cover (item 3) has a bottom scraper in its lower section, a screw conveyor and a housing cover on the top, and guides for sliding blades in the intermediate section. The casing cover is fixed to the frame. Twelve sliding blades installed in the dredging drum are paired with each two facing each other connected by connecting rods and move in unison. As the dredging drum rotates, those sliding blades on the upper side are pushed by the guides and the upper housing cover to be retracted into the drum, while the blades at opposite side are forces out of the drum to form a rectangular bucket chamber between two side plates of the drum.

Principle of Motion

Figure 2 shows the motion of dredging equipment.

① Dredging equipment moves forward and rotates
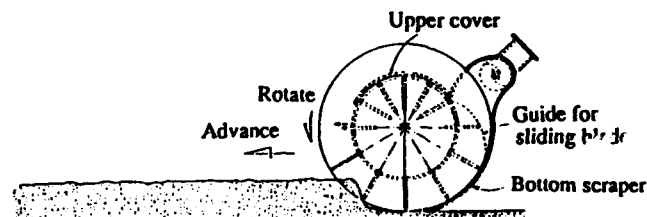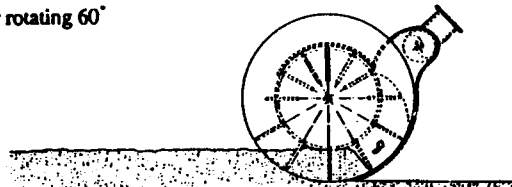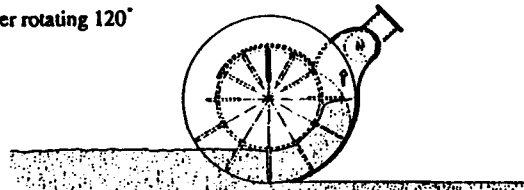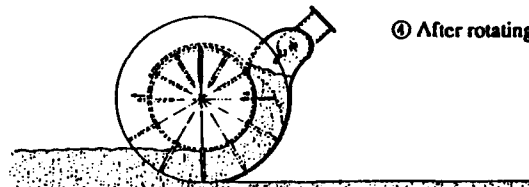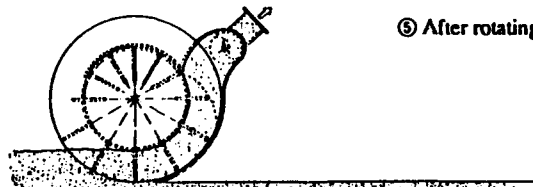
Figure 2. Details of dredging motion

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a. When the dredging drum rotates and moved forward, the buckets at the lower part of the drum are consecutively penetrate into the bottom sediments. By synchronizing the speed of rotation and advance, the relative speed difference between the bucket and the ground is brought to zero, and the bottom sediments are enclosed inside the buckets without disturbance of the ground.

b. As the bottom scraper advances, the bottom sediments in the buckets are cut and lifted up.

c. The dredging drum rotates and the bucket holding bottom sediments ascents along the bottom scraper and further above to the screw conveyor chamber, then the sliding blades gradually slide into drum and the bucket disappears.

As is clear form this principle of motion, the theory that made clean and dense dredging possible comprises the following three functions, and their details are as follows:

a. **Discharging water while the sliding blades penetrate into the bottom sediments.** As shown in the principle drawing Figure 3, when the bucket having several holes in its bottom is pressed into the bottom sediments, the water inside the bucket is forces out through these holes and replaced with the bottom sediments. The process is continuous due to the rotation of the dredging drum and made possible the intaking of bottom sediments into the bucket without adding extra water.

b. **Discharging water while the bottom sediments are being lifted.** Figure 4 shows how water is discharged while the bottom sediments are being lifted. When water is lifted together with the bottom sediments as shown in bucket chambers A and B, its fluidness and the pressure from the bottom sediments which are filled in the upper screw-conveyor chamber allow water to flow down through the drainage holes provided in each sliding blade and so the water is prevented from going up into the screw chamber.
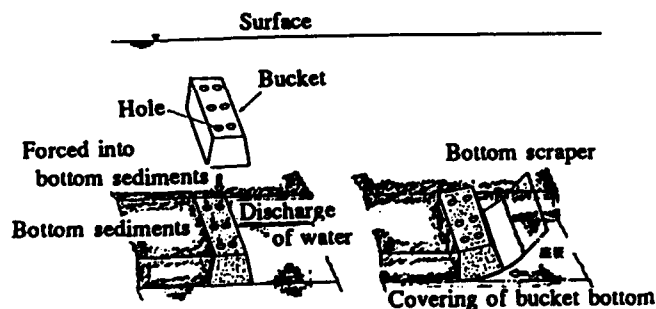
Figure 3. Discharge water function while penetrating
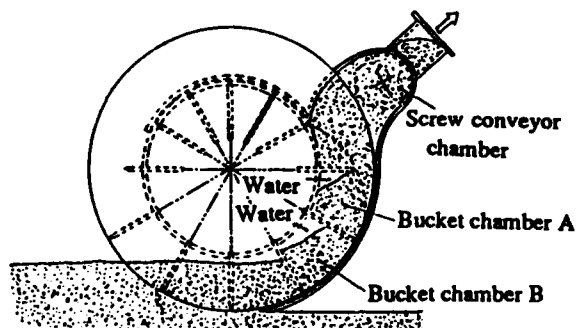
Figure 4. Discharging of water while bottom sediments are lifted

c. __Preventing extra water to enter.__ The purpose of providing a cover above the screw-conveyor chamber and retracting the sliding blades into the inside cylinder of the dredging drum is to prevent the entry of extra water from the above, as well as to give the sliding blades at the bottom part a reaction force to penetrate into the bottom sediments, and also special rubber sealings to effectively prevent the entry of water.

Lifting and Transfer of Dredged Bottom Sediments

Bottom sediments filled in the screw-conveyor chamber are carried to the end part of the chamber and then discharged. The discharge pipe is connected to the suction pipeline of a positive-displacement type pump of which the flow rate may be controllable, and the bottom sediments discharged from the screw-conveyor chamber are sucked by the pump keeping the natural water content of bottom sediments as they were at the bottom and transferred out of the dredger.

The screw-conveyor's plug effect prevents entering of water by means of the suction force of the pump. Image drawing Figure 5 shown the flow of dredged bottom sediments from collection through lifting up to transfer.
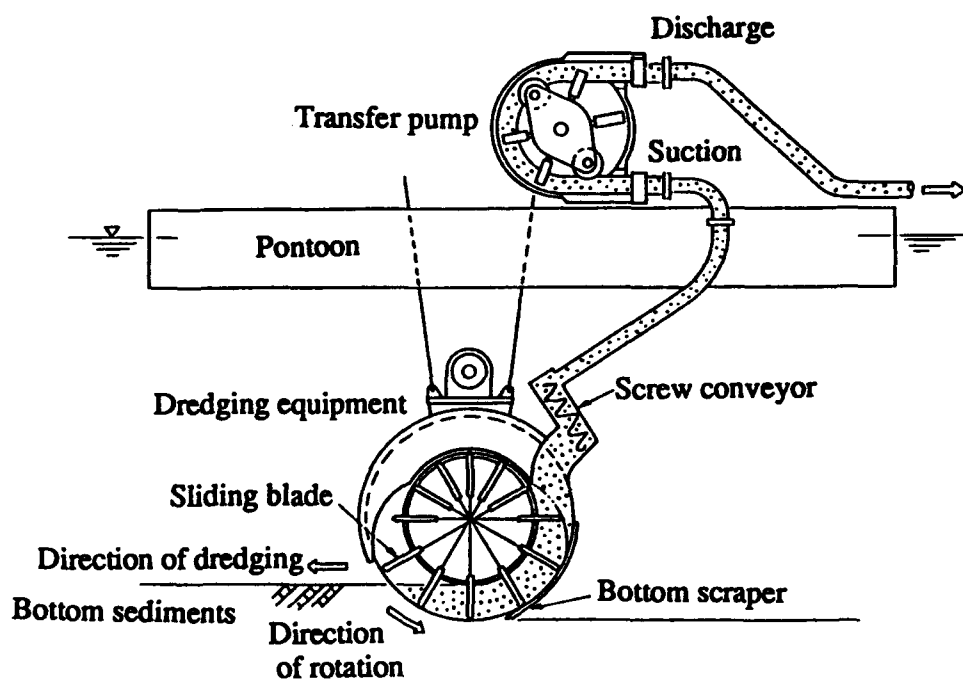
Figure 5. Flow of dredged bottom sediments

Composition of System

As shown in Figures 6 and 7, this dredging system in composed of the dredging equipment, a transfer pump and its suction/discharge pipelines, a maneuvering winch, an obstacle remover, and an automatic tracking laser positioning system for the display and monitoring of the dredging position. Dredged bottom sediments are transferred by a high-pressure transfer pump to

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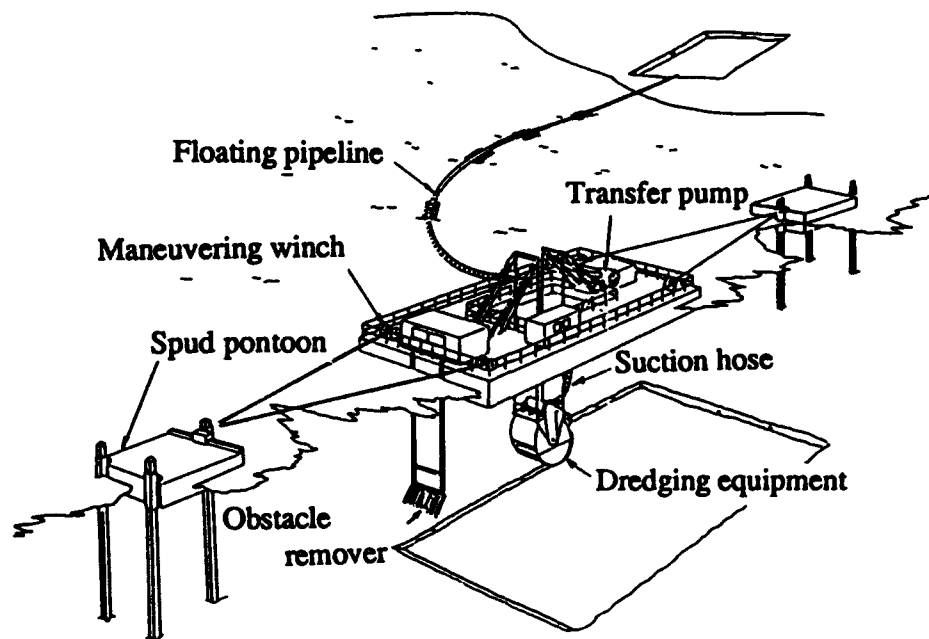
Figure 6. Conceptual drawing of system for lake/river use
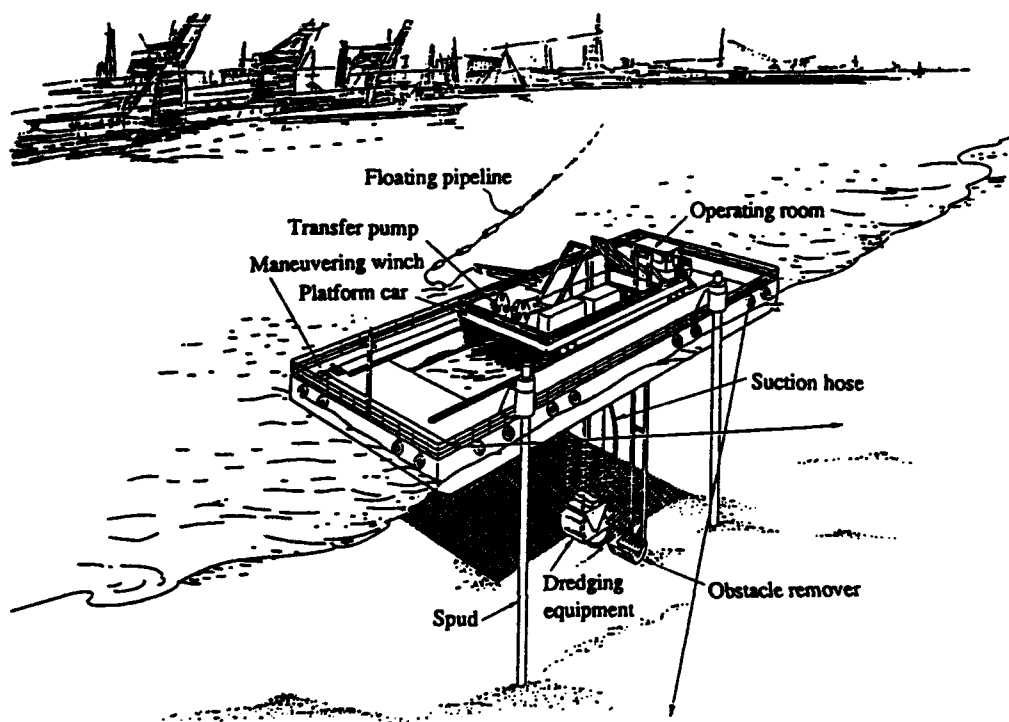
Figure 7. Conceptual drawing of wave-resistant system for harbor use

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its destination via a floating pipeline. In the case of long-distance transfer, a booster pump should be used as needed.

The obstacle remover collects small obstacles in the bottom sediments before dredging. The combination of a fixed rake biting into the bottom sediments and an elevator rake meshed with it and rotating effectively removes obstacles.

This dredging system can be set up for both lake/river use and harbor use. The suitable setup may be chosen. Figure 6 is a conceptual drawing of the system for use in a lake, marsh, or river (pontoon traveling type). It has a divisible and portable structure, and overland transportation is possible. Figure 7 shows the wave-resistant system for harbor use (platform car shifting type). They are operated as follows:

a. For lake river use. The dredger pontoons are maneuvered by means of ropes hung between two spud pontoons located far apart (about 50 to 60 m), without laying anchoring wires.

b. For harbor use. A platform car on which the dredging equipment is mounted moves back and forth in the opening at the center hull of the dredger. The operation is carried out by means of two maneuvering wires and tow spuds.

Distinctive Features of System

The features are listed below.

a. High density dredging (the solid concentration of 80-100 percent) with no addition of water and long-distance transportation of slurry maintaining high density are possible.

b. Bottom sediments with a wide range of properties (natural water content between 80-400 percent) can be dredged.

c. Dredging is operated without disturbing the bottom sediments, so the environmental turbidity is very little.

d. The bottom scarper ensures flat and reliable finish of dredging.

HISTORY OF DEVELOPMENT

Because of its unprecedented dredging principle and mechanism, the development of this system began with theoretical analyses of the dredging principle and the transfer system of dredged slurry. Next, fundamental tests using a model were carried out to confirm the feasibility of the system. Then the actual development proceeded through the designing and producing of a small testing machine to a field performance tests and finally tests at various dredging sites.

Analysis of Dredging Principle

Dredging Theory

In general, the excavation theory of a cutter used by cutter suction dredges are expressed by a trochoid curve (Figure 8). Its principle is that the cutter, usually composed of five or six blades, rotates at a speed of 10-20 rpm, then moves crossways mincingly along the curve in Figure 8 cutting the soil in thin slices, raking up and mixing with water to suck up by a pump.

As against this, a theoretical curve of the sliding blades of the newly developed dredging system in shown in Figure 9. To synchronize the advancing speed with the speed of rotation, the situation is similar to that of an automobile tire. The locus of a point on a revolving circumference shows rectilinear motion near at the lowermost point as in Figure 9. The principle is making use of this X of the cycloid curve, and the sliding blades penetrate into the bottom sediments almost unresisted, not disturbing the bottom or moving in at after the penetration, thus causing no turbidity.
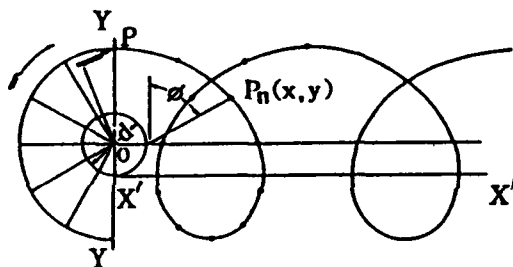
Figure 8. Trochoid curve   Figure 9. Cycloid curve
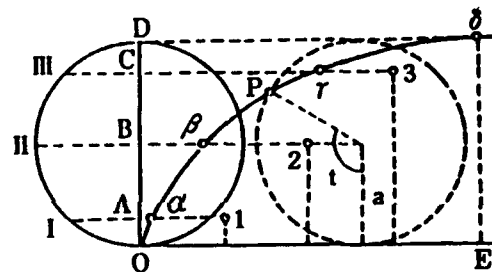
Correlation with Soil Strength

For quantification of the above theory, the sliding blade has to have correlation in strength with the bottom sediments into which it penetrates. At the same time, the force required for penetration to lifting up of dredged bottom sediments in the cover (rotating torque of the dredging equipment) must be calculated. Formulae (1)-(4) are for the calculation of these forces. The required torque for the dredging equipment can be obtained by multiplying radius length of rotation to these forces.

Penetrating force of sliding blade

$$R = 8 \ CP \cdot AP + Ca \cdot As \qquad (1)$$

Component force $R1 = R \cdot \sin \theta$

Adhesive force of bottom sediments to the side plates

$$S = \frac{3}{2} \cdot r \cdot r^2 \left[\frac{\theta}{180} \cdot \pi - \sin\theta \right] \qquad (2)$$

Force of blade pressing bottom sediments

$$P_p = B \left\{ \frac{1}{2}(\gamma_t - \gamma_w)H^2 + 2rH \right\} \qquad (3)$$

Force to lift up dredged bottom sediments

$$F = 4\,q(\gamma_t - \gamma_w)(1 + \mu) \qquad (4)$$

where

    CP — adhesive force at blade tip
    Ca — average adhesive force per full penetrated blade length
    AP — area of blade tip
    As — area of blade side
    θ — blade penetrating angle
    r — blade tip rotating axis
    B — blade width
    γ_t — weight per unit volume of bottom sediments
    γ_w — weight per unit volume of water
    H — thickness of bottom sediments
    r — shearing strength of bottom sediments
    q — capacity of bucket chamber
    μ — friction coefficient of bottom sediments and blade

Formulae (5 and (6) are for the calculation of strengths of the blade member against the above external forces. Table 1 is the results of trial calculation for three types of bottom strength.

Bending stress caused by normal load

$$\sigma = \beta \cdot p \cdot \frac{B^2}{H^2} \qquad (5)$$

Bending stress caused by concentrated load

$$\sigma_{max} = P \cdot \frac{H}{z^2} \qquad (6)$$

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TABLE 1. CORRELATION BETWEEN GROUND AND BLADE STRENGTHS

Item	Notation	Unit	Case 1	Case 2
Natural water content	W	%	100	300
Weight per unit volume	γt	t/m^3	1.45	1.17
Shearing strength	τ	t/m^3	1.20	0.30
Penetrating force of a blade	R	t	0.32	0.08
Adhesive force of bottom sediments to the side plates	S	t	1.10	0.28
Force of blade pressing bottom sediments	Pp	t	0.89	0.20
Force to lift up dredged bottom sediments (4 chambers total)	F	t	0.31	0.12
Effective driving torque	Tr	t - m	2.54	0.69
Load/blade (1 peace)	fu	t - m	1.01	0.27
Bending stress (normal)	σ	t/m^2	0.50	0.12
Bending stress (maximum)	σ max.	t/m^2	1.33	0.33

where

β = stress modulus
p = uniformly distributed load
P = concentrated load
z = section modulus of blade member

Principle of Slurry Transfer

For the transportation of dredged bottom sediments lifted, as it is not added with extra water, a special transfer pump system is needed. Here it uses a squeeze pump which is a kind of concrete pump. The theoretical formula for the pipeline-transfer of slurry that used this pump follow. Table 2 gives examples of trial calculations.

<Theoretical formulae taking slurry viscosity into consideration>

Slurry resistance in pipeline-transfer

$$H_f = f_B \cdot \frac{\gamma_m \cdot L \cdot v^2}{2 \cdot g \cdot D} \qquad (7)$$

Plastic viscosity of slurry

TABLE 2. TRIAL CALCULATIONS FOR PIPELINE TRANSFER

Item	Notation	Unit	Case 1	Case 2
Natural water content	W	%	150	300
Weight per unit volume	γt	t/m^3	1.37	1.22
Solid concentration by apparent volume percent	σ	%	100	100
Solid concentration by true volume percent	C_v	%	20.6	11.4
Plastic viscosity	μn	Pa·s	0.021	0.006
Yield rate	tv	N/M^2	15.1	2.30
Specific plug radius	a	--	0.78	0.71
f (a)	--	--	0.201	0.276
Reynolds number	R_{eB}	--	249	1840
Coefficient of resistance	f_B	--	0.050	0.032
Pipeline length	L	m	500	500
Pipeline diameter	D	m	0.15	0.15
Slurry resistance in pipeline-transfer	Hf	m	136	22.3
Pump head	Hr	m	150	33.0

$$\mu_B = 1.14 \cdot 10^{-3} \cdot \exp(14.2 \cdot C_v) \tag{8}$$

Yield value of slurry

$$\tau_y = 2.33 \cdot 10^3 \cdot C_v^{3.19} \tag{9}$$

Specific plug radius

$$\mu_B = \frac{D \cdot \tau_y (a^4 - 4a + 3)}{24 \cdot v \cdot a} \tag{10}$$

Reynolds number

$$R_{eB} = \frac{\gamma_m \cdot v \cdot D}{g \cdot \mu_B} \cdot \frac{a^4 - 4a + 3}{3} \cdot f(a) \tag{11}$$

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f(a)

$$f(a) = \frac{9}{5} \cdot \frac{5 + 6a - 11a^2}{(3 + 2a + a^2)^2} \tag{12}$$

From Formulae (8), (9), and (10), "a" if obtained, and from (11) and (12), "R_{eB}" is obtained. Read the value of "f_B" from Figure 10, then substitute in (7) to obtain "H_f".

where

H_f — Slurry resistance in pipeline-transfer
f_B — Coefficient of resistance
μ_B — Plastic viscosity
C_v — Solid concentration by true volume percent
v — Current velocity
τ_y — Yield value of slurry
y — Yield value
D — Inner diameter of pipeline
a — Specific plug radius
R_{eB} — Reynolds number
γ_m — Specific gravity of liquid in pipeline
g — Acceleration of gravity
$f(a)$ — Function of "a"
L — Pipeline length
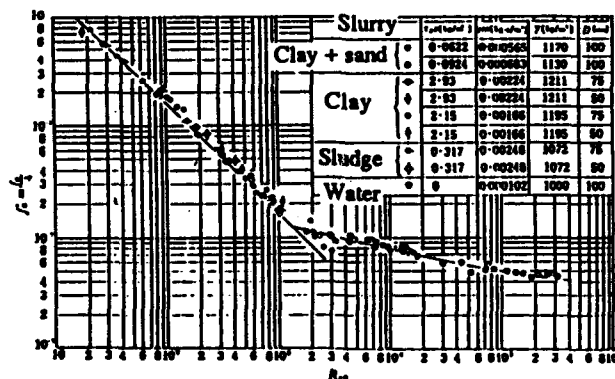
Figure 10. Coefficient of resistance

Tests Using Model in Laboratory Basin

Setup for Tests

The setting up for the tests comprised a laboratory basin (6 m x 3 m x 2 m), a squeeze type transfer pump, a sludge mixer, a discharge tank, etc. The dredging equipment model was set on a frame of a platform car which can

run back and forth and crossways over the basin. Inside the basin a simulated bottom sediment (bentonite/fly ash) ground was made (Figure 11). The model shown in Figure 12 was made of acrylic resin so that it could be observed from outside. Figure 13 shows the test setup.
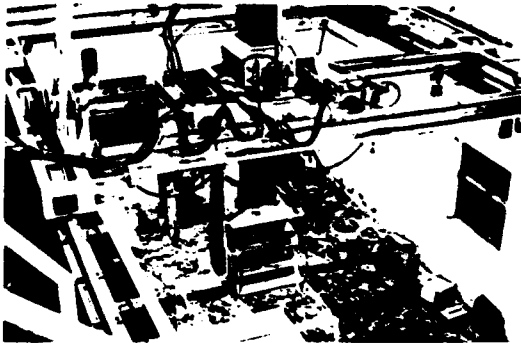
Figure 11. Laboratory basin
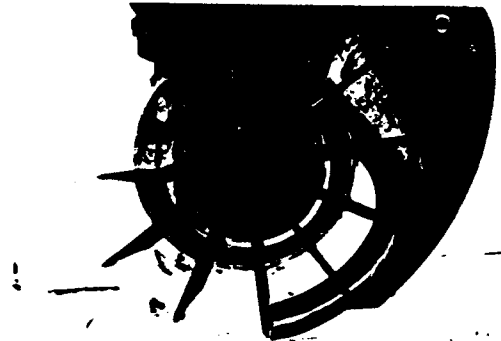
Figure 12. One-third scale model
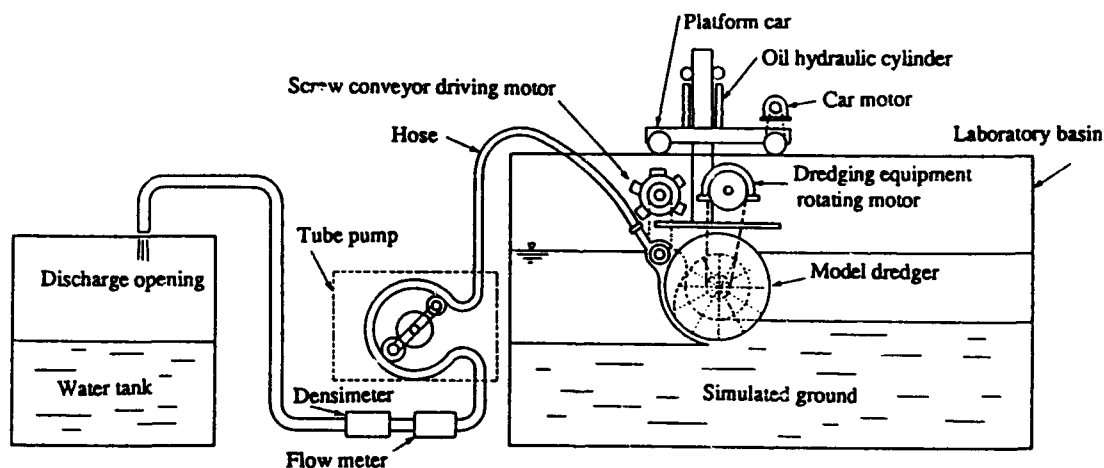
Figure 13. Test setup

Contents of Tests

The specifications of the model are given in Table 3. The model was one-third the size of a small testing machine. Tests were conducted by varying the thickness of bottom sediments to be dredged, dredging advance pitch (overlap), dredging speed, pump flow rate, and soil properties (natural water content).

In addition to performance data including the solid concentration, dredging volume, configuration of dredges area, and amount of turbidity caused, such test data as loads applied to the dredging equipment and to the screw conveyor were self-recorded and their performances were analyzed by a computer. At the same time, its structure and strength were investigated.

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TABLE 3.   PARTICULARS OF TESTS

Particles	Model Tests	Field Tests
Dredging width (m)	0.5	1.2
Soil thickness (m)	0.1	.03
Dredging speed (m/min)	1.5	3.0
Dredging volume (m³/h)	4.5	65
Transfer pipe diameter (mm)	50	200
Dredging drum diameter (m)	0.65	2.1
Dredging equipment width (m)	0.5	1.2
No. of sliding blades	12	12
Ground	Simulated bottom sediments ground	Accumulated bottom sediments ground

Test Results

a. **High-density dredging performance.** Figures 14 and 15 are the graphs of solid concentration. The solid concentration in basic conditions (basic particulars) was as high as above 85 percent when the ratio of handled soil volume (by the dredging equipment) to pump flow volume was less than 1:1. The solid concentration can be adjusted by changing pump flow rate. In conditions with a thin soil layer or a less dredging width, the high solid concentration can be maintained by adjusting the pump flow rate. Figures 16 and 17 show high-density slurry being discharged during the model test.

b. **Turbidity preventive function.** Figure 18 shows the net contents of turbidity generation. Even in high-density dredging the turbidity is low, i.e., below 1×10^{-3} ton/m³. Depending on the operating conditions it may be even lower.

c. **Accuracy of flat finish dredging.** As is evident from Figure 19 showing the configuration of dredged section recorded during overlap dredging, a very flat finish was achieved.

Performance Tests on Small Testing Machine

Production of the Small Testing Machine

Based on the result obtained from the tests using one-third scale model, a small testing machine on a practical scale was produced. Prior to the actual designing, the machine was designed with scrupulous care on a trial basis and its practicality in field use was discussed. The result of the discussion was incorporated in the designing of the components. Figure 20 is an external view of the small testing machine.

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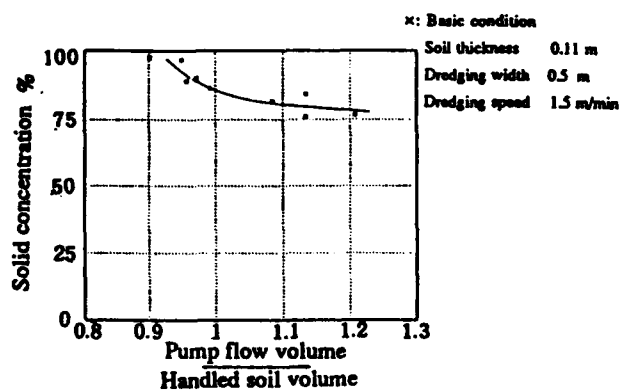
Figure 14. Solid concentration
(basic condition)
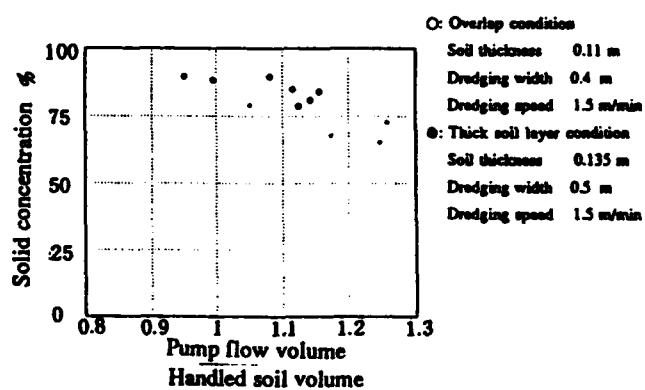
Figure 15. Solid concentration
(overlap/thin soil
layer conditions)

Figure 16. Discharging of dredged
soil (not using
transfer pump

Figure 17. Discharging of dredged
soil (using transfer
pump)

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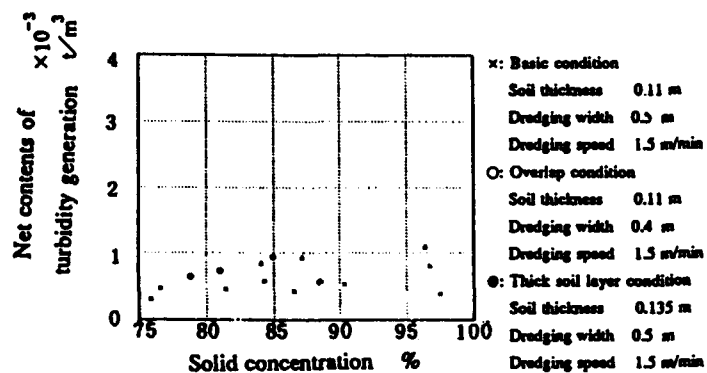
Figure 18. Net contents of tur-
            bidity generation
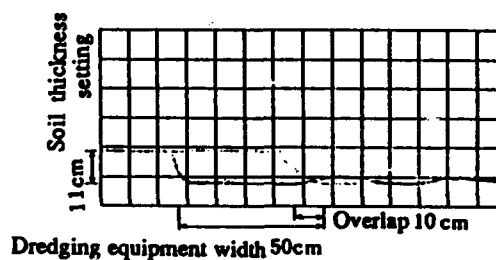
Figure 19. Accuracy of flat
            finish dredging
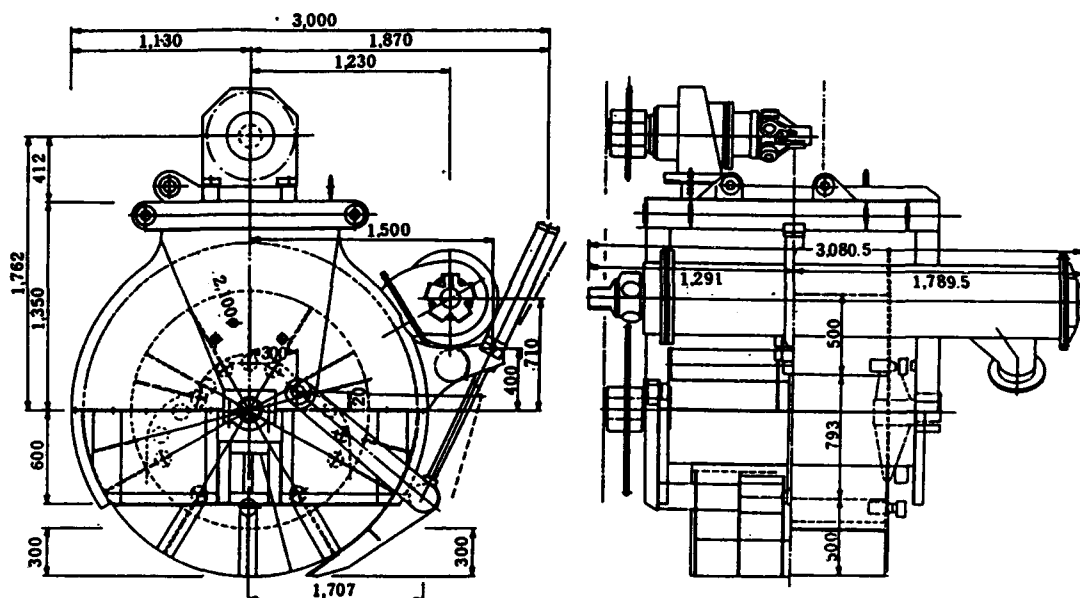
Figure 20. External view of the small testing machine

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Setup of Tests

Figure 21 is an arrangement plan for the test of the small testing machine. Figures 22 and 23 show exterior views of the test setup.

Support   Wire

7,500

PRINCIPALS

1. Dimensions	L × B × D	20.51m × 10.14m × 1.22m
Planned draft		0.7m
2. Dredging equipment		2.1m² × 1.2m
3. Transfer pump	Type	Squeeze pump
	Capacity	70m³/h × 15kgf/cm² × 2 set
	Suc. dia. × del. dia.	200mm × 150mm
4. Maneuvering winch		3.0t × 0~15m/min
5. Generator		300kVA
6. Dredging capacity		30~50m³/h
Dredging depth		max. 7.5m

Maneuvering winch   Rest room   Oil hydraulic unit

Obstacle remover   Squeeze type pump   Hose   Dredging equipment   Dredging equipment lifting winch

Operating room   Obstacle remover lifting winch   Center well

Generator   Measurement room

Figure 21.   Arrangement of the small testing machine

Figure 22.   Exterior view of test setup

Figure 23.   The small testing machine

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Outline of Performance Tests

Performance tests were conducted using the test setup intended to attain a target dredging capacity of 30-50 m^3/h. Bottom sediments in a river in an urban area was chosen for the tests. The test site had a depth of 5-6 m. Performance test dredging in a soil thickness of 0.5 m was carried out in the bottom sediments with natural water content ranging from 150 to 400 percent. the items checked by the tests are listed in Table 4.

TABLE 4. CHECKED ITEMS

Dredging Characteristics	Major Items Checked
1) Dredging performance	• Dredging volume per operating hour • Solid concentration • Accuracy of flat finish dredging • Occurrence and other turbidity related matters
2) Load performance	• Each machine capacities required for dredging and the capacity balances between machines
3) Maneuvering performance	• Straightness while dredging • Hull shift workability
4) Ability to deal with obstacles	• Work efficiency • Strength of machines concerned
5) Others	
Target values i) Solid concentration ii) Dredging capacity	above 80% max. 80 m^3/h (per dredging hour)

The following were confirmed as fundamental requirements, and the effectiveness of this dredging system in the field was proved by the test.

a. It was proved that a high-density dredging (solid concentration exceeding 80 percent) equal to that in the tests on one-third scale model was possible in the field tests. Figure 24 compares examples of solid concentrations with those obtained in the tests on one-third scale model.

b. The amount of environmental turbidity caused was very small; less than 1/5-1/10 was caused by conventional systems (grab, cuter-suction, etc.). An example of the time series graphs of turbidity measured is shown in Figure 25.

c. The accuracy of flat finish was from -1 to +5 cm where dredged soil thickness was 30 cm.

d. The obstacle remover (Figure 26) caught obstacles without fail, and its usefulness was proved.

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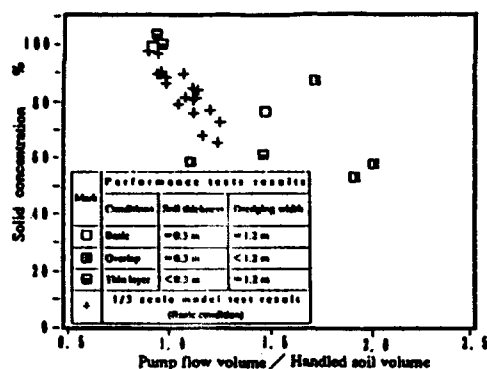
Figure 24. Comparison of solid concentration
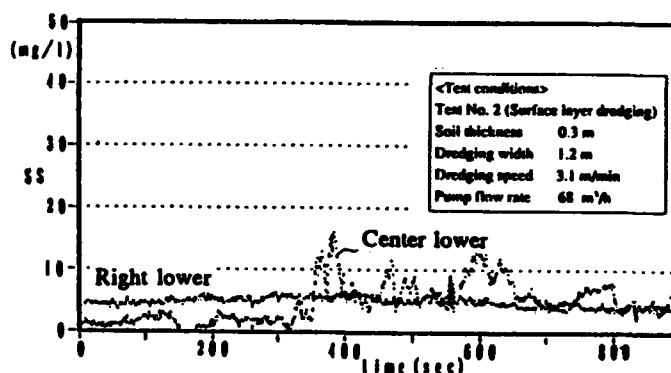
Figure 25. Time series graph of turbidity

e. The load performances of the machines were properly balanced with their capacities and showed that they would be able to fully cope with changes in operating conditions.

Positive Field Tests

After improving part of the setup based on the performance test results, positive field tests using the small testing machine were carried out to confirm the practicability of the system when used in actual dredging sites. The setup of the tests was basically the same as that for the performance tests.

Outline of Test Dredging Work

The phases of the work are as follows:

Figure 26. The obstacle remover

a. Test site: A water area in the Yonago Bay Nakaumi, Tottori Prefecture.
b. Test period: February/ March 1991.
c. Working conditions:
   (1) Type of soil: clayey.
   (2) Dredging depth: approx. 4.5 m.

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(3) Dredging volume: approx. 1,000 m³.
        (4) Discharge length: 100 m.

Test Results

        The test results were just as confirmed by the performance tests as far
as dredging performance and machine performance were concerned. By means of
continuous operation for many hours and execution in a wide area, the mate-
rials on the durability of the machines and practical operation technique for
real work were obtained. Table 5 gives examples of data in varied test condi-
tions. Time series graphs of solid concentrations and amounts of environmen-
tal turbidity caused are shown in Figures 27 and 28, respectively. Figures 29
and 30 show the exterior view and the sampling of dredged soil.

TABLE 5. TEST DATA COMPARISON

Case	Test conditions (Mean values of results)		Solid concentration (%)	Apparent specific gravity Dredged soil per natural ground	Dredging volume per dredging hour (m³/h)	Turbidity (ppm)
No. 1	Dredging speed Soil thickness Pump flow rate	3.6 m/min 0.3 m 93 m³/h	85 (max. 100)	1.15 (max. 1.17) per 1.17	approx. 79	approx. 1-3 max. 19
No. 2	Dredging speed Soil thickness Pump flow rate	5.4 m/min 0.3 m 77 m³/h	85 (max. 99)	1.15 (max. 1.17) per 1.17	approx. 66	approx. 1-3 max. 11
No. 3	Dredging speed Soil thickness Pump flow rate	5.9 m/min 0.3 m 90 m³/h	85 (max. 91)	1.15 (max. 1.16) per 1.17	approx. 76	approx. 1-3 max. 11
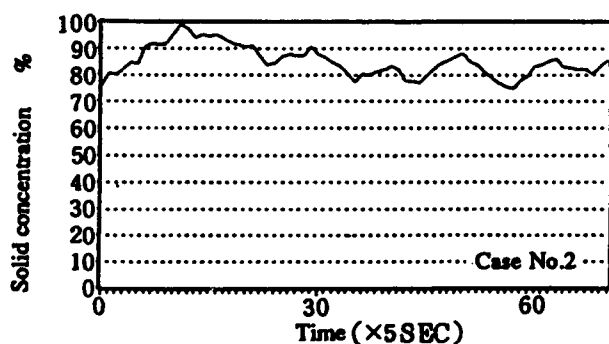
Figure 27. Time series graph of
            solid concentration
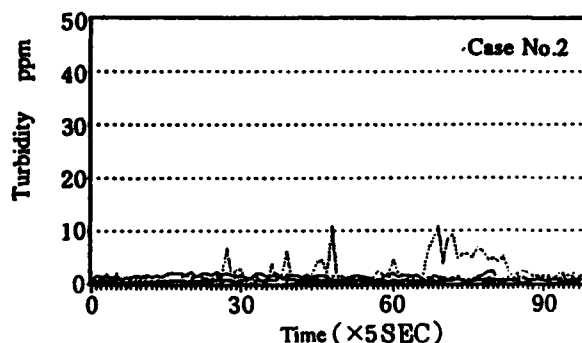
Figure 28. Time series graph of
            environmental
            turbidity

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Figure 29. Exterior view
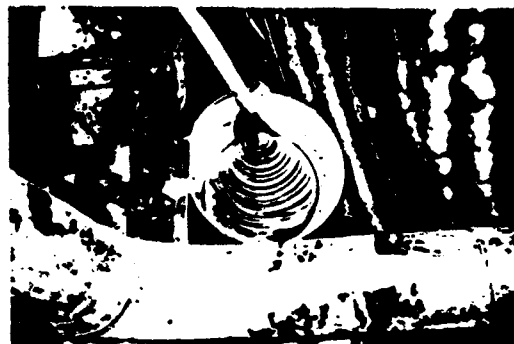
Figure 30. Sampling of dredged soil

OUTLINE OF EXECUTION OF REAL WORK

Outline of Dredging Operation

As a real work, the maintenance dredging of the anchorage area in from of the coal unloading quay was carried out in Port of Onoda, Yamaguchi Prefecture. Dredged soil was loaded on a box barge and transported by sea to the disposal area. The dredging operation executed was as follows:

a. Term of work: May/September 1991.
b. Type of dredging soil: clayey (about 200 percent natural water content).
c. Dredging depth: 7.5 m (design).
d. Dredging volume: 47,600 m^3.

Change of Setup to Platform Car Shifting System

Since the area to be dredged was a part of harbor, the influence of wave and current was taken into account. Thus, instead of the previous maneuvering method using spud pontoons, the platform car shifting method was chosen. Its method was to run a platform car mounted with the dredging equipment in the opening at the center hull of the dredger. The dredger wa maneuvered by means of two anchoring wires and two sets of spud systems installed on its port side. Figure 31 is a general arrangement plan of the dredger. Figures 32 and 33 show the situation of dredging operation.

Results of Work

Because of the passage of entering and departing ships in the dredging area, the dredges had to shunt frequently and needed repeated positioning. However, the adoption of an automatic tracking laser positioning system helped to execute the work relatively smoothly.

The discharge hose had minor trouble. There were several large obstacles such as fishing nets and rocks, and removing them from the obstacle remover also took time. Nevertheless, the system displayed a capacity

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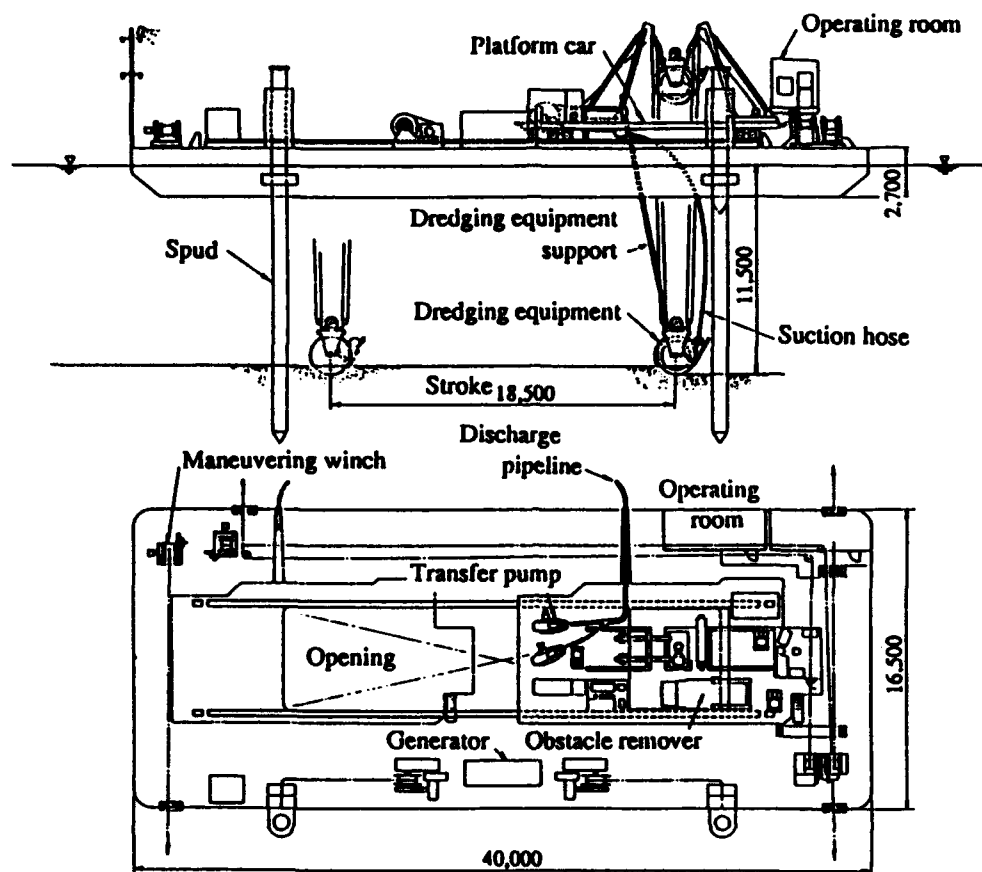
Figure 31.   General arrangement

Figure 32.   External view

Figure 33.   Discharge of dredged
soil

comparable to the efficiency set in the execution plan (dredging volume per operating hour: 45 m^3/hr), and the work was completed within the scheduled term.

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CONCLUSION

The creation of desirable waterside residential areas is an important environmental problem not only in the U.S. and Japan but in the whole world. It is very important that the two countries continue to exchange technical information on an even larger scale with the aim of advancing the technology in sludge dredging and bottom sediments cleaning.

PHYSICAL SEPARATION TECHNIQUES FOR CONTAMINATED SEDIMENT

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ABSTRACT

Savings in the overall cost of environmental remediation can be expected when low-cost mineral processing techniques are used to reduce the volume of contaminated material requiring expensive contaminant destruction or controlled disposal. Mineral processing methods do not destroy contaminants, but they can concentrate the pollutants in a smaller volume of material. This volume reduction can make a subsequent destruction technology more efficient or economical, or reduce the cost of disposing of the sediment in a controlled facility.

The Bureau of Mines, U.S. Department of the Interior, in cooperation with the Great Lakes National Program Office, U.S. Environmental Protection Agency, has conducted a study of mineral processing methods for remediation of contaminated sediment. The study sediments, from rivers and harbors on the Great Lakes in the United States, contained varying, but relatively low, levels of heavy metal contamination, along with organic contaminants such as polychlorinated biphenyls (PCBs). The Bureau conducted investigations in size classification, magnetic separation, gravity separation, and froth flotation to concentrate contaminants. The most effective application of mineral processing technology, on Saginaw River sediment, was the use of size classification to isolate metal and organic contaminants. Froth flotation was also found to be effective on organic contaminants.

INTRODUCTION

Background

This research was performed under an interagency agreement between the Bureau of Mines (Bureau), U. S. Department of the Interior, and the Great Lakes National Program Office, U. S. Environmental Protection Agency (EPA). Funding was provided by the EPA. This work is part of the Assessment and Remediation of Contaminated Sediments (ARCS) program authorized by the U.S. Congress in the Water Quality Act of 1987.

The five Great Lakes are the United States' largest freshwater resource. In fact, they contain 18 percent of all of the world's fresh surface water. Yet through the years, the pollution of the Great Lakes has become legendary. In the past decade, remarkable progress has been made on improving Great Lakes water quality, and the quantity and diversity of life in the lakes is increasing. Encouraging as this is, the legacy of years of pollution remains in the contaminated sediments beneath the rivers and harbors feeding into the Lakes. These sediments

continue to be a source of contamination in the Great Lakes long after point
sources of the pollution have been identified and eliminated.

The pollution in the Great Lakes has come from the widest imaginable range of
sources, and includes heavy metals such as arsenic, chromium, and lead, inor-
ganic pollutants such as nitrates and phosphates, and organic contaminants
such as PCBs and polynuclear aromatic hydrocarbons (PAHs). The Bureau's pro-
gram initially focused on heavy metal contamination, but now includes the
organic contaminants as well.

To address the problem of contaminated sediments, the United States and Canada
have jointly identified 41 sites around the Great Lakes as Areas of Concern.
Under the Water Quality Act of 1987, the U. S. Congress has commissioned the
EPA, through the ARCS program, to study the effects of polluted sediment and
identify remediation strategies at five priority Areas of Concern. The Bureau
has performed characterization and mineral processing evaluations on samples
from four of the five priority Areas of Concern.

Sediment Samples

Examples in this paper are from tests performed on samples of contaminated
sediment from the Saginaw River, in Michigan on Lake Huron. Analysis of this
sample is shown in Table 1. For comparison purposes, Table 1 also presents
analyses of the other three sediment samples studied by the Bureau: sediment
from the Ashtabula River, in Ohio, and from the Buffalo River, in New York
(both on Lake Erie), and sediment from the Indiana Harbor Ship Canal, part of
the Grand Calumet River system in Indiana (on Lake Michigan). The Indiana
Harbor sample is the most polluted, followed by the Ashtabula, Buffalo, and
Saginaw samples.

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Table 1.   Chemical Analyses of Contaminated Great Lakes Sediments

	Analysis, parts per million, dry weight			
Constituent	Ashtabula River	Buffalo River	Indiana Harbor Ship Canal	Saginaw River
Antimony	NA*	2.4	7.8	NA
Arsenic	16.1	10.3	30.8	5.6
Barium	NA	140	197	NA
Cadmium	6.5	2	8	4
Chromium	76	60	440	160
Copper	81	70	278	78
Iron	30,800	20,700	142,000	14,000
Lead	132	100	830	41
Mercury	0.57	0.47	0.74	0.22
Nickel	31	37	94	61
Selenium	NA	0.37	1.59	NA
Silver	NA	0.27	2.7	NA
Zinc	603	167	3,280	273
Total PCBs	NA	0.4	0.2	6
Total PAHs	NA	5.6	96	3.1
Oil and grease	17,300	5,000	58,000	3,000

Not analyzed.

Mineral Processing Technology

The Bureau's contribution to the ARCS program is to evaluate the application of mineral processing (or physical separation) technologies to removal of low levels of contamination from large volumes of sediment. Physical separation techniques are widely used in the mining industry to recover valuable minerals or metals from ores. Methods such as size classification, magnetic separation, gravity separation, or froth flotation, collectively known as mineral processing, can be applied in some cases to separate contaminants from the bulk of polluted sediment. The objective is to reduce the volume of contaminated material requiring treatment by concentrating the contaminants, in the same way an ore is beneficiated. This concept is very familiar to the mining industry, but is new to the field of contaminated sediment remediation. Since these methods are economically applied on a very large scale to ores of low value-to-mass ratio, they are among the least expensive processes in modern industry. An example is a copper flotation mill that may be capable of profitably treating more than 100,000 tons per day of ore that contains only $10 worth of copper per ton.

As applied to an environmental remediation situation, such as contaminated sediments, a few important points about mineral processing technology should be remembered. First, mineral processing makes particle-particle separations. No chemical bonds are broken, and no phases are destroyed. This is in contrast to many other remediation technologies, where a process such as incineration actually destroys the contaminant. Second, mineral processing separations are based on differences in the physical properties of particles, so that no separation can be achieved if all particles are physically similar. Third, mineral processing is usually a high-capacity operation. Since most ores processed contain low levels of valuable metal, this technology must have a low cost per unit of mass processed. For example, in processing copper, five or six separate mineral processing operations will be performed, plus smelting and refining, all on an ore that contains less that $10 worth of copper per ton. Finally, the capacity and efficiency of most mineral processing operations decreases with particle size.

A few contractors offer pretreatment or "soil-washing" technologies, usually consisting of one or more mineral processing operations. Best results will be obtained when the pretreatment system is chosen based on a detailed knowledge of the physical and chemical characteristics of the sediment. The mineral processing unit operations appropriate to the physical characteristics of the sediment can then be arranged into an integrated system. Bench-scale mineral processing testing to verify performance is inexpensive, and scale-up reliability is well documented.[*]

Sediment Characterization

Detailed characterization of the physical properties of the sediment will determine the selection of a mineral processing method or methods. Characterization includes (1) particle size analysis using sieves, hydrocyclones,

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[*] N. L. Weiss, ed. 1985. SME Mineral Processing Handbook. Society of Mining Engineers of the American Institute of Mining, Metallurgical, and Petroleum Engineers, New York.

sedimentation, with chemical analysis to determine distribution of contaminants; (2) mineralogy, or identification of chemical phases, using scanning electron microscopy with energy-dispersive techniques, and possibly x-ray diffraction; (3) density measurements using the helium pycnometer, and sink-float separations in dense media; (4) magnetic separability, using high-intensity wet and dry separators; and (5) evaluation of surface properties applicable to froth flotation using zeta potential measurements and microflotation tests. Equally important is a knowledge of the history of the contaminated site which could provide clues about the nature of the contaminant-bearing phases.

If discrete phases containing contamination have been identified, an appropriate mineral processing method can be selected. Mineral processing methods are selected to exploit differences in the known physical properties of the phases found to be present. For example, if most of the contamination is found to be associated with the fine silt or clay particles, a size classification technique is appropriate. At one Great Lakes site, the sediment was found to contain a large proportion of magnetic iron ore. Selection of a magnetic separation technique may allow this material to be separated from the contaminated sediment and recycled to the steel-making process.

Size Classification

Size classification is the cheapest and simplest technique that could be
applied to sediments. Size classification would be employed when a size chem-
istry analysis shows that a significant amount of the contamination is associ-
ated within a specific particle size range. Particle size separations down to
0.5 micron can be performed. Equipment used includes trommels; fixed, rotat-
ing, and vibrating screens; spiral, rake, and drag classifiers; and hydrocy-
clones.

The potential of size classification for contaminant removal is evaluated by
separating samples of the sediment into several size fractions, and analyzing
each for contaminants. The data can be plotted, as in Figure 1, to show the
amount of contamination found to reside in particles finer than a given size
as a function of the mass associated with those same particles. If the con-
tamination is evenly distributed through all particle sizes, the graph will
show a diagonal line from lower left to upper right. These data from the
Saginaw River sediment show that chromium, lead, nickel, and PCB contamination
are strongly associated with the fine particles, so that more than 80 percent
of the PCBs are associated with the finest 20 percent of the sediment.

A separation of fine from coarse particles would typically be performed using
a hydrocyclone. Tests to determine the suitability of hydrocyclone for pre-
treatment of sedi-
ments have been con-
ducted in the
laboratory using cal-
ibrated sieves.
Appreciable reduc-
tions in these con-
taminants for Saginaw
River sediment were
achieved in a clean
sand product amount-
ing to 81 percent of
the sediment mass,
and the contaminants
were concentrated in
the remaining 19 per-
cent of the mass.
These data are shown
in Table 2.

Particle size separa-
tion in a hydro-
cyclone occurs
rapidly based on the
terminal settling
velocity of particles
in water in a cen-
trifugal field. The
slurry of sediment (usually 10 to 25 percent solids) enters the device
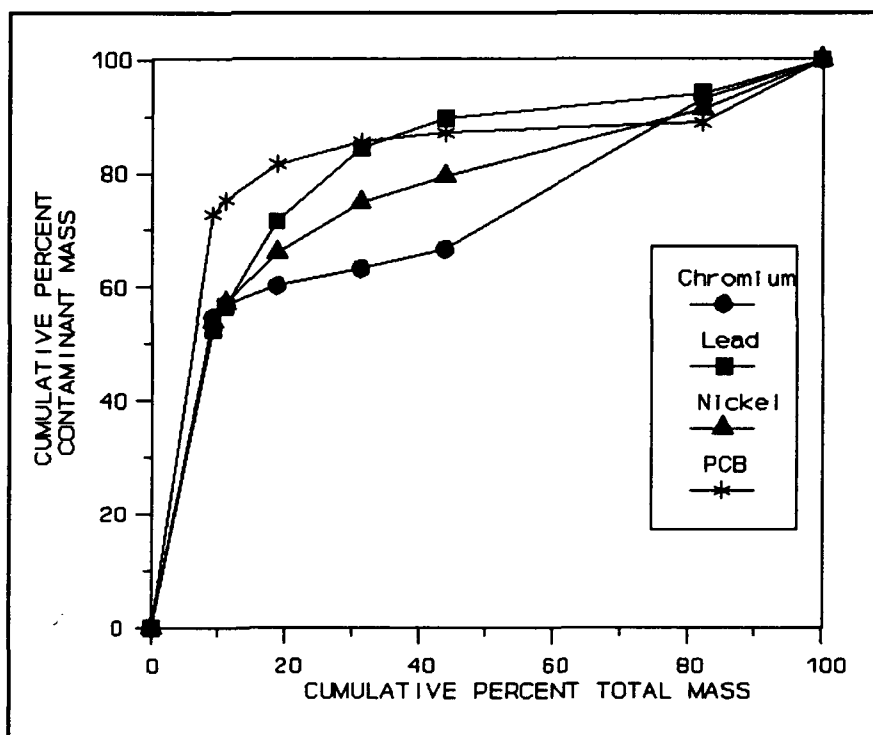
Figure 1. - Partitioning of contaminants by size separation of Saginaw River Sediment.

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Table 2. Removal of Contaminants from Saginaw River Sediment by Particle Size Separation

Constituent	Untreated Sediment Analysis ppm	Sand >75 m Analysis ppm	Sand >75 m Distribution pct	Silt <75 m Analysis ppm	Silt <75 m Distribution pct
Chromium	161	79	40	516	60
Lead	51	18	28	197	72
Nickel	65	27	34	230	66
PCB	18	4	18	77	82
Total mass			81	19	

tangentially at high velocity, creating a swirling flow pattern. The larger (and, therefore, heavier) particles settle outward and travel down the wall of the device, exiting through the bottom apex. Smaller (lighter) particles are carried with the water to the core of the cyclone and exit at the top. Twenty-three-centimeter hydrocyclones, separating at about 75 microns, were used in an ARCS program demonstration project at Saginaw Bay, Michigan.

Hydrocyclones are the most popular size classification device because of their simplicity and high capacity. Hydrocyclones up to 90 centimeters in diameter, treating several thousand gallons of slurry per minute, are commonly used. Arrays of 66-cm hydrocyclones are used to treat copper ore at a mine in Utah.

Gravity Separations

Gravity separations also have applications for contaminated sediments. Frequently, organic contamination is associated with solid organic material or detritus. These particles have much lower density than the natural mineral particles of the sediment. Heavy metal contaminant phases would be significantly more dense than the natural mineral particles. Gravity separations work best on particles larger than 75 microns, but separations among particles as small as 10 microns can be achieved at low capacity with certain equipment. Equipment commonly used includes dense medium separators, jigs, shaking tables, flowing film concentrators, centrifugal separators, and elutriators.

Water elutriation, a gravity separation method employing a rising water current opposing the free settling of sediment particles, was evaluated to further clean the sand fraction from hydrocyclone separation of Saginaw River sediment. It is shown in Table 3 that PCB levels could be reduced to 0.3 parts per million (ppm) by removing only about 2 percent of the remaining sand. This was the low-density material that followed the rising current of the elutriator and was carried over the top of the device. This is an example where mineral processing operations can be combined to produce the desired result.

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Table 3. Further Removal of PCBs from Saginaw River Sand
by Water Elutriation

	Sand	Light Product		Dense Product	
Constituent	Analysis ppm	Analysis ppm	Distribution pct	Analysis ppm	Distribution pct
PCB	1.2	41.1	74	0.3	26
Total mass			2		98

Froth Flotation

Froth flotation is used to process millions of tons of ore daily. Copper, iron, phosphates, coal, and potash are a few of the materials that can be economically concentrated by this method. It is based on manipulating the surface properties of minerals with reagents so that the mineral of interest has a hydrophobic (water-hating) surface, like wax. The minerals to be rejected have, or are made to have, a hydrophilic (water-loving) surface. When air bubbles are introduced, the hydrophobic minerals attach themselves to the bubbles and are carried to the surface and skimmed away. Flotation has been successfully applied to particles as small as 10 microns. Almost all flotation is conducted in stirred, aerated tanks of up to 56 cubic meters, although vertical columns and air-sparged hydrocyclones are used occasionally.

When using flotation to remove oily contaminants from sediment, the role of a surfactant more closely resembles that of a detergent. Most organic contaminants are naturally very hydrophobic, and the objective in using a surfactant is to reduce the oil phase's hydrophobicity to the point where it will be wetted by the water phase and detach itself from solid surfaces. Surfactants are able to accomplish this because such molecules have a lipophilic (fat-soluble) head, which is absorbed into the oil phase, and a hydrophilic tail, which extends into the water phase. The result of this is that the overall hydrophobicity of the oil phase is decreased. The strength of a surfactant's attachment to an oil phase is approximated by the hydrophile-lipophile balance (HLB) of the surfactant. Once freed of the solid surface, an oil droplet is assisted to the surface by air bubbles and skimmed away.

A variety of surfactants have been selected, based on their detergent properties, for investigation with contaminated sediments. A number of different surfactants have been used by the Bureau in this study for removing organic contamination from river sediment. The most promising appear to be ethylene oxide-based amine and alcohol surfactants.

In our research for the ARCS program, froth flotation is showing promise as a means for recovering organic contamination from sediment. In much of our organic work, the oil and grease analysis is used as an indicator parameter for organic contaminants. Preliminary results show that considerable reductions in organic contamination, to less than 100 ppm oil and grease, are achieved by separation of an organic-laden froth, or concentrate. The results also show that this contamination can be concentrated in a small volume, from 11 to 26 percent of the original mass, by a single stage of flotation.

Table 4 gives results of flotation tests on Saginaw River sediment. The most satisfactory results, based on the oil and grease analysis of the tailings, were obtained at neutral or alkaline pH. To verify conclusions drawn from the oil and grease analyses, products from two of the tests were reanalyzed for total PCBs. These additional data indicated comparable separations to the oil and grease results.

Table 4. Removal of Organic Contamination from Saginaw River Sediment
by Froth Flotation Using Triton Surfactants

Triton Surfactant*	pH	Mass Distribution pct	PCB Analysis ppm	Oil & Grease Analysis ppm	Oil & Grease Distribution pct	PCB Analysis ppm	Oil & Grease Analysis ppm	Oil & Grease Distribution pct
RW-150	4	11	NA	27,575	96	NA	144	4
RW-150	7	19	62^2	15,946	97	0.71	106	3
RW-150	10	18	NA	1,561	93	NA	2593	
RW-50	4	24	NA	1,821	76	NA	178	24
RW-50	7	26	31^2	12,038	97	1.1	125	3
RW-50	10	15	NA	1,588	94	NA	19	6
X-114	4	20	NA	16,356	97	NA	137	3
X-114	7	19	NA	16,441	96	NA	183	4
X-114	10	15	NA	1,758	96	NA	12	4

* Triton RW-50 and 150 are amine ethoxylates with 5 and 15 moles, respectively, of ethylene oxide per mole of surfactant. Triton X-114 is an octylphenol ethoxylate with an average of 8 moles of ethylene oxide per mole of surfactant. Surfactant concentration in all tests was 0.1 wt pct in solution.
** Initial PCB analysis was 18 ppm.

Pretreatment Process Costs

The cost savings associated with mineral processing pretreatment of contaminated sediment are dependent on the amount of volume reduction. In other words, the amount of unpolluted material that can be separated out of the sediment, the cost of pretreatment, and the cost of ultimate treatment (or disposal) all affect the economics of pretreatment. The total cost for dealing with polluted sediment is the sum of the cost of pretreatment on the entire sediment volume, plus the cost of treating the concentrated polluted fraction.

In making a decision to investigate pretreatment, one can require that the ratio of the total cost per unit volume (including pretreatment) to the cost per unit volume of ultimately treating the contaminated material must be less than one. In other words, it must be less expensive to pretreat the entire volume, and then treat the reduced volume of contaminated material, than it is to simply treat the entire volume of sediment without pretreatment. As an example, if the cost of pretreatment is $50 per cubic meter, and the ultimate remediation cost (e.g., incineration) is $250 per cubic meter, then the needed volume reduction is 50/250 or 0.2. If pretreatment could reduce the volume requiring incineration by greater than 20 percent, then a savings in the overall cost of dealing with this contaminated sediment could be achieved.

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requiring incineration by greater than 20 percent, then a savings in the over-all cost of dealing with this contaminated sediment could be achieved.

SUMMARY

Mineral processing technology is available from several vendors and contractors throughout the world. Remediation-oriented companies have offered some mineral processing technologies under the title of "soil-washing." In May 1992, the ARCS program demonstrated pretreatment of Saginaw River sediment. The on-site processing plant was provided by a private contractor, and was centered around three stages of hydrocyclone size separation, separating PCB-contaminated fines from relatively clean sand. The plant also included size separations by trommel and by vibrating and rotating screens. Also available were a hindered settling gravity separation unit and attrition scrubbers for removing surficially bound contamination. Results of the demonstration will be available in 1993.

Mineral processing pretreatment methods do not destroy contaminants, but they can reduce the volume of sediment requiring more extensive or expensive treatment. For successful application, the contaminants to be removed must reside principally in a physically separable phase (or phases). This physically separable phase can be characterized by differences in grain size, density, magnetic susceptibility, or surface properties from those in the bulk of the sediment. Also, this phase must represent a sufficiently small fraction of the sediment, so that the volume reduction achieved justifies the cost of mineral processing pretreatment. Finally, it must be less expensive to treat a smaller volume of concentrated contaminated sediment than it would be to treat the entire volume at lower contaminant concentrations. Detailed grain size analysis, size chemistry, and mineralogical characterization, followed by bench-scale testing, are the methods for determining if a sediment meets these criteria.

INTRODUCTION OF NEW METHOD OF DISPOSING DREDGED MUDDY SOIL WITHOUT DISTURBING MARINE ENVIRONMENT

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ABSTRACT

A new method of disposing dredged muddy soil has been developed to make use of the dredged sludge while preventing pollution arising from the treatment of sludge from affecting the fishing industry. In order to prevent pollution from occurring by mixing the sludge with the solidifier and placing it underwater, the method of placing and the fluidity of the treated sludge become vital factors.

In this report, an outline of this new non-polluting method of treatment is introduced along with the preliminary experiment and onsite prototype experiment results of this method. In the preliminary experiment, tests of the performances of the solidifier of cement origin especially developed for this method and the experiment on the method of placing underwater are introduced. The onsite experiment involved an experiment of the method of placing underwater using a prototype, a practical-level machine. The following gives the results obtained from these experiments.

a. The fluidity of the new solidifier was excellent compared with ordinary portland cement and quicklime.

b. In the preliminary experiment, the method of placing underwater was tested, and the interior of the treated sludge was found closely packed.

c. The onsite demonstration showed that underwater placing could be carried out with almost no effect on the water quality.

INTRODUCTION

In recent years, removing sludge which has accumulated in the seas, lakes, swamps, and rivers had become a social problem requiring quick action because it deteriorates the water quality of various regions, obstructs ships and gives rise to other problems. However, the present status is that public

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dredging works have not progressed as scheduled because of a deficiency in the number of places for depositing or treating dredged sludge. Under this circumstance, we have developed a nonpolluting method of treating sludge which would solve such space problems for dredged sludge. Here, the sludge is mixed with cementious solidifier (sludge mixed with cementious solidifier will be hereinafter called treated sludge). Then, the sludge is placed underwater before it hardens in a manner such that pollution is kept to an absolute minimum. The material can be fully utilized for reclamation, thus resolving the problem of a lack of space for depositing on treating dredged sludge.

The distinctive feature of this method is that it hinders the dissociation of the treated sludge in the water as much as possible,m eliminating water pollution caused by the hardening in the water.

In order to accomplish the above purposes, we have developed a new unit for underwater placing and cementious solidifier.

This report gives (a) an overview of this method of treatment, (b) part of the descriptions of experiments conducted to confirm the performance of the solidifier newly developed for this method, and (c) the results of the demonstrations performed by using a manufactured prototype, acting as a practical unit.

OVERVIEW OF THE METHOD

Figure 1 shows a conceptual plan. In this method, after the workability of the dredged sludge has been adjusted, it is mixed with a cementious solidifier. Then, after giving it an adequate fluidity, an underwater placing unit is used to place the material to the sea bed. It was ensured that at the time of placing, the discharge opening of the underwater placing unit is always preinserted in the treated sludge. With this technique, and the use of the new solidifier, which prevents the dissociation of the sludge, permit placing of underwater with hardly any diffusion of pollution in the water. The system configuration of this method of treatment is as follows: (a) pneumatic conveying plant, (b) workability adjuster, (c) solidifier mixing unit, (d) underwater placing unit, and (e) monitoring and measuring instruments and cementious solidifier. This solidifier especially developed for this method was a unique characteristic, featuring fluidity, resistance to dissociation and deodorizing characteristics.
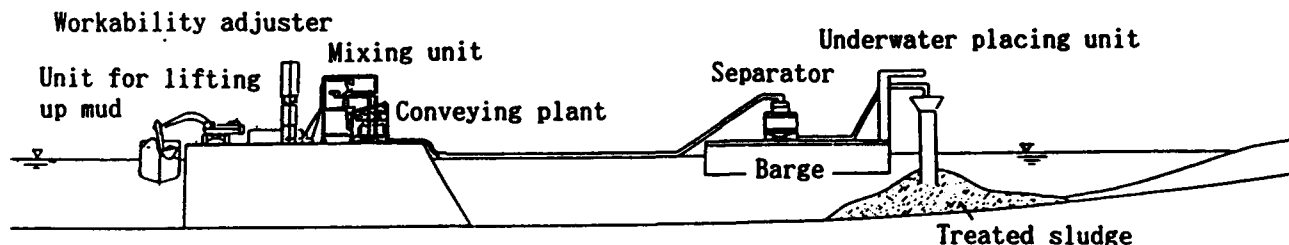
Figure 1. Conceptual plan of the method of treatment

The procedure for the method is as follows:

a. The workability of the dredged sludge is adjusted.

b. Based on the indoor test conducted beforehand, the required amount of solidifier is added to the sludge. Then, a continuous mixer is used to stir and mix them.

c. A conveying plant is used to convey the sludge treated with the solidifier through pipes up to the barge where an underwater placing unit is located at the site of reclamation.

d. After the dissociation of air, treated sludge conveyed by the conveying plant is supplied continuously by conveyor pumps top the underwater placing unit. This unit features a discharge opening unit with built-in auger. Then, the supplied sludge is placed underwater. For on land works, a conveyor pump is used for direct installation.

DEVELOPMENT OF SOLIDIFIER

The development of the solidifier necessitated research on the following major aspects:

a. To reduce dissociation of the treated sludge during underwater placing.

b. To maintain fluidity of the treated sludge during underwater placing.

c. To maintain hardening strength under water.

d. To improve deodorizing effect on the sludge.

By maintaining the fluidity of the treated sludge, the treated sludge can be moved smoothly during underwater placing operation. At the same time, its combined effects with the increased resistance to dissociation of the sludge eliminates muddiness, prevents pH increase during underwater placing operation, and also secures continued strength.

TEST ON FLUIDITY OF THE TREATED SLUDGE

In order to test the fluidity of the treated sludge, flow tests of ordinary portland cement (hereinafter called O.P.C.), quicklime and the newly developed solidifier (hereinafter called S.C.) were conducted based on a flow table using instruments employed in the JIS R 5201, "Physical Testing Methods for Cement."

Setting Conditions

Three types of solidifier, namely S.C., O.P.C., and quicklime were added to the dredged sludge in powder form. In addition, water was added to the S.C. and the O.P.C. in a one-to-one ratio to produce solidifier slurry (S.C. slurry hereinafter called S.C.S and O.P.C. slurry hereinafter called O.P.C.S.), which were also added to the dredged sludge. The solidifier was added in a 3, 5, and 10 percent ratio by weight with respect to the wet sample sludge. The kneading time using a Hobart-type mixer was ten minutes.

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In the flow test, the fluidity was measured just after kneading, 7 min after kneading, and 15 min after kneading.

The sample sludge was taken from the bed from the Bay of Shiofama at the center section of the bay using an Eckman barge mud collector. Table 1 shows the properties of the sample sludge. Note that in the test, water content of the sample sludge 'w' was adjusted to 250 and 300 percent.

TABLE 1.   SOIL PROPERTIES OF SAMPLE SLUDGE DURING
            FLUIDITY TEST

Factor		Measured Value
Specific gravity of soil particle		2.644
Grain size distribution		
Gravel fraction (2-75 mm)	%	0
Sand fraction (75 μm-2.0 mm)	%	3.2
Silt fraction (5-75 μm)	%	40.8
Clay fraction (under 5 μm)	%	56.0
Maximum grain size	mm	2.0
Liquid limit	%	146.0
Plastic limit	%	58.9
Plasticity index		87.1
Water content	%	264.9
Wet density	g/cm^3	1.233
Void ratio		6.825
Degree of saturation	%	102.6

Test Results and Observations

Figure 2 presents the flow test results of the treated sludge when the types and ratio of the solidifier added were changes. figure 3 fives the flow values resulting from the addition of the powdered O.P.C. and S.C., and the slurry.

Comparing the effects of the solidifier type on the flow value in Figure 2 indicated that S.C. had a higher flow value than O.P.C. As the ratio of S.C. added increased from 3 to 5 percent, the flow value dropped slightly while it increased as the ratio increased from 5 to 10 percent. This behavior is explained by the increased amount of fluidizing agent contained in S.C. The O.P.C. showed almost the same trends, except that the flow value decreased in the 3 to 10 percent range. The flow value of the quicklime decreased almost in a straight line as the ratio increased. increasing the ratio of the quicklime reduced its flow value, which was less than that of O.P.C.

According to Figure 2, increasing the ratio of S.C.s and O.P.C.s added increased the flow values. This increase occurs essentially because the added material is a slurry produced by an addition of an equal amount of water to the solidifier by weight. The S.C. exhibited virtually the same increase as that of S.C.s up top a ratio of 5 percent. Its flow value, however, dropped
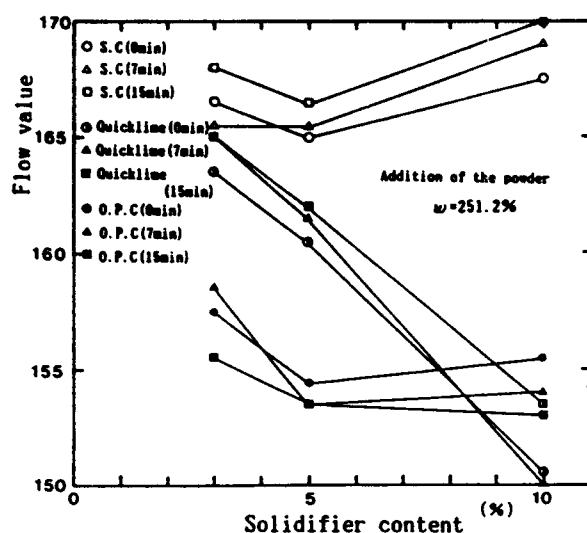
Figure 2. Flow test results when types and ratio of Solidifier changed
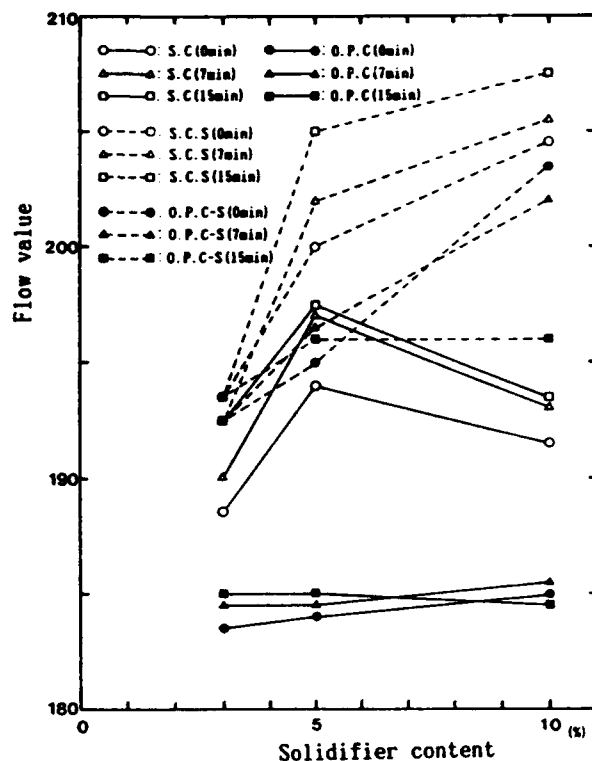
Figure 3. Relationship between the ratio of solidifier added and the flow values resulting from addition of O.P.C., S.C., and slurry

below 5 percent when the added ratio reached 10 percent. In comparison, the flow value of the O.P.C. stayed about the same or dropped slightly even when the ratio increased.

In Figures 2 and 3, the numbers in brackets indicate the standing time after kneading. The effects of time elapse after kneading on the flow value were tested by taking measurements up to 15 min of time elapse. The test showed that the flow values increased with increasing time elapse after kneading. On the other hand, O.P.C. and O.P.C.s showed a decrease in the flow values with increasing time elapse. This decrease is believed to be caused by the effects of the fluidizing agent contained in S.C.

PRELIMINARY UNDERWATER PLACING EXPERIMENT

The possibility of placing the treated sludge in the water and the hardening strength during underwater placing were determined.

Testing Method

In the test. a model of the underwater pipe incorporating a 100-mm diam auger illustrated in Figure 4 was used to place the treated sludge in a water-filled φ200- by H300-mm acrylic tank. Then, this condition was preserved for

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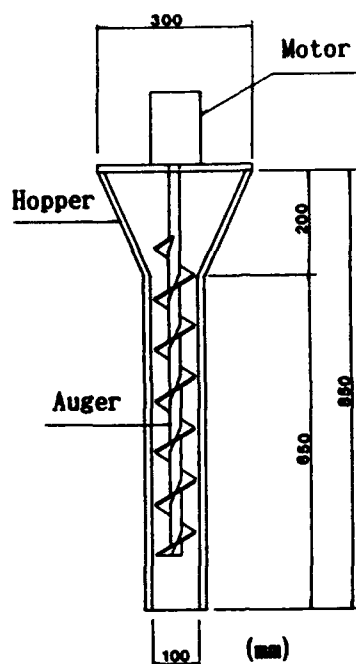
Figure 4. Installation unit model

three days. A ϕ50- × H100-mm specimen for the unconfined compression test of the sample of treated sludge prepared in the air based on the Soil Engineering Standard, "Practice for Making and Curing Noncompacted Stabilized Soil Specimens," was carried out. The unconfined compression test was carried out by conforming to JIS A 1216.

Setting Conditions and Sample Sludge

Table 2 gives the conditions for setting for installation both in the water and in the air. The ratio of the solidifier added to the dredged sludge was defined in terms of the wet dredged sludge by weight. During underwater installation, this ratio was set at 4 and seven percent while, in the air, this ratio was 4, 7, and 10 percent. Table 3 presents the properties of the sample sludge, which was taken at the sea bed from the Bay of Shiogama at the center section of the bay.

TABLE 2. SETTING CONDITIONS

Setting for Installation	Water Content (%)	Solidifier Content (%)
In the water	300	4
	325	4
	350	4,7
In the air	300	4,7,10
	325	4,7,10
	350	4,7,10
	375	4,7,10

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TABLE 3. SOLID PROPERTIES OF SAMPLE SLUDGE DURING
UNDERWATER INSTALLATION

Factor		Measured Value
Specific gravity of soil particle		2.547
Grain size distribution		
Gravel fraction (2-75 mm)	%	0
Sand fraction (75 μm-2.0 mm)	%	5.0
Silt fraction (5-75 μm)	%	24.0
Clay fraction (under 5 μm)	%	71.0
Maximum grain size	mm	4.76
Liquid limit	%	165.4
Plastic limit	%	43.9
Plasticity index		121.5
Water content	%	200.1
Wet density	g/cm^3	1.259
Void ratio		5.069
Degree of saturation	%	100.5

Test Results

Tables 4 and 5 and Figure 5 show the results of the unconfined compression test of the treated sludge. Almost no differences were observed among the average values of the unconfined compressive strength. However, the scatterings of data for the unconfined compressive strength during installation in the water were large. The strength at the lower part of the test piece during installation in the air was high while that of the upper part was low compared to those done in the water. The installation condition is illustrated in Figure 6. Virtually no treated sludge dissociated or diffused in the water during installation. No muddiness was produced. The condition of the sample after installation in the water is illustrated in Figure 7. Cracks can be seen on the upper 2 to 3 cm where water immersed. However, the lower part of the treated sludge, which was densely packed, was an excellent solid.

ONSITE PROTOTYPE EXPERIMENT

In the experiment, sludge dredged from the Bay of Shiogama in Shiogama-City, Miyagi prefecture, was used. The experiment of the treatment of the dredged sludge by mixing solidifier was carried out: (a) to find out its suitability for allowing reclamation in the water, (b) to find out its effects on the performances of the solidifier and water quality during placing, and (c) to understand its executability as a total system. A small-scale practical-level prototype was developed to conduct a large water tank test and installation experiment in the water.

TABLE 4. UNCONFINED COMPRESSIVE STRENGTH DURING INSTALLATION IN THE AIR

Test No.	Water Content (%)	Solidifier Content (%)	Unconfined Compressive (kgf/cm^2) Strength 7-day	28-day
1	304.3	4	1.42	1.62
		7	2.63	3.94
		10	1.99	4.23
2	326.4	4	1.21	1.67
		7	2.47	3.88
		10	2.20	4.40
3	354.5	4	1.10	1.52
		7	1.07	3.18
		10	1.90	3.45
4	379.7	4	1.33	1.38
		7	1.75	2.80
		10	1.90	3.45

TABLE 5. UNCONFINED COMPRESSIVE STRENGTH DURING INSTALLATION IN THE WATER

Test No.	Water Content (%)	Solidifier Content (%)	Unconfined Compressive Strength (kgf/cm^2) 7-Day 1	2	3	Average
5	302.6	4	1.60	1.45	0.95	1.33
6	325.8	4	1.55	1.45	0.95	1.32
7	348.1	4	1.72	1.64	--	1.68
8	345.2	7	2.20	2.10	1.60	1.97
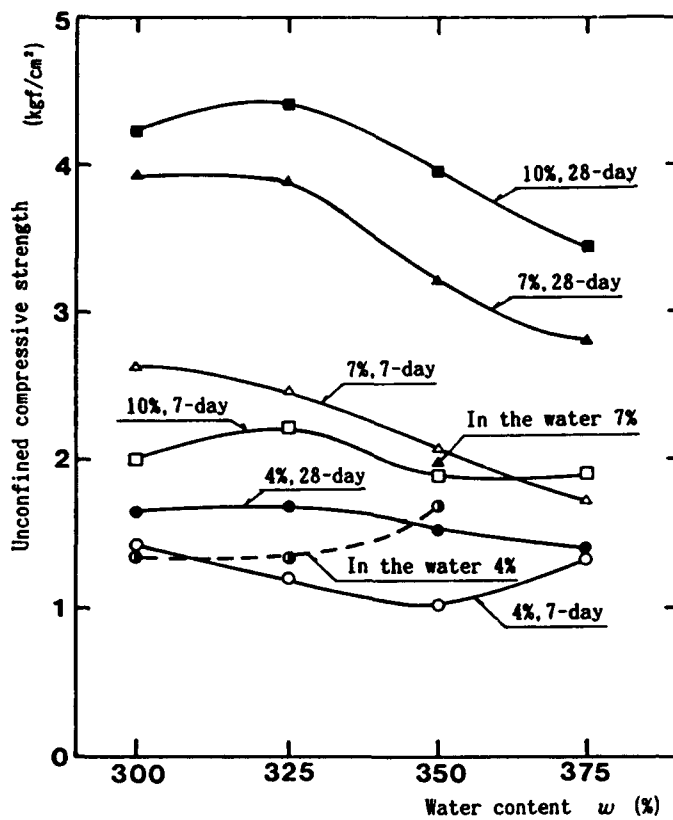
Figure 5. Relationship between the
unconfined compressive
strength and the water
content ratio
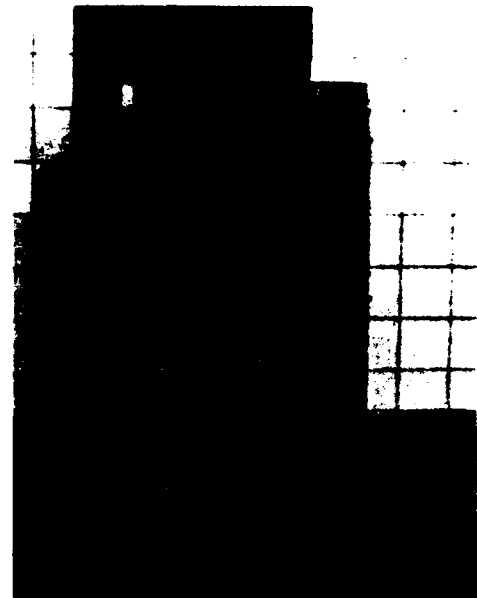
Figure 6. Conditions for
installation
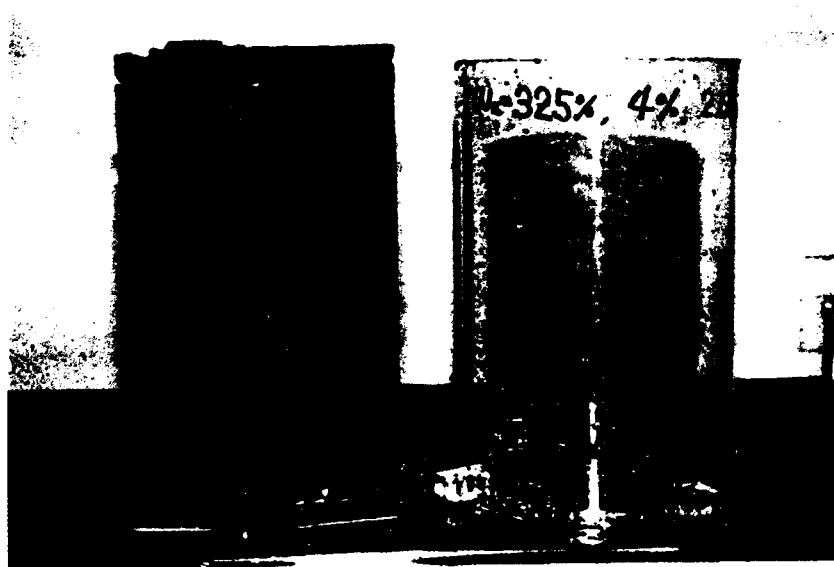
Figure 7. Conditions for installation in the water

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Large Water Tank Experiment

Unit for Experiment

The experiment was conducted using the system shown in Figure 8. Figure 9 illustrates the experimental condition. The system of this unit has a placing capability of 35 m³/h. The system comprises a unit for lifting up mud, workability adjuster, pneumatic conveying plant, mixing unit, and unit for underwater reclamation newly developed for this method. the unit for underwater reclamation includes a separator, unit for stirring and mixing, and an underwater placing unit. The following gives an outline of each component unit.
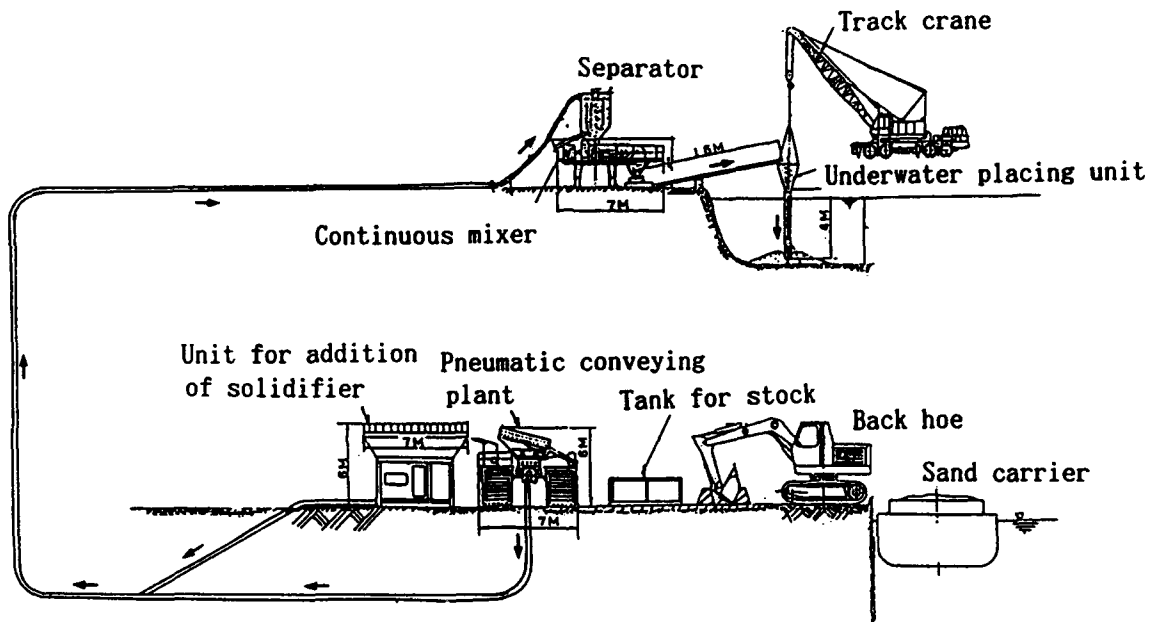
Figure 8. Conceptual plan of the experimental system
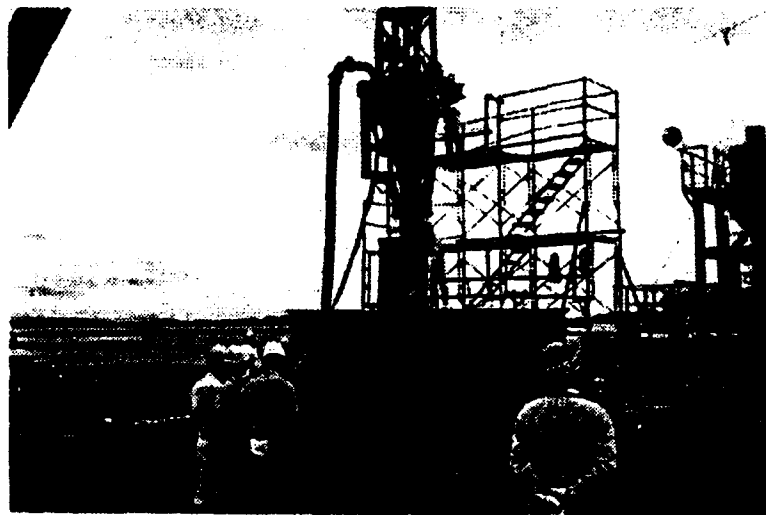
Figure 9. Condition of large water tank experiment

a. **Separator.** Separated the high-pressure air used during compression and the dredged sludge to reduce the shock generated by compressed pressure. It has a cyclone-type storage hopper featuring a controllable discharge mechanism.

b. **Unit for stirring and mixing.** Continuously stirs and mixes the dredged sludge with solidifier.

c. **Underwater placing unit.** Places the treated sludge in the water without creating muddiness. Installation by free-fall cannot be carried out because the density of the wet treated sludge during underwater placing is only about 1.2 kg/cm_3 and because it has adhesive properties. For this reason, a screw mechanism built in the body is used to forcefully place the sludge. In addition, a switch gear is mounted on the discharge opening to prevent the treated sludge from falling freely in the water during the start of the operation.

The system as described previously is used to place treated sludge in a 5- by 2-m large water tank. changes in the fluidity of the treated sludge and the water quality during the placing operation were measured. The water tank was filled with the Gulf water filtered beforehand.

Outline of Experiment

Table 6 indicated the conditions for the water quality measurement experiment. In experiment numbers one to three, treated sludge was placed in saltwater, and in experiment number 4, treated sludge was placed in fresh water (tap water). In the experiment carried out in the saltwater, the water content ratios of the sample varied considerably. This variation in the ratios, however, results from adjustments made to vary the fluidity of the treated sludge. Table 7 presents the conditions for measuring the water quality. As shown in Figure 7, water for measuring the water quality was obtained as follows. Ten pipes for collecting water were installed in the water tank. Then, a bellows quantitative pump was used to collect 100 ml of water for each of all ten pipes once every two min from the ϕ 8-mm and 10-mm long stainless pipe bent in an L shape employing a silicon tube. The turbidity and the pH of the collected water was measured immediately after the experiment. Figures 11 and 12 five the conditions for setting the pipes used for collecting water.

TABLE 6. CONDITIONS DURING WATER QUALITY MEASUREMENT EXPERIMENT

Test No.	Water Content (%)	Solidifier Content (%)	Initial Water Volume (m³)	Placed Treated Sludge Volume (m³)	Kind of Water
1	248.4	4	9.6	7.7	Saltwater
2	273.1	4	10.3	1.8	Saltwater
3	225.7	4	7.0	4.3	Saltwater
4	248.0	4	7.0	5.9	Fresh water

TABLE 7. CONDITIONS FOR MEASURING WATER QUALITY

Factor	Condition
Number of collecting point	10
Frequency of collecting water	Before installation, Once every two minutes
Item of water measurement	Turbidity (NTU), pH
Method of measurement	Turbidity, pH meter
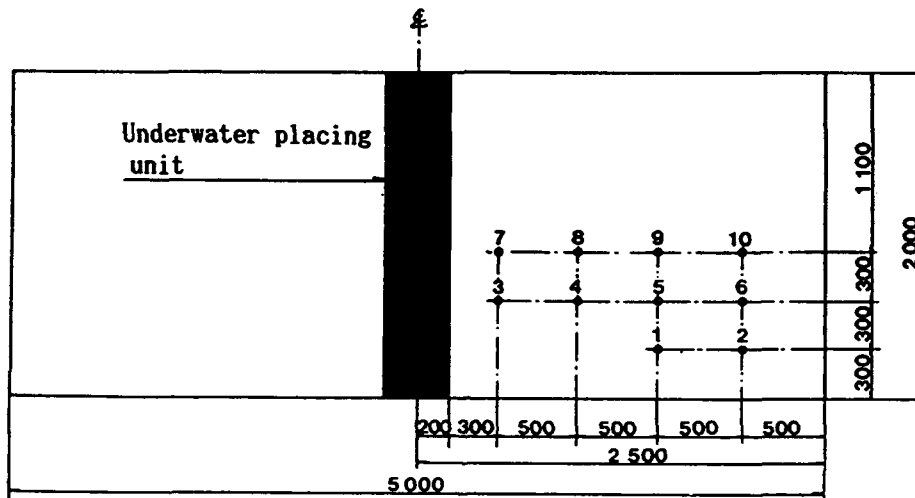
Figure 10.   Figure indicating locations of water collection
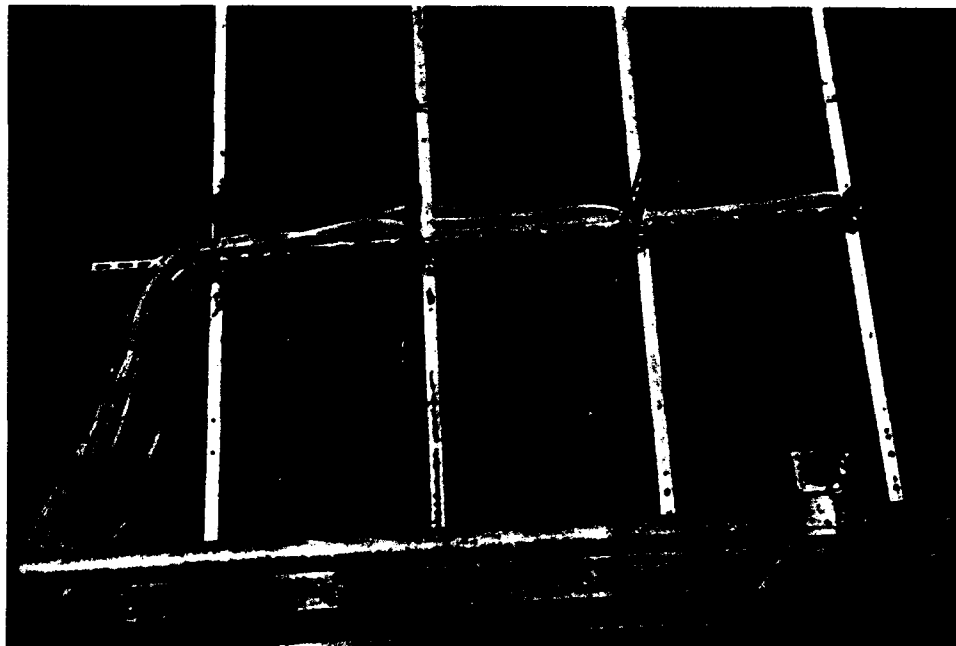
Figure 11.   Conditions for setting pipes for water collection

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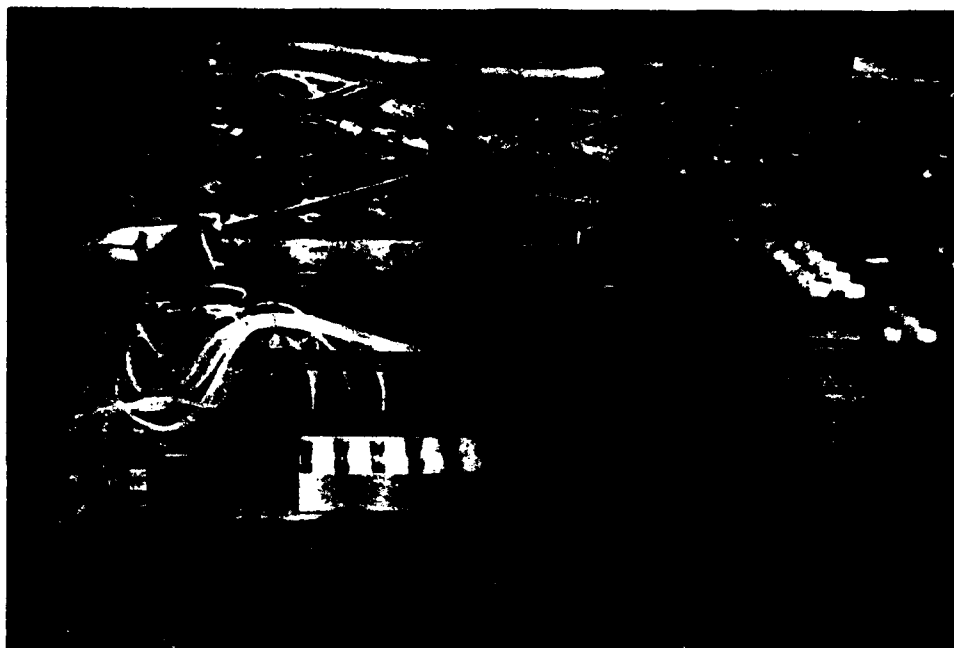
Figure 12. Conditions for setting pumps for water collection

Table 8 presents the soil properties during the experiment. Although this sample was collected from the same place as where the preliminary experiment was conducted, it has a silt-and-clay combined content of 97 percent. Its fluidity during placing was measured by taking pictures every 30 sec from the start with a camera mounted on the front of the water tank by opening a window, a transparent acrylic plate at the front part of the water tank.

TABLE 8. SOIL PROPERTIES DURING THE EXPERIMENT

Factor		Measured Value
Specific gravity of soil particle		2.561
Grain size distribution		
Gravel fraction (2-75 mm)	%	0
Sand fraction (75 μm-2.0 mm)	%	3.0
Silt fraction (5-75 μm)	%	24.0
Clay fraction (under 5 μm)	%	55.0
Maximum grain size	mm	4.2
Liquid limit	%	150.8
Plastic limit	%	44.7
Plasticity index		106.1
Water content	%	160.0
Wet density	g/cm^3	1.305
Void ratio		4.123
Degree of saturation	%	100.

Result of Experiment

Figure 13 shows the changes in the form of the treated sludge with the passage of time for each experiment. In the figure, the changes in the form of the treated sludge are represented by continuous lines, dotted lines, and dashed lines. Numbers one through nine at the side of the lines represent the observation number of the treated sludge form performed every two min from the start. Figure 13 shows that after the treated sludge ascends approximately 60 cm, it moves horizontally. For the ascending sludge, with decreasing water content ratio, the starting height at which the sludge moved horizontally tended to increase.
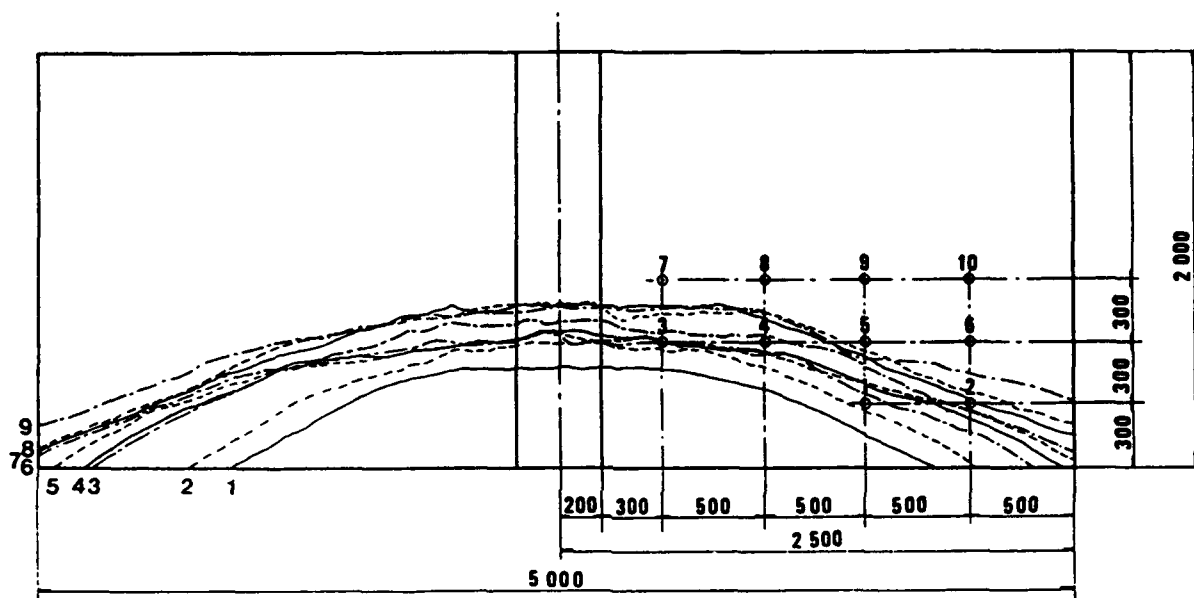
Figure 13. Changes in the surface of the treated sludge with time
(Sheet 1 of 4)
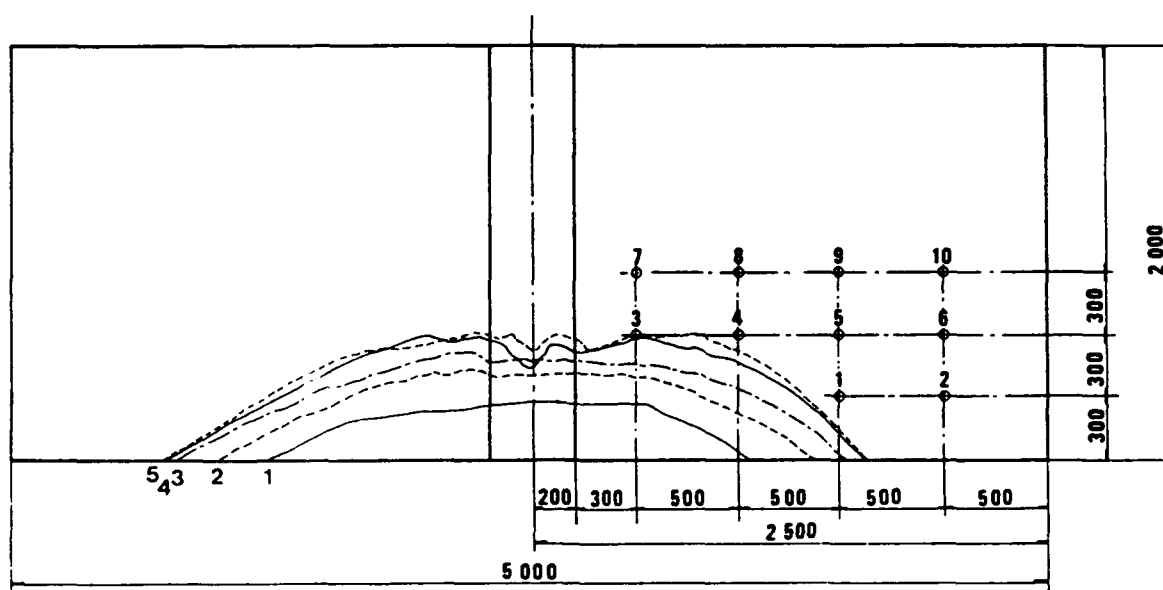
Figure 13. (Sheet 2 of 4)
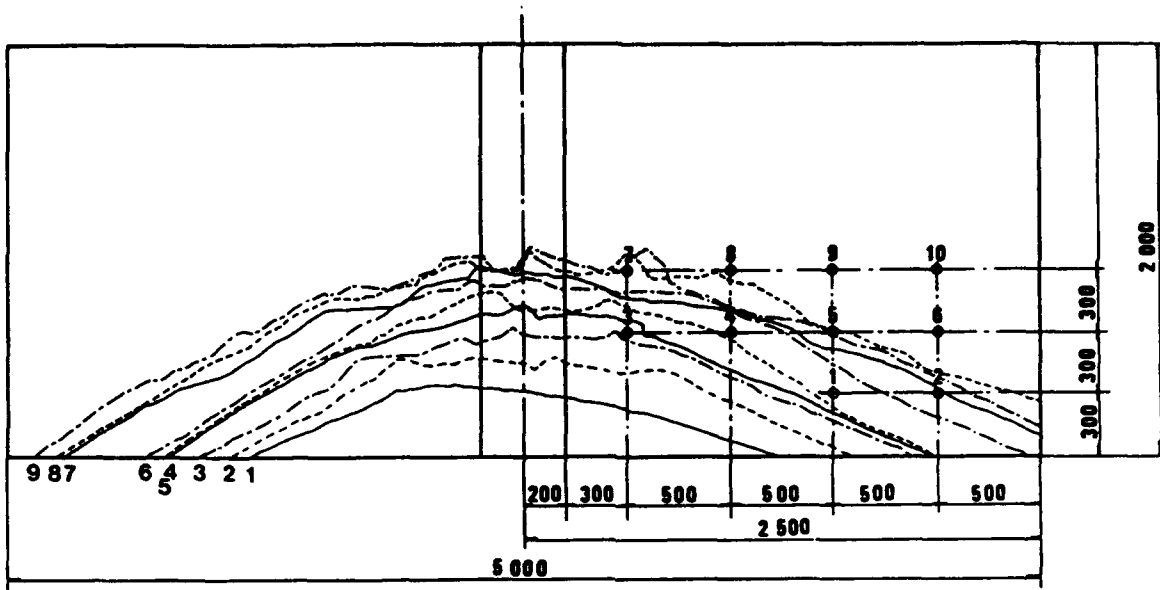
Figure 13.   (Sheet 3 of 4)
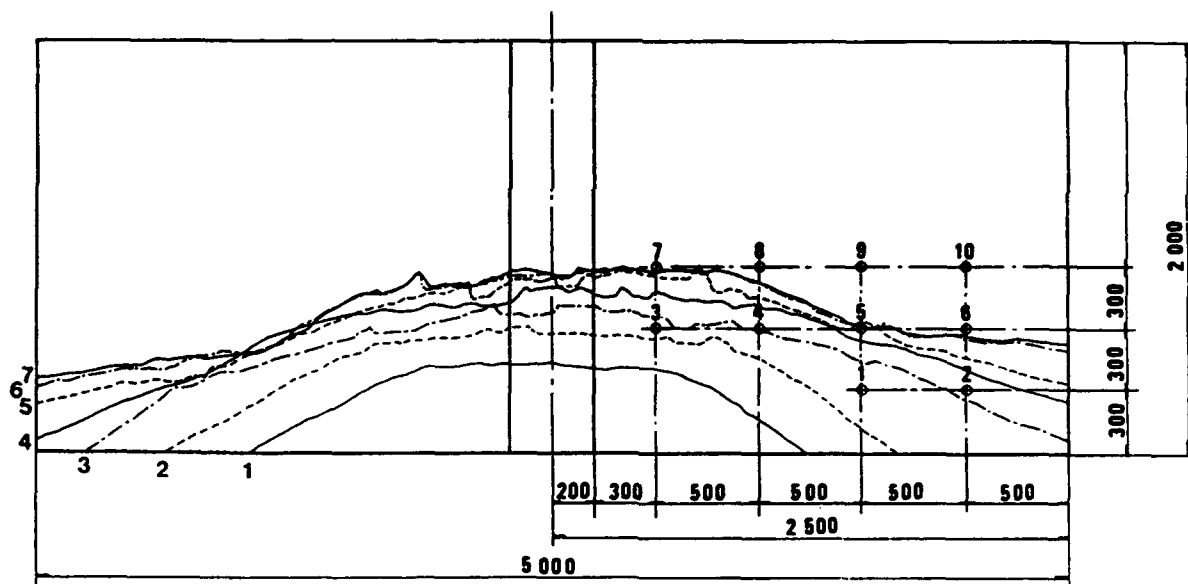
Figure 13.   (Sheet 4 of 4)

Figure 14 indicates the results of measuring water quality during the observation of the form of the treated sludge. The results of pH measurement showed that all number one points had an initial value of 7.76 and a maximum value of 7.92 with an increase of 0.16. Note that the water-collecting inlet was separated 15 cm from the surface of the treated sludge. At number 2, the initial value was 7.89 and the maximum value 7.96 was an increase of 0.07. Next at number 3, the initial value was 7.90 and the maximum 8.11 with an increase of 0.21. Here, the distance from the water-collecting inlet to the surface of the treated sludge was approximately 10 cm. Other points which were measured at the same time had an increase of 0 to 0.04.

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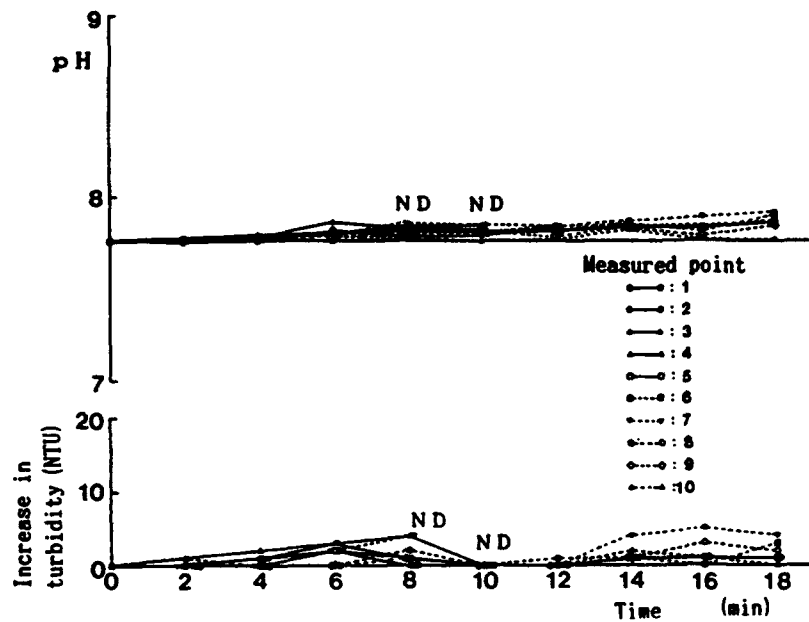
Figure 14.   Changes in the water quality with time
             (Sheet 1 of 4)
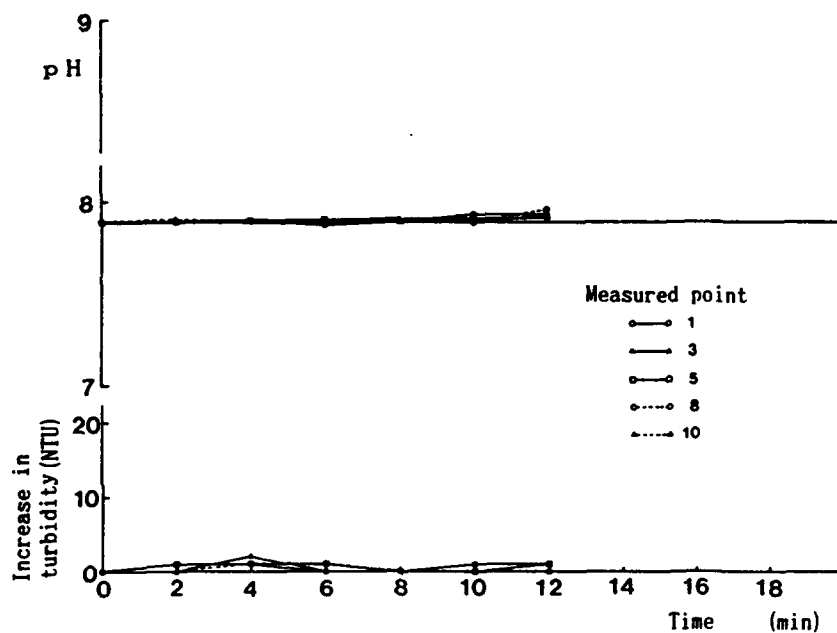
Figure 14.   (Sheet 2 of 4)
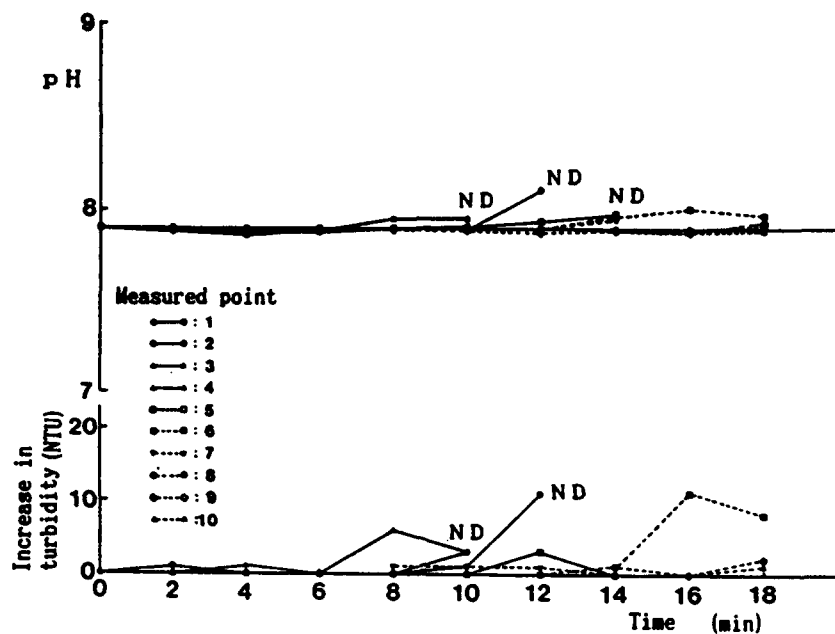
Figure 14.   (Sheet 3 of 4)
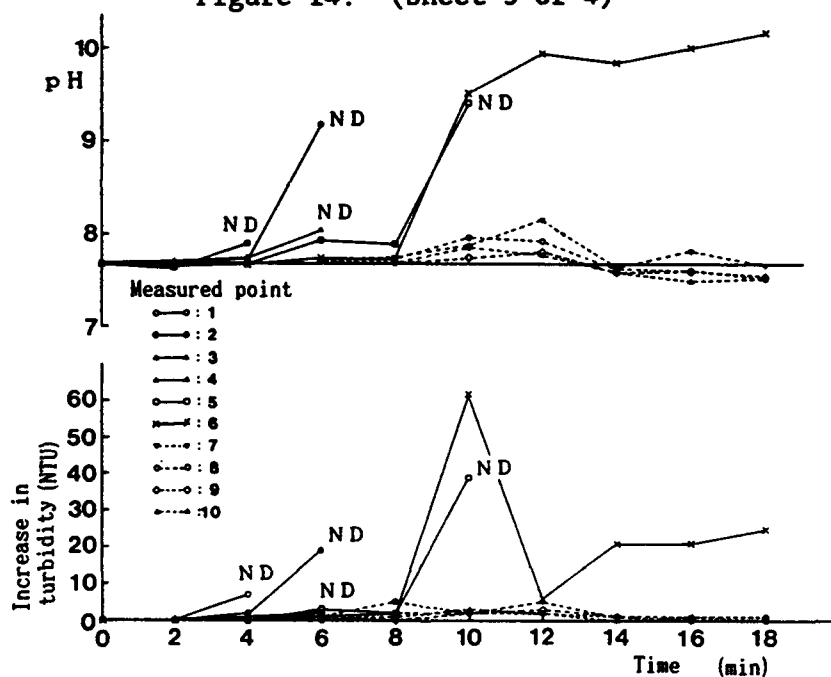
Figure 14.   (Sheet 4 of 4)

Number 4 represents the results of the test performed in fresh water.
The initial value was 7.69 and the maximum 10.18. However, the values of
numbers 2, 3, 5, and 6 had a high pH of at least 8 because of measurements
taken at a distance separating the water-collecting inlet and the surface of
the treated sludge by only zero to a few centimeters. This measurement may
have been caused because the sludge surface might have been touching the
inlet. At other points, the increase in the pH were slight, being 0.28 at
most.

The turbidity of the saltwater test numbers 1 through 3 had a maximum increase of 11 Nephelometric Turbidity Units (NTU). However, this maximum increase was observed twice only for test number 3. For other measures points, the maximum was 5 NTU. Measurements were taken 1 to 2 cm directly above the surface of the treated sludge. the turbidity increased by 0 NTU to 3 NTU at other points. The relation between the turbidity and the suspended solids (SS) was obtained beforehand.

In the freshwater test number 4, the maximum was 65 NTU. this value, however, corresponds to the measures point at which the pH was 8 or above measured at a distance separating the surface of the sludge and the water-collecting inlet by zero to a few centimeters. Thus, the surface of the sludge may have been touching the inlet.

Considering all the experiments carried out in saltwater, the average increase in the pH was 0.027 with an insignificant maximum increase of 0.16. The average increase in the turbidity was 0.83 NTU (equivalent to 0.93 mg/1 when converted to SS), and the maximum increase 11 NTU (12/3 mg/1 when converted to SS), which were extremely small.

Measurements of the water quality at a place of 30 cm or more from the surface of the treated sludge showed that the average increase in the Ph was 0.015 and the average increase in the turbidity 0.5 NTU, demonstrating that there was almost no effect on the water quality. The relationships between the distance separating the inlet and the surface of the treated sludge during water collection and the increase in the turbidity are shown in Table 9. the average increase was 2.37 NTU at distances ranging from 0 to 30 cm., 0.52 NTU at 30 to 650 cm, and 0 NTU or 1 NTU for distances above 60 cm. the average was 0.28 NTU meaning that there were almost no effects on turbidity.

TABLE 9. RELATIONSHIPS BETWEEN DISTANCE FROM THE SLUDGE SURFACE
AND THE INCREASE IN TURBIDITY

Distance From the Sludge Surface (cm)	Average of Increase in the Turbidity (NTU)	Converted to SS (mg/1)
0-30	2.37	2.65
30-60	0.52	0.58
60<	0.28	0.31

Underwater Placing Experiment in Saltwater

An underwater placing experiment in saltwater, under conditions close to the actual work, was performed.

Unit for Experiment

The unit used was the same as that employed in the Large Water Tank Experiment. Figure 15 illustrates the layout used for the experiment. A section measuring approximately 10 by 10 m was dug out to make a pond, in

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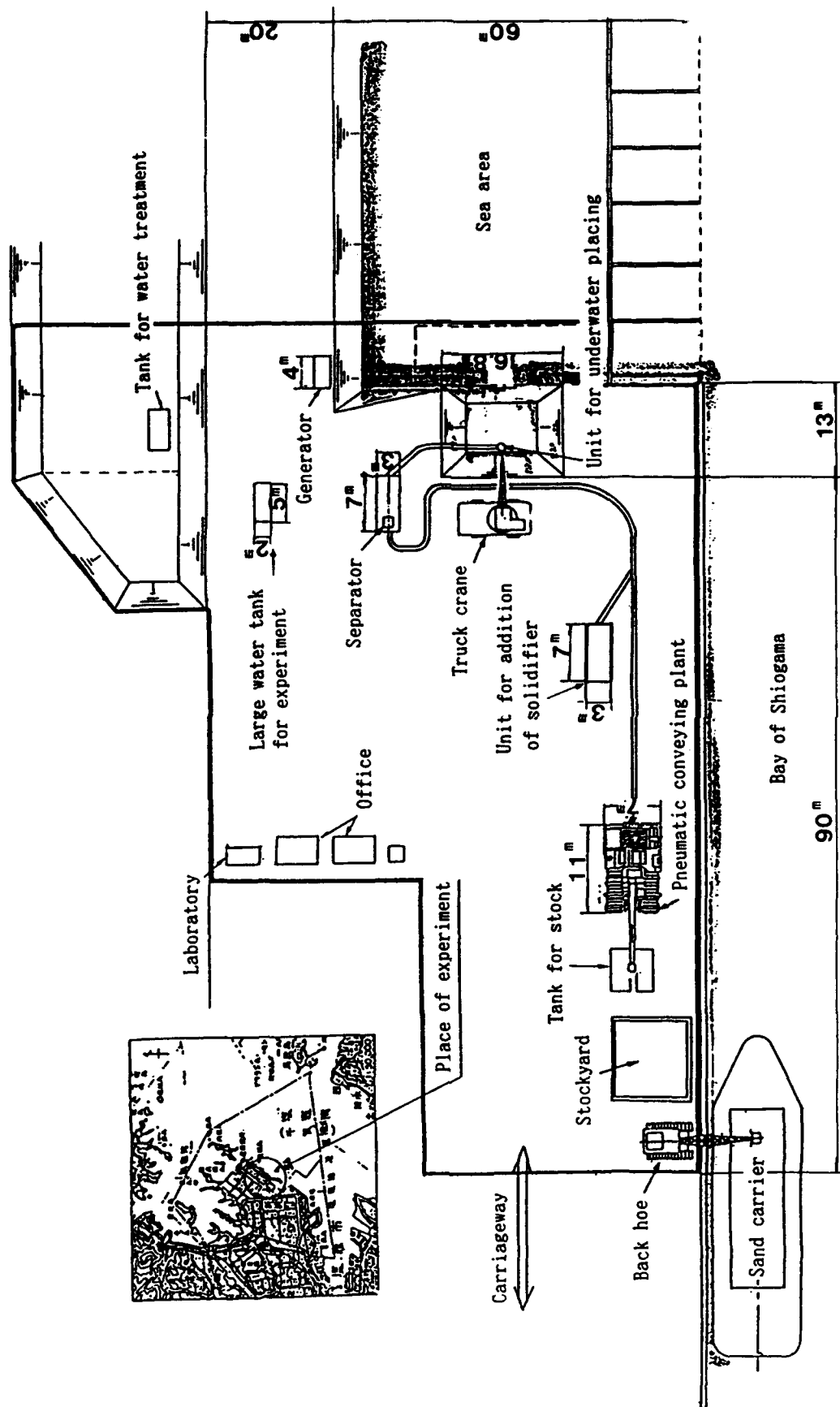
Figure 15. Position of unit for experiment

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which the experiment was carried out. An opening was made to let in
saltwater.

Outline of Experiment

In the experiment, the ratios of the solidifier added were 4 or 5 per-
cent. The amount of treated sludge placed was approximately 39 m^3. After the
operation, the form of the solidifier was observed and the hardening strength
of the collected cores determined.

Results of Experiment

Figure 16 illustrates the form of the sludge after the operation. The
sludge surface was fairly smooth. The run-off gradient was generally 1:5.

Solidifier content (%) 5%

Solidifier content(%) 4%
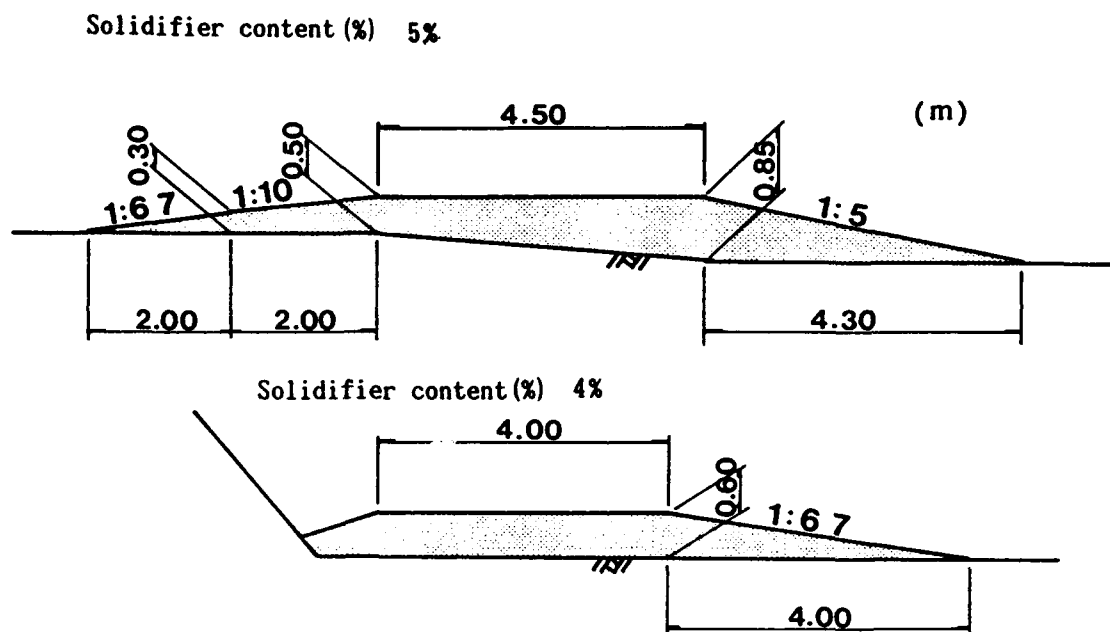
Figure 16. Form of hardening materials

Table 10 shows the results of the unconfined compression test of the
core collected after the operation as well as those of the cone penetration
test. The unconfined compressive strength value virtually met the target
28-day strength of qu - 1.0 kgf/cm^2 in 7 days. The relationship between the
unconfined compressive strength and the cone bearing capacity was qc - 6 to
13 qu.

CONCLUSION

The preliminary experiments and onsite prototype experiments showed that
the placing of the treated sludge in the water for reclamation using a unit
for underwater placement ca be carried out without deteriorating the water

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TABLE 10.   RESULTS OF STRENGTH TEST

Solidifier Content (%)	4		5	
Depth (cm)	10-30	30-50	10-30	30-50
qc (kgf/cm^2)	13.1	12.2	10.7	16.0
qu (kgf/cm^2)	1.45	0.95	1.66	2.29
qc/qu	9.0	12.8	6.4	7.0

quality if satisfactory quality control and site control are maintained to prevent dissociation of the material.

This method of treatment permits reclamation without deteriorating the water environment. In addition, it enhances the effective use of the dredged sludge by permitting the reclaimed ground to be used soon after reclamation. We are planning to study the long-term effects on the environment and the changes in strength and to develop a practical unit based on demonstrations.

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RESTORATION OF LAKES AND MARSHES TO APPLY THE TREATMENT OF BOTTOM SEDIMENTS USING BIO-REACTOR (BIOTECHNOLOGY)

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Makoto Natori, Supervisor
Experiment Group of Rikuzen Takada City
Tatsuo Matsuno, Tadashi Owada

ABSTRACT

Marsh Furukawa in Rikuzen Takada City, Iwate prefecture, is a considerably polluted marsh that is caused by organically polluted bottom sediments. With the prime objectives to improve the quality of the bottom sediments and water, several experiments were carried out by using bio-reactors, At first, dredged polluted muddy water was treated by the bio-reactors, and subsequently polluted substances were decomposed and oxidized. This treatment succeeded in reducing polluted substances and removing rot odor from the bottom sediments; therefore, facilitating subsequent treatments. Possibilities are found in the restoration of the self-purification functions of the marsh by returning the treated bottom sediments to the marsh, i.e. recovery of ecosystem. After the spill-water was treated, it also was discharged to marsh Furukawa.

From the results of the series of experiments, it was found that the principle subject for purification works could be carried out practically, i.e., obtaining disposal sites for the dredged bottom sediments. Following these experiments, larger scale demonstration tests were conducted to improve the polluted bottom sediments.

INTRODUCTION

With the direct purification method for lakes and marshes based on biotechnology, a series of tests were carried out to treat bottom sediments (black colored rotten mud) and suspended sludges on the marsh. This treatment helped to reduce and prevent rot odor of the mud and to facilitate further treatments in subsequent steps. The objectives of the experiments were the restoration of self-purification functions of the marsh and regenerations of phytobenthoses and benthic animals.

MARSH FURUKAWA

Marsh Furukawa in Rikuzen Takada City, Iwate prefecture, is the biggest natural marsh in Iwate and faces Hirota-bay in Rikuchu coast (Figure 1).
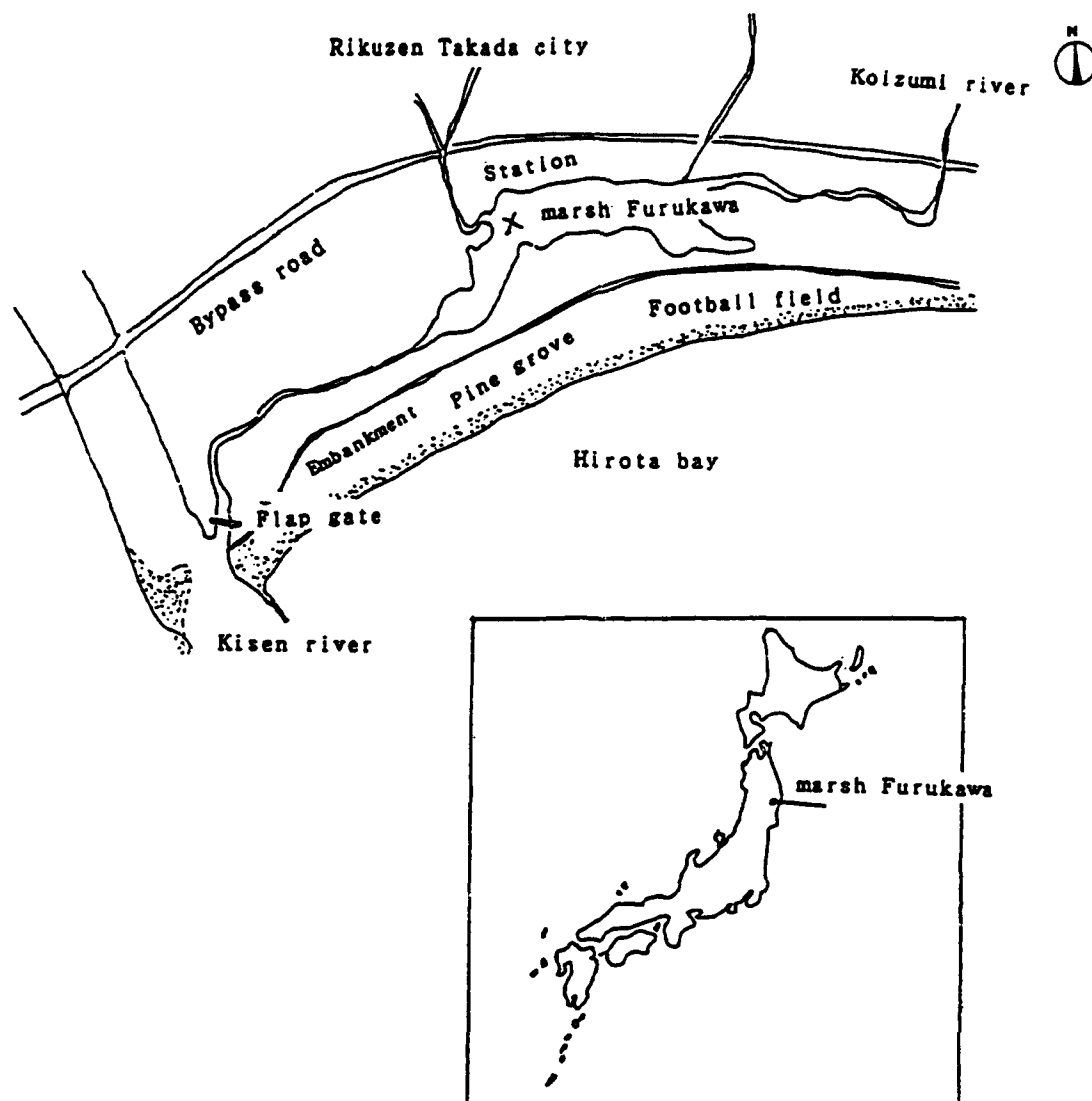
Figure 1. Bird's-eye view of marsh Furukawa

Marsh Furukawa has brackish water, an area of 90,000 m^2, the storage capacity
of 159,000 m^3, and average water depth of 1.77 m.

In the past marsh Furukawa had plenty fish and shells, wild birds, and
even salmons in the river. People enjoyed the environment. In 1960, after
Sanriku-coast was hit by tidal waves caused by the Chile earthquake, the tide
embankments were constructed along Takada pine groves. Marsh Furukawa became
a partly closed water area because exchange water between marsh Furukawa and
Hirota-bay were obstructed after the tide embankments were constructed.
Consequently, the marsh has been eutrophicated since 1970's by polluted sub-
stances discharged from Rikuzen Takada City.

The area surrounding marsh Furukawa has been designated the "Sanriku
Rias Resort" as a people's resort area in the community. Their enthusiasm is
indicated in the slogan, "Restoration of beautiful marsh and creation of the
marsh where people can study nature."

Water Quality of Marsh Furukawa

Present water quality of the marsh in shown in Figure 2.

Vertical distribution of water quality

i. Test date 1987/01—Water temp. 6.1—10.5°

ii. Central part ～ Water depth 2.5 m
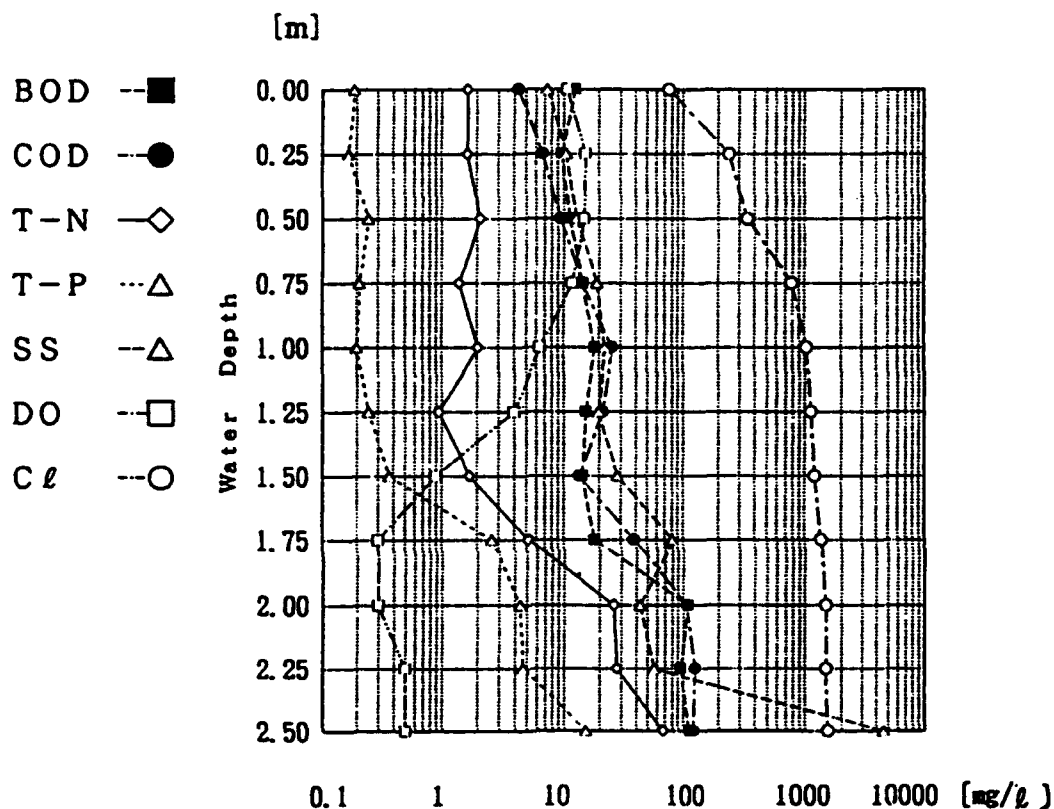
Figure 2. Water quality of marsh Furukawa

The above figure indicates water qualities at each stage of every 25-cm depth in the marsh for analyzing BOD (biochemical oxygen demand), COD (chemical oxygen demand), T-N (total nitrogen), T-P (total phosphorus), SS (suspended solids), DO (dissolved oxygen), and Cl (chloride) items. Marsh Furukawa is classified as "B"-type marsh by the standards shown as pH 6.5-8.5, COD less than 5 mg/ℓ, SS less than 15 mg/ℓ, SS less than 15 mg/ℓ, and DO more than 5 mg/ℓ. Water quality of the marsh is characterized as follows:

a. The COD value becomes higher as depth increases. Increment of COD is much more than that of BOD concentration. Also, increment of the COD value is related to the amount of nitrogen and phosphorus; on the other side, DO concentration is less as depth increases.

b. SS concentration is highest in the deep areas, and suspended sludge exists at the bottom.

c. Concentrations of both nitrogen and phosphorus become higher with depth and the concentration of the bottom layer is 50 times as much as surface layer.

d. DO shows more than 5 mg/ℓ below 1 m from the surface. DO decreases as depth increases, indicating almost a nonoxygen state at the bottom.

e. Cl is high because of brackish marsh.

Analysis of Bottom Sediments

The analysis of the bottom sediment used dredged muddy water as shown in Table 1. The bottom sediment is black colored and viscous and has extraordinary rancidity. It is much polluted; volatile solids ratio exceeded 20 percent; oxidation reduction potential (ORP) figure showed minus 580 mV; DO was not detected; and amounts of N and P were a lot. Results of bacteria tests showed that a number of coliform groups were contained in the sediments, far more than general kinds of bacteria. It is foreseen to affect fishes and shells.

TABLE 1.   ANALYSIS OF THE BOTTOM SEDIMENTS

Item	Unit	Analytic Value	Item	Unit	Analytic Value
Appearance		black	Cd	mg/kgDS	0.3
Odor		rot	Pb	mg/kgDS	21.7
SS	%	8.92	As	mg/kgDS	10.8
VSS	%	1.86	Cu	mg/kgDS	82.3
VSS/SS	%	20.8	T-Cr	mg/kgDS	ND
pH		8.8	Zn	mg/kgDS	310
DO	mg/ℓ	ND	T-Hg	mg/kgDS	0.09
ORP	mV	-580	PCB	mg/kgDS	ND
N	mg/kgDS	5,340	Fe	mg/kgDS	43,000
C	mg/kgDS	2,760	Bacteria	/cc	810,000
Si	mg/kgDS	12,500			
S	mg/kgDS	209,000			

Bottom Sediments Volume

It is estimated that approximately 35,000 m^3 of the bottom sediments deposited on the bottom of the marsh.

Pollution Mechanism of Marsh Furukawa

Domestic waste water from Rikuzen Takada City has caused pollution of the marsh. Waterweeds and microorganism grown in the marsh died in due time, depositing on the bottom of marsh and finally becoming putrefactive to affect the sediments' quality worse. Moreover, heavy seawater that flows into the marsh stays at the bottom, obstructing water circulation in the marsh. It was proved that the bottom water that stayed just above the bottom sediments was much more polluted than surface water; that is, the condition of the polluted bottom water coincided with degree of the polluted bottom sediments.

TESTING FACILITY

Testing Equipment

Transparent acrylic water tanks with effective capacity of 30 ℓ were utilized during the experiments. The bottom of the tanks were "V" shaped (90 deg) for smoothing circulation of sludge water and observing sedimentation of sludge. For effective testing, six water tanks were installed; each tank was filled with a different combination of the bottom sediments and activated sludge for acclimation. For observation and recording, the results of test progress, DO and ORP meters were installed on the tanks.

Since an appropriate mixture ratio between the bottom sediments and activated sludge was not known before tests began. five water tanks (from No. 1 to No. 5), which give different mixture ratios, were prepared as shown in Figure 3. After the simplified analysis of the test results at the site was examined, several kinds of tests were carried out by using No. 2 water tank (67 percent of bottom sediments plus 33 percent of activated sludge) to compare with the test results of the No. 1 water tank (100 percent of bottom sediments).
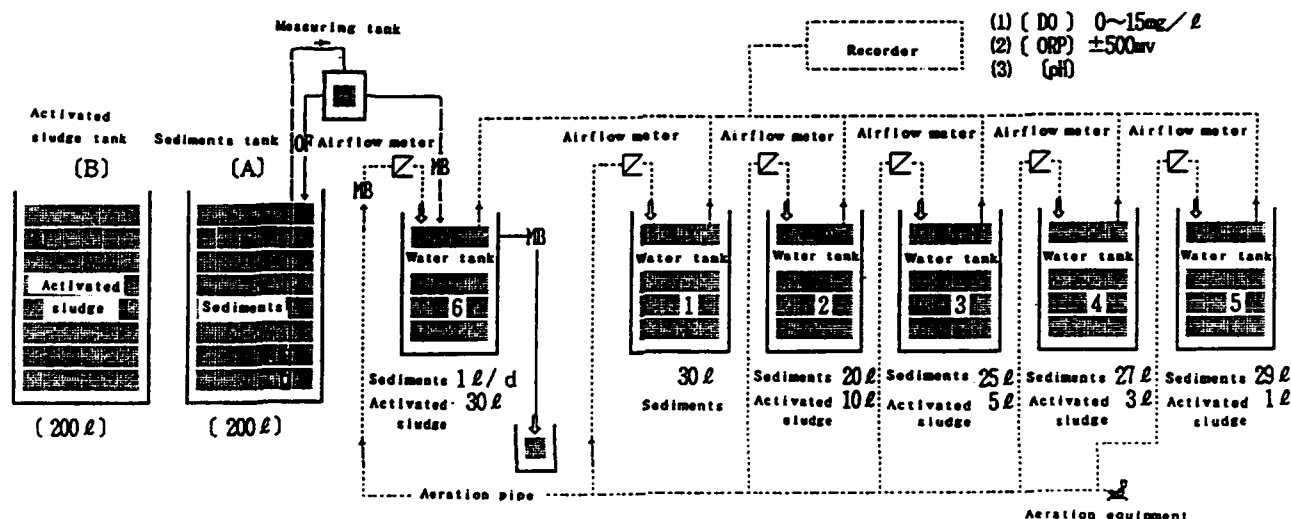
Figure 3. Testing equipment

Test Operations

The operation method of this test was done by the batch-type operation in which aeration and sedimentation continuously operated for an 8-hr period; each period was repeated three times; that is, 24 hr were operated continuously.

These operations were automatically controlled by the previously programmed sequencer. changes in concentration of DO, ORP, and pH were recorded by the instrument in each tank, and functions of the bio-reactors were analyzed. Figure 4 indicates the operation time chart.

	Test term	Sedimentation + Aeration = cycle		Aeration intensity
		time	time	
A	1987/10/28~12/28	5.0+ 3.0	= 8h /c×3c/ d	200Nℓ/h
B	1987/12/28~1988/1/4	4.0+ 4.0	= 8h /c×3c/ d	200Nℓ/h
C	1988/ 1/ 5~ 2/05	3.0+ 5.0	= 8h /c×3c/ d	50Nℓ/h
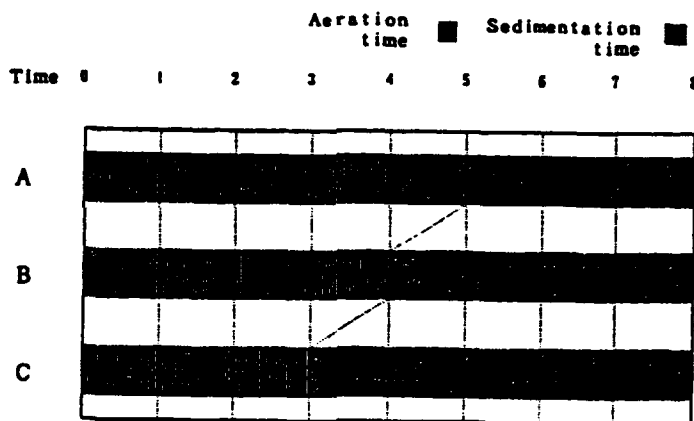
Figure 4.   Time chart of operation

TEST RESULTS

Test results for sludge concentration and water quality are described below.

Sludge Concentration

It was expected that the sludge concentration in the testing tanks would be reduced by the biological treatment. The sludge concentration in the No. 1 water tank (100 percent of bottom sediments), however, was maintained in a stabilized state as shown in Table 2, whereas in the No. 2 water tank (67 percent of bottom sediments plus 33 percent of activated sludge) the sludge concentration was largely reduced as shown in Table 3.

Figure 5 indicates the changes of SS and volatile solids (VSS) in No. 1 and No. 2 water tanks and SS in supernatant and treated water in the tanks.

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TABLE 2. CHANGES OF SLUDGE CONCENTRATION IN NO. 1 WATER TANK
(SEDIMENTS 100 PERCENT)

Days Item		Starting Day		30 Days		75 Days	
MLSS	mg/ℓ	75,000	100%	56,100	74.8%	73,800	97.3%
VSS	mg/ℓ	14,900	100%	18,900	126.8%	14,800	99.3%
SS-VSS	mg/ℓ	60,100	100%	37,200	61.8%	59,000	98.1%

TABLE 3. CHANGES OF SLUDGE CONCENTRATION IN NO. 2 WATER TANK
(SEDIMENTS 67 PERCENT PLUS ACTIVATED SLUDGE 33 PERCENT)

Days Item		Starting Day		30 Days		75 Days	
MLSS	mg/ℓ	54,800	100%	36,400	66.4%	22,200	40.5%
VSS	mg/ℓ	12,400	100%	14,600	117.7%	5,850	47.2%
SS-VSS	mg/ℓ	42,400	100%	21,800	51.4%	16,350	38.6%

The above figure shows the changes of sludge concentration in the No. 1 water tank (bottom sediments only) and the No. 2 water tank (sediments plus activated sludge). The sludge concentration in the No. 2 water tank was reduced as testing time passed. Thus, the reduction by using the activated sludge was resulted effectively.

Water Quality Tests

Changes in water quality are shown in Tables 4 and 5.

Consideration of Sludge Concentration and Water Quality Tests

By these tests, it was found that there were large differences in the changes of sludge concentration between No. 1 and No. 2 water tanks. It also was proved that the use of the activated sludge process for acclimation effectively resulted in reducing the amount of the bottom sludge.

It took 75 days for the tests to get the results of the nitrification observed which the activated sludge added to the bottom sediments for acclimation. It also took 100 days for the test to get the expected water quality with performing de-nitrogen treatment by reducing airflow of aeration. According to the activated sludge process, it takes two to three weeks to reach reaction of nitrification and de-nitrate by batch-type treatment, while a longer term is necessary for the acclimation to treat the bottom sediments by biotechnology. Basically, nitrification and de-nitrate reaction can be controlled with a similar process as a biological denitrification treatment. Removal efficiency of phosphorus is better in the t   and expected water

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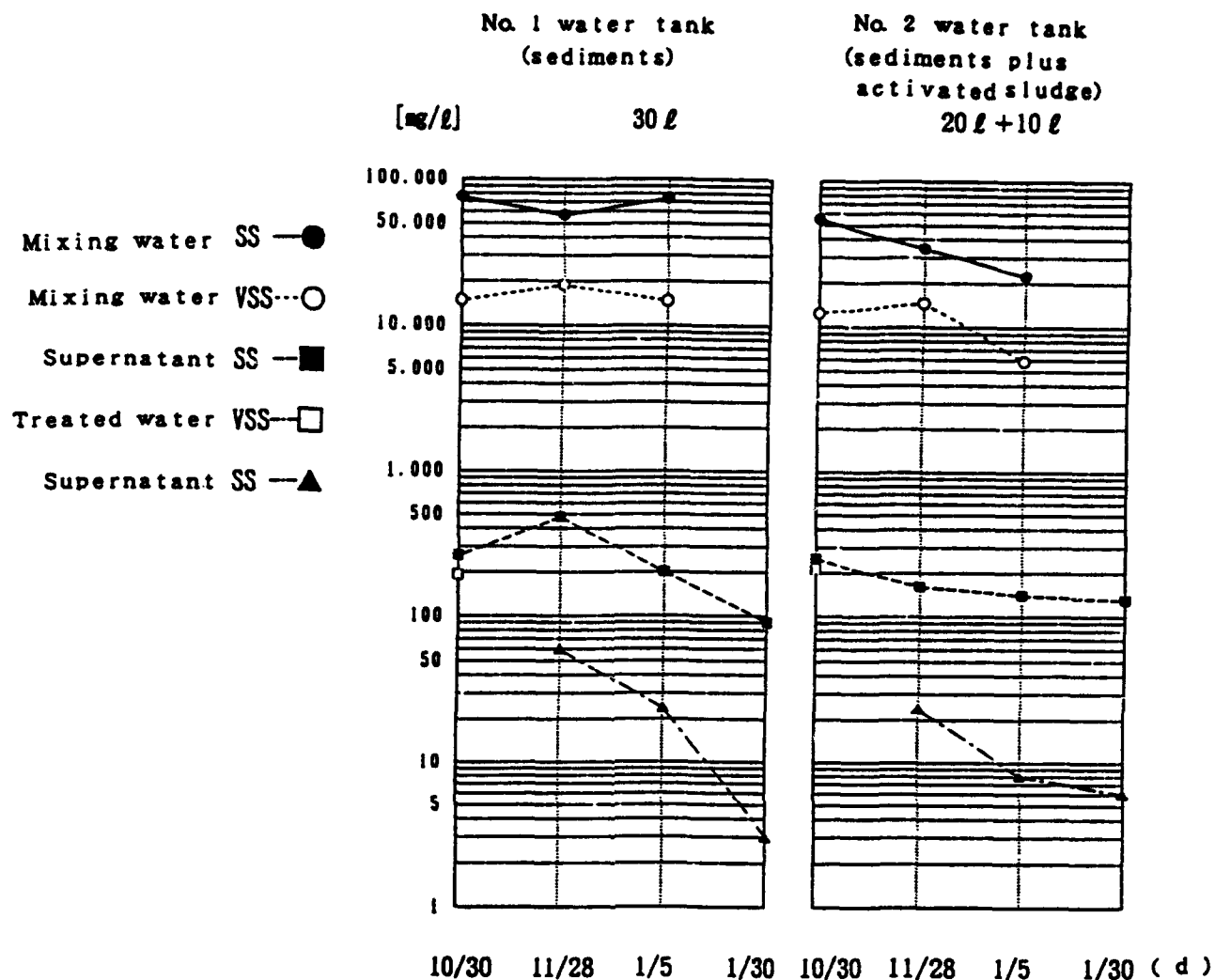
Figure 5.   Changes of SS an ⌐S in No. 1 and No. 2 Water Tanks and SS
            in Supernatant   ⌐eated Water in the Tanks

quality is obtained by a sand filter process without coagulating treatment.
This de-phosphorus would be caused by the reaction of metallic salts contained
in the bottom sediments rather than by biological de-phosphorus treatment.

The test results did not show the large difference in the changes in
water quality in the No. 1 and No. 2 water tanks. The effect of the activated
sludge sued as a seeding sludge was not observed and was expected before the
test. A few days later, the rot odor from each testing water tank reduced and
remained a slight odor, same as normal activated sludge.

Changes in Sludge Composition

Changes in the composition of the bottom sediments by the biological
treatment in No. 2 tank were analyzed for 30 and 75 days.

TABLE 4. TREATED WATER QUALITY IN NO. 1 WATER TANK (SEDIMENTS 100 PERCENT)

[mg/ℓ]

Test Days Item	Starting Day		30 Days	75 Days	100 Days
	Mixing Water	Supernatant	Treated Water	Treated Water	Treated Water
pH	8.0	5.8	6.1	6.5	6.8
BOD5	2,220	96	4.0	8	1.2
COD Mn	5,510	91	46.9	21.8	5.2
NH-N	66	8.4	60.4	10.8	0.2
NO2-N	ND	ND	0.1	2.5	ND
NO3-N	ND	ND	0.5	22.3	0.9
KJ-N	222	72.5	70.6	46.7	2.1
T-N	222	72.5	70.7	71.5	3.0
PO4-P	4.1	0.02	0.04	0.004	0.004
T-P	138	4.0	0.6	0.3	0.06

TABLE 5. TREATED WATER QUALITY IN NO. 2 WATER TANK (SEDIMENTS 67 PERCENT PLUS ACTIVATED SLUDGE 33 PERCENT)

[mg/ℓ]

Test Days Item	Starting Day		30 Days	75 Days	100 Days
	Mixing Water	Supernatant	Treated Water	Treated Water	Treated Water
pH	7.3	6.2	5.8	5.4	6.9
BOD5	2,100	105	3.0	5	1.0
COD Mn	5,800	130	35.5	21.8	6.2
NH-N	15	10.1	51.6	19.2	0.3
NO2-N	ND	ND	0.6	41.3	ND
NO3-N	ND	ND	0.6	41.3	1.2
KJ-N	250	98.2	60.4	5.2	0.7
T-N	250	98.2	61.0	46.6	1.9
PO4-P	6	0.02	0.006	0.004	0.004
T-P	102	3.7	0.6	0.2	0.06

Reduction Tendency of the Bottom Sediments Volume

Reduction tendency of the bottom sediments volume by test is shown in Table 6. The volume of the bottom sediments (1,644 g) in No. 2 tank was reduced to 40.5 percent, or 666 g.

TABLE 6.   REDUCING TENDENCY OF THE BOTTOM SEDIMENTS
(NO. 2 WATER TANK)

Item	Unit	Starting Day	30 Days	75 Days
MLSS	mg/ℓ	54,800	35,400	22,200
"	g	1,644	1,092	600
"	%	100	66.2	40.5

Changes in the Composition of the Bottom Sediments

The results of the tests showed that the reduced volume of the bottom sediments brought some different changes indicating increase or decrease of the composition ratio (mg/kg DS). It seemed to be the tendency for some changes to occur while the biological treatment was performed. Changes in the composition of the bottom sediments are shown in Table 7.

TABLE 7.   CHANGES IN COMPOSITION OF THE BOTTOM SEDIMENTS
(NO. 2 WATER TANK)

Item	Unit	Starting Day	30 Days	75 Days
C	mg/kgDS	60,000	71,000	89,000
N	mg/kgDS	4,630	5,190	6,920
P	mg/kgDS	2,250	3,240	5,360
S	mg/kgDS	10,200	4,760	2,100
Si	mg/kgDS	172,000	164,000	149,000
Fe	mg/kgDS	38.600	53,900	94,200

In regard to the composition of which volume did not change by the biological treatments, the ratio of this composition (mg/kg DS) in the bottom sediments tends to increase with reduction of the sediments. Also, with respect to the composition of which the volume reduction is larger than the volume reduction of bottom sediments by the biological treatments, the ratio of this composition (mg/kg DS) tends to decrease.

Some compositions (p, Fe) in the sludge were unchanged in volume by the reducing effect on sludge, whereas other compositions (C, N) decreased in volume, while the concentrations (mg/kg DS) of these composition increased by the biological treatment. The volume of compositions (Si, S) in the sludge decreased, in parallel with the decrease of concentration.

Changes in the volume of each sediment by the biological treatment, which was contained in the sludge of the No. 2 tank (30 ℓ), were calculated from analyzed values (mg/kg DS) on Table 7 and from the volume (g) of the composition in reduced bottom sediments. The volume of composition for soluble and volatile substances was excluded.

Changes in the composition volume (g) and its ratio (percent) are shown in Tables 8 and 9.

TABLE 8. CHANGES IN COMPOSITION VOLUME OF THE BOTTOM
          SEDIMENTS (G) (NO. 2 WATER TANK)

Item	Unit	Starting Day	30 Days	75 Days
C	g	98.64	77.53	58.27
N	g	7.61	5.67	4.61
P	g	3.69	3.54	3.57
S	g	16.77	5.20	1.40
Si	g	282.6	179.1	99.2
Fe	g	63.46	58.85	62.7

TABLE 9. CHANGES IN COMPOSITION RATIO OF THE BOTTOM
          SEDIMENTS (PERCENT) (NO. 2 WATER TANK)

Item	Unit	Starting Day	30 Days	75 Days
C	%	100.0	-21.1	-39.3
N	%	100.0	-25.5	-39.4
P	%	100.0	- 4.4	- 3.6
S	%	100.0	-68.9	-91.6
Si	%	100.0	-36.7	-64.8
Fe	%	100.0	- 8.3	- 1.2

Each change in the composition of the improved bottom sediments in No. 2 tank treated by the biological treatment is as follows:

a. Si . . Reduction tendency is similar to the bottom sediments.

b. P,Fe . Reduction has not occurred.

c. C,N . . Reduction is less than the reduction of the bottom sediments volume.

d. S . . . Reduction is more than the reduction of the bottom sediments volume.

Figure 6 shows the quantitative changes (g) of the composition in sludge, and Figure 7 shows the changes (percent) of the composition in sludge in No. 2 water tank.

    i. Test date 1987/10—88/02

    ii. Test tank   No. 2 water tank

    iii. Sediments 20ℓ+Activated sludge 10ℓ
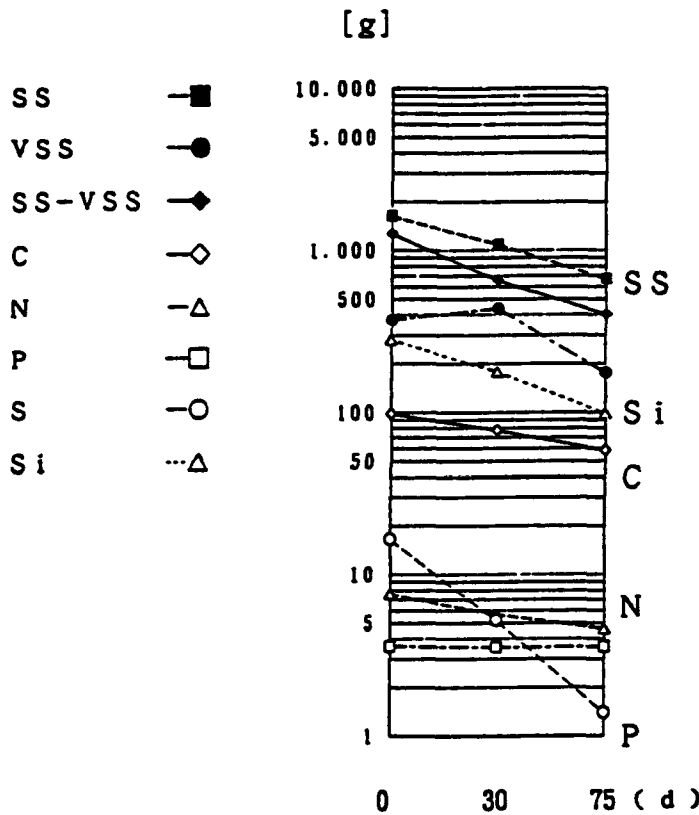
Figure 6. Changes in composition
of the improved bottom
sediments (g)
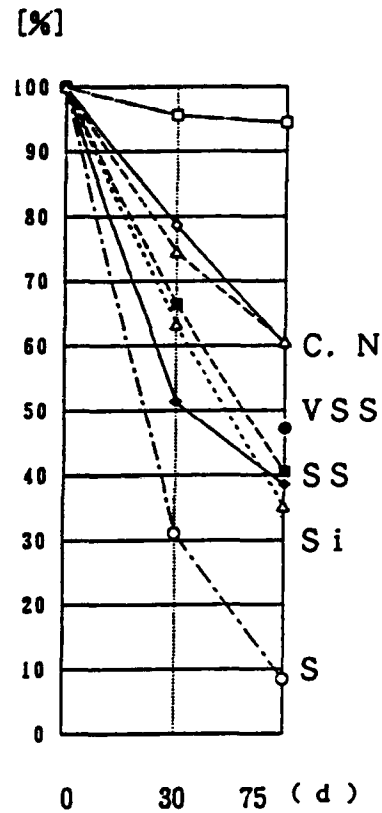
Figure 7. Changes in composition
of the improved bottom
sediments (percent)

In general, the amount of organic matters which consist of the sludge is changeable by the biological treatment. In this experiment, however, it was observed that each composition indicates a different pattern of change to the biological treatment.

Release Test

The release tests were conducted for both the bottom sediments and the improved one and studied the state of nutrient salts and the effect on water quality.

Test Method

Predetermined volumes of the bottom sediments and the improved bottom sediments were put into test tubes (ID 20 cm), and the marsh water added to both tubes. the tubes were sealed with paraffin to prevent dissolved oxygen loss. The tubes were stirred gently not to cause diffusion of sludge, thus keeping predetermined temperature to observe conditions of water quality.

Test Substance

Bottom sediments, improved bottom sediments, and marsh water of marsh Furukawa were the basic ingredients of the test.

Test Equipment Outline

The drawing below is an outline of the equipment.
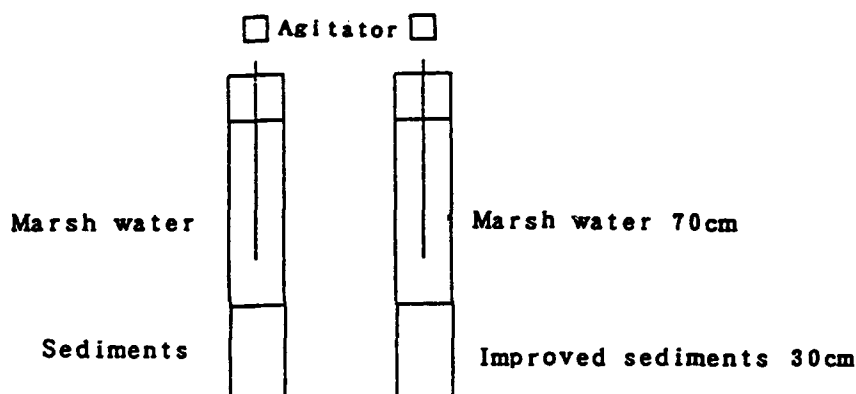
Changes in Water Quality in the Release Test

Tables 10 and 11 that follow show the changes resulting from release tests on bottom sediments and improved bottom sediments.

Figure 7 shows the results of release tests from the bottom sediments and the improved bottom sediments. The figure also indicates test results under the de-oxygen state. There are obvious differences in the release characteristics (release rate and quantity) between two kinds of the bottom sediments. Especially total nitrogen has a remarkable difference; that is, total nitrogen in the improved sediments shows a decreasing tendency against releasing.

Figures 8 and 9 show the release quantity and rate of the bottom sediments and the improved bottom sediments.

The release test result for COD is shown in Figure 10. This figure resulted from the release tests under the de-oxygen state. Changes in the COD value tended to lag behind the BOD value. Co-relations were observed between COD and BOD values.

TABLE 10.   CHANGES IN WATER QUALITY IN TANK BY RELEASE
TEST (BOTTOM SEDIMENTS)

[mg/ℓ]

Days Item	1	3	5	10	20	30
BOD_5	1.2	1.9	2.0	1.8	1.5	2.0
COD_{Mn}	3.5	4.8	5.0	6.2	7.9	8.1
Sulfide	0.8	1.1	1.5	1.8	3.0	4.6
Kj-N	0.32	0.58	0.99	1.56	2.54	4.5
NH_4-N	0.02	0.77	0.85	0.93	2.22	4.54
NO_2-N	0.028	ND	ND	ND	ND	ND
NO_3-N	0.8	ND	ND	ND	ND	ND
T-N	1.17	1.35	1.84	2.50	4.76	10.46
PO_4-P	0.004	0.032	0.088	0.098	0.140	0.185
T-P	0.012	0.034	0.125	0.28	0.53	2.16
DO	5.6	1.2	0.5	0.4	0.4	0.4

TABLE 11.   CHANGES IN WATER QUALITY IN TANK BY RELEASE TEST
(IMPROVED BOTTOM SEDIMENTS)

[mg/ℓ]

Days Item	1	3	5	10	20	30
BOD_5	1.2	1.2	1.0	0.9	0.8	0.6
COD_{Mn}	3.5	4.6	3.6	3.2	3.1	3.0
Sulfide	0.8	ND	ND	ND	ND	ND
Kj-N	0.32	0.38	0.20	0.12	0.18	0.58
NH_4-N	0.02	0.12	0.10	0.12	0.02	0.06
NO_2-N	0.028	ND	ND	ND	ND	ND
NO_3-N	0.8	0.57	0.42	0.20	0.20	0.21
T-N	1.17	0.96	0.62	0.32	0.38	0.77
PO_4-P	0.004	0.004	0.004	0.006	0.008	0.010
T-P	0.012	0.030	0.025	0.028	0.024	0.022
DO	5.6	1.8	0.8	1.0	0.8	0.8

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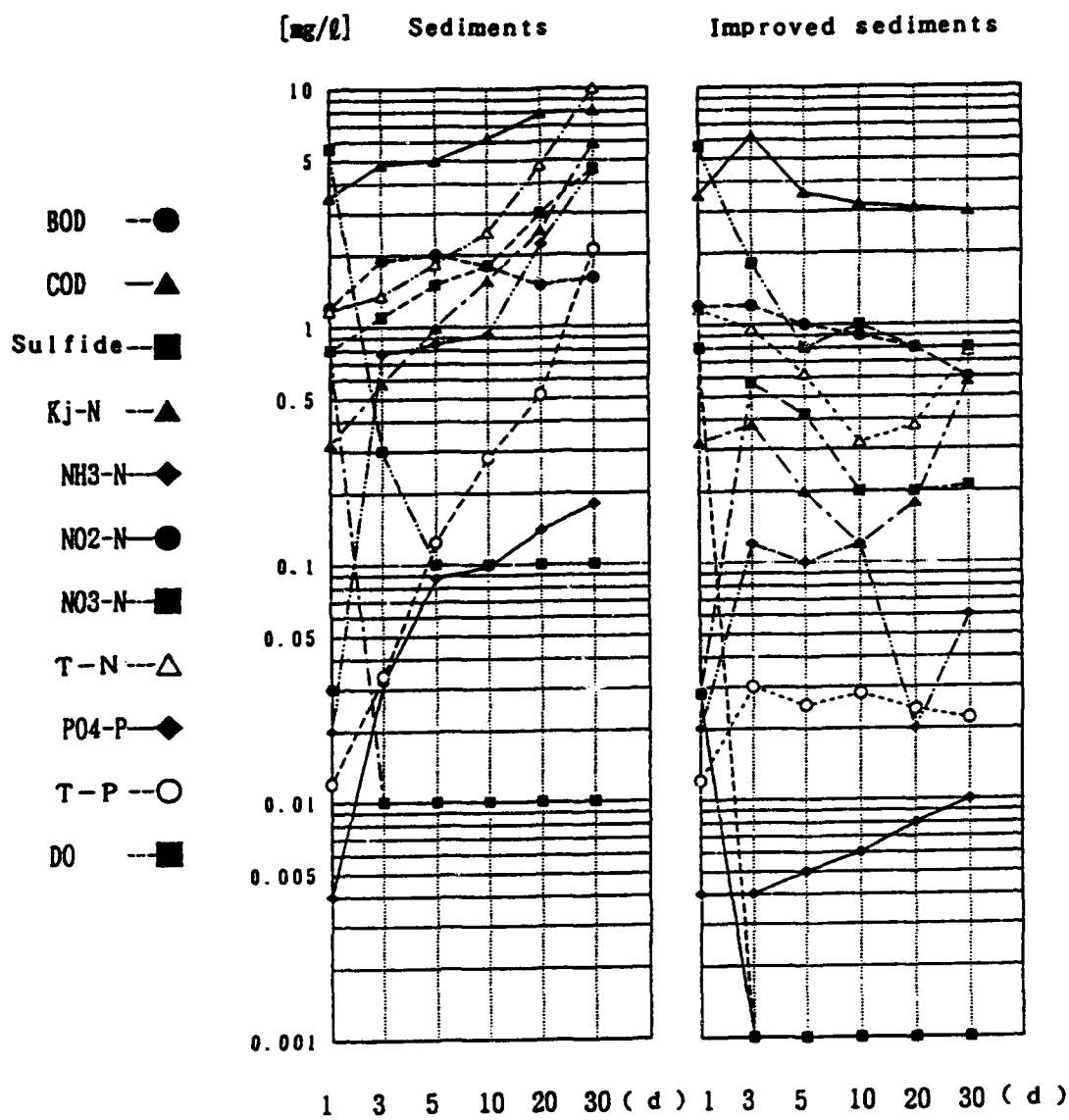
Figure 7. Release test results from the bottom sediments and
the improved bottom sediments
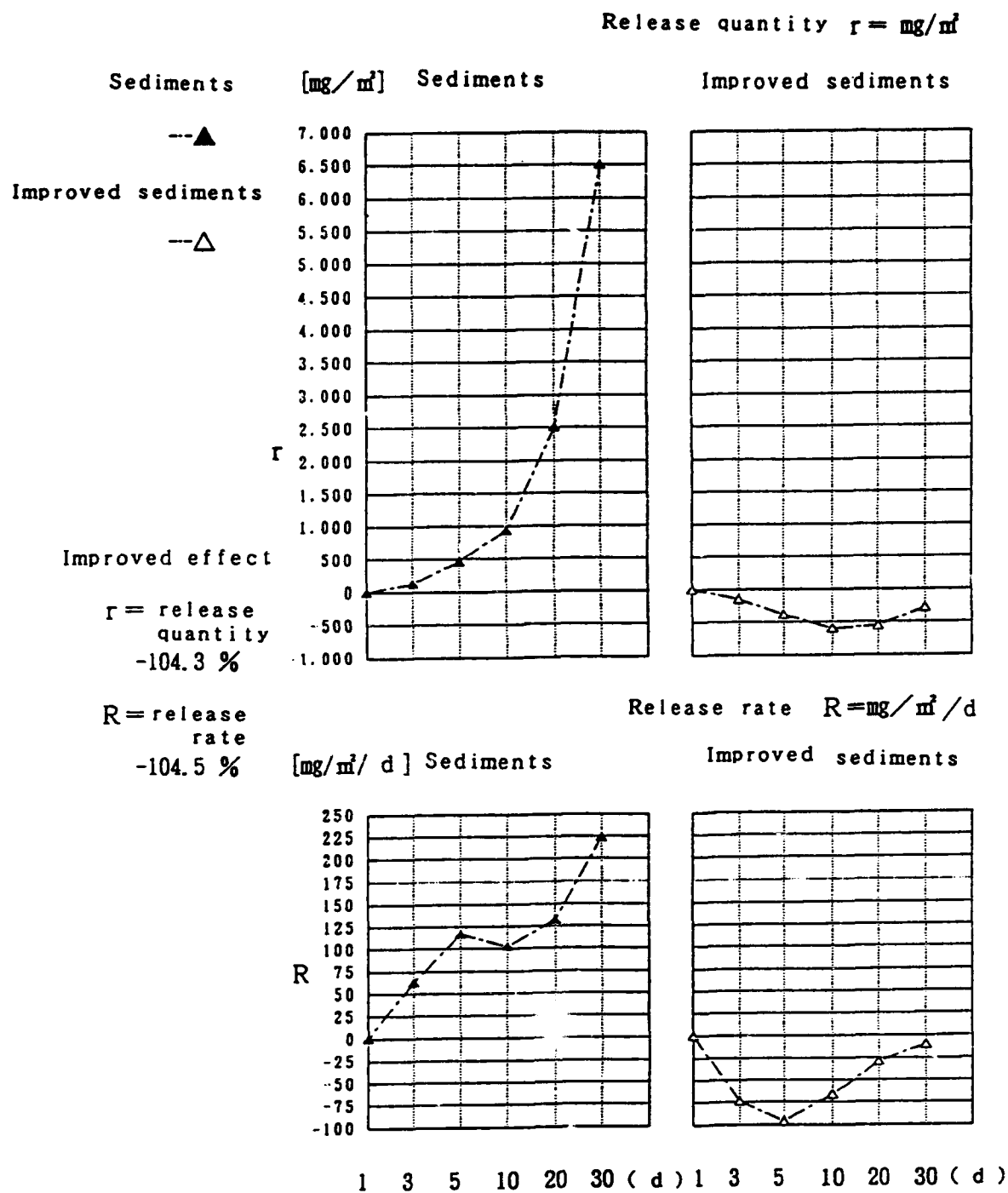
Figure 8. Release test results of nitrogen from the bottom sediments and the improved bottom sediments
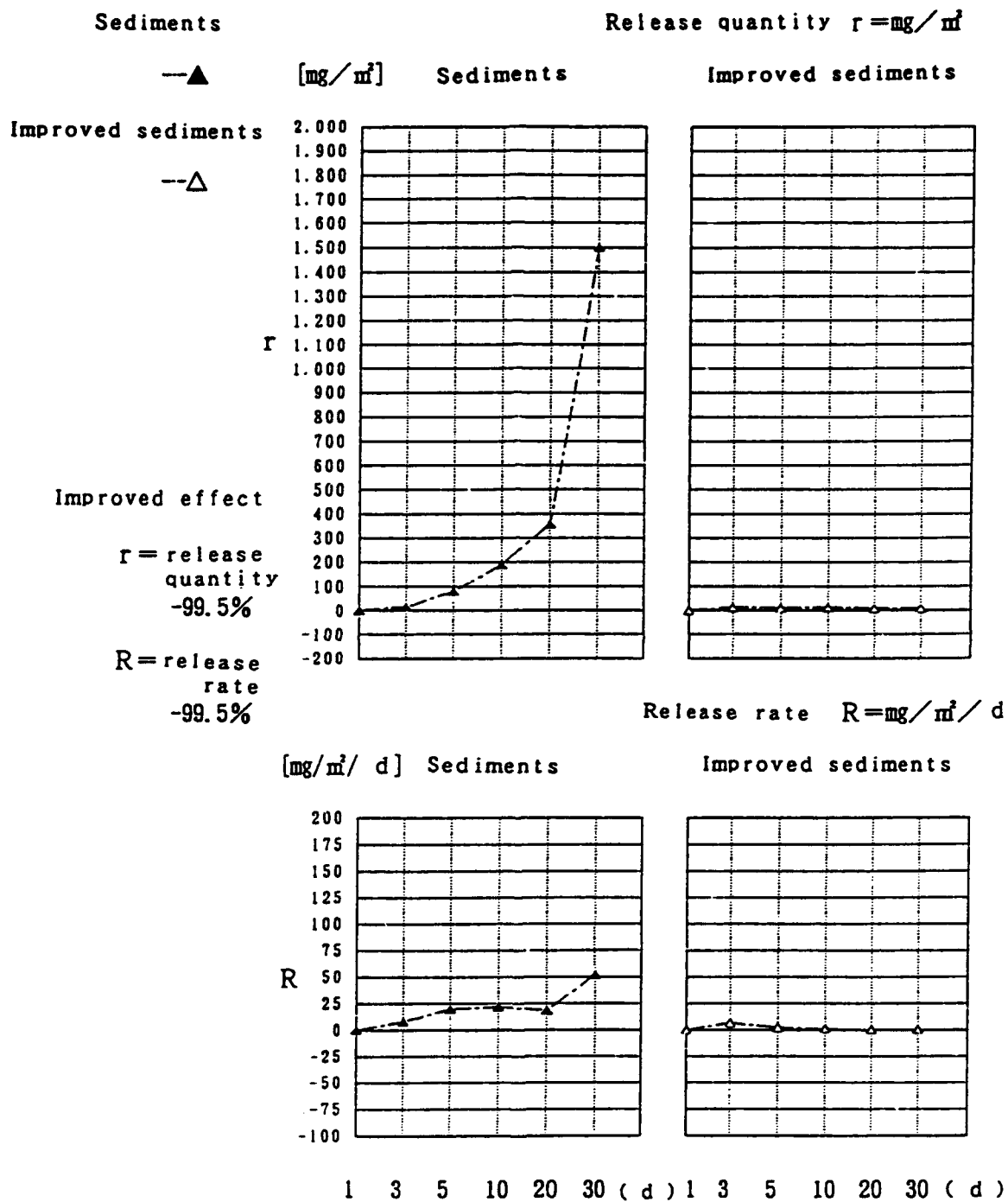
Figure 9. Release test results of phosphorus from the bottom sediments
and the improved bottom sediments

Sediments

Release quantity $r = mg/m^2$

COD—▲

Sediments

Improved sediments

BOD—●

7.000
6.500
6.000

Improved sediments

5.500
5.000

COD —△

4.500
4.000

BOD —○

3.500
3.000
2.500
2.000

Improved effect

1.500
1.000

BOD = release
quantity
-175 %

500

0

-500

COD = release
quantity
-113 %

-1.000

Release rate $R = mg/m^2/d$

BOD = release
rate
-175 %

Sediments

Improved sediments

COD = release
rate
-113 %

250
225
200
175
150
125
100
75
50
25
0
-25
-50
-75
-100

1   3   5   10 20 30 (d) 1   3   5   10 20 30 (d)
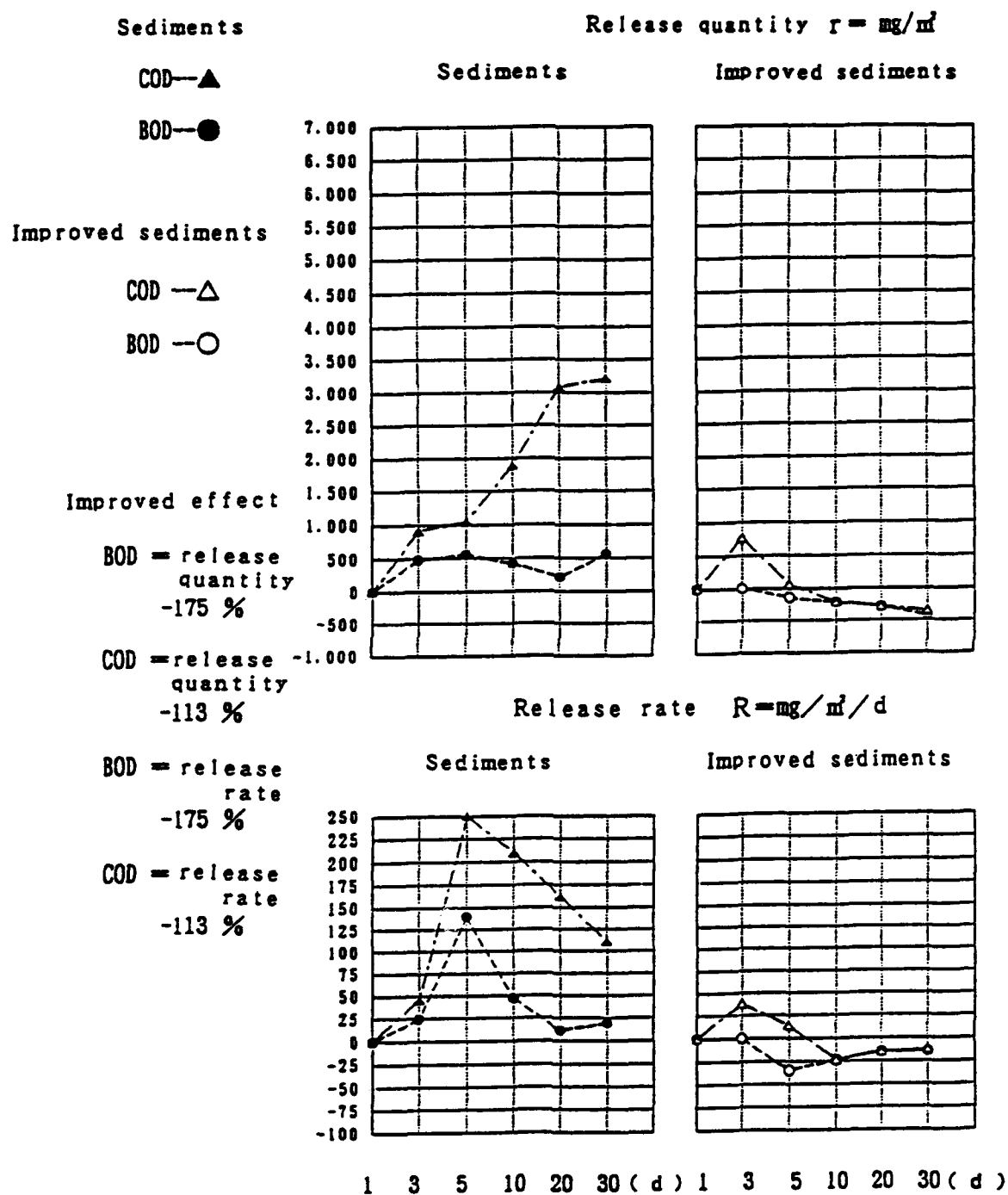
Figure 10.   Release test results of COD from the bottom sediments and
the improved bottom sediments

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Gas Generation Test

The gas generation test was carried out to study sludge characteristics for the bottom sediments and the improved bottom sediment. The 100 g of the bottom sediments picked up from the marsh and the same amount of the improved bottom sediments from the No. 2 water tank were put separately into two flasks (capacity 2 ℓ). The 900 mℓ of distilled water was added into each flask, and the flasks were quickly plugged by rubber plugs. Then the test equipment was arranged as shown in Figure 11.
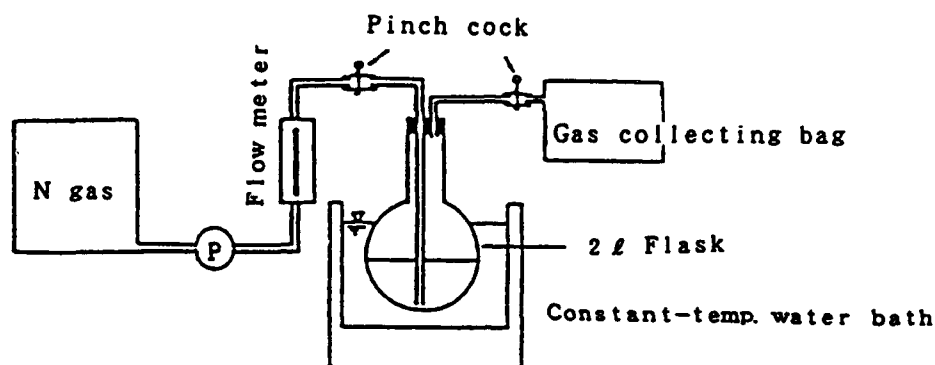
Figure 11. Gas generation test equipment

When the temperature in the flasks reached the constant temperature, after keeping it constant one hour, the pinch cock was opened to send nitrogen gas to the flasks at the speed of 1 ℓ/min for 10 min, and generated gas was gathered in the collecting bag attached to the end of the pipe to analyze it promptly.

The test result is shown in Table 12. The bottom sediments which were treated by the biological treatment restrained generation of rot odor.

TABLE 12. GAS GENERATION RATE

Item		Bottom Sediments	Improved Bottom Sediments
Ammonia	NH_3-N	105	16
Sulfide	HS	280	ND
Methane	CH	2,100	8

CONCLUSIONS

It was recognized that there was possibility for the organically polluted bottom sediments to be improved by use of the bio-reactor. Test results showed that the improved bottom sediments might restrain the generation of COD, nitrogen, and phosphorus that caused eutrophication. The test results would apply to better effect the restoration of water quality and

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ecosystem. The summary below includes the improved sediments, reduction of pollution, treatment of spillwater, and rot odor in the experiments.

Improved Bottom Sediments

a. Improved sediments treated by the biological treatment have a color of light brown and no rot odor.

b. With respect to reduction of the polluted bottom sediments, addition of the activated sludge and acclimation condition should be considered as well as retention time and aeration intensity.

c. Volatile solids ratio (VSS/SS) of the improved bottom sediments increased in comparison with the bottom sediments.

d. ORP of the improved bottom sediments is between 450 and 520 mV.

e. Nitrogen causes inorganic feature, nitrification, and de-nitrate reaction.

f. Phosphorus is stabilized by metals, and oxidation reaction occurred in the bottom sediments; the release of phosphorus into the water is restrained.

g. Improved bottom sediments retain a large amount of oxygen, which is generated by oxidation of metal substances (iron, etc.) in the sediments and will be useful for the improvement of the bottom sediments condition.

h. Improved bottom sediments contain bacteria (1,050 /cc) and coliform groups (230 groups /cc) which restrain malignant bacteria.

Volume Reduction of the Bottom Sediments

a. Test result in which the activated sludge was added shows the reduction effect of the volume of the polluted bottom sediments.

b. Test result in which the activated sludge was not added observed no reduction effect of the volume.

c. Reduction ratio of the bottom sediments in No.2 water tank was 33 percent after 30 days and 58 percent after 75 days.

d. Reduction rate in the No. 2 water tank was from 0.7 to 1.0 SS percent/d.

e. Reduction rate in the No. 2 water tank was from 600 to 400 SS mg/ℓ/d.

f. Reduction tendency of the bottom sediments in No. 2 water tank was observed in volatile solids (VSS).

g. Reduction would be effected by the quality of the bottom sediments, retention time, aeration intensity, and characteristics and amount of the activated sludge applied.

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<u>Odor</u>

    <u>a</u>. The smell or rot odor in the bottom sediments was like an addled egg.

    <u>b</u>. Rot odor caused in each testing water tank vanished in a few days after the biological treatment.

    <u>c</u>. Spillwater in each tank has no rot odor.

<u>Spillwater Treatment</u>

Since marsh Furukawa is classified as "B" type, it will be able to improve the spillwater quality by treating COD, SS, T-N, and T-P contained in it.

<u>Prospects</u>

It is considered that this technique should be applicable in cases of difficult dredged bottom sediments. These treatment techniques should be applied to bottom sediments with high organic properties, while excluding the treatment of the bottom sediments contaminated by heavy metals.

The first experiments for the bottom sediments used bio-reactors for treatment purposes, but there are many problems awaiting solution. Tests and analyses must be repeated over and over again.

The problems are as follows:

    <u>a</u>. Preparation of the guideline to improve bottom sediments by the biological treatment.

    <u>b</u>. In case of returning the improved bottom sediments into the marsh, it should be analyzed with bioassay to determine the effects on the ecosystem of the marsh.

    <u>c</u>. Development of technology and equipment for returning the improved bottom sediments back into the marsh by means of spraying it with equipment.

    <u>d</u>. Establishment of energy-saving technology for bio-reactor treatment.

CLOSURE

This report described the experimental results for the treatment of the bottom sediments by using bio-reactors. It is planned that the middle scale of the second experiment will be carried out in this year at Marsh Furukawa.

The treatment facility of the polluted bottom sediments has been operating at the prawn farm in Okinawa, using the above technology. Also, in 1990, the large scale demonstration experiments (capacity 25 m³/d) had been conducted based on the above technology in the biggest lake in Japan, and the data have now been analyzed.

PCB VOLATILIZATION FROM DREDGED MATERIAL,
INDIANA HARBOR, INDIANA

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ABSTRACT

This paper summarizes the theory and application
of a model to predict the mass loss of polychlorinated
biphenyls (PCBs) from dredged material through vola-
tilization. A comparison to other contaminant path-
ways is presented for both in-lake and upland
disposal.

BACKGROUND

Contaminated sediments placed in a confined disposal facility (CDF)
provide the potential for volatile organic chemicals (VOCs) to be released
through volatilization. Theoretical models have been developed to describe
the physical and chemical processes involved in transferring the VOC from the
solid or liquid phase to the air (Thibodeaux 1989). To date, PCBs have been
the VOC of concern; however, the theory presented is applicable to other VOCs
including polycyclic aromatic hydrocarbons (PAHs). The documentation provided
is not sufficient to fully understand the development of the models described
in this paper. The user should refer to the original reports for complete
understanding of model development and limitations.

INTRODUCTION

Volatilization is the process whereby a compound passes into the air
from a solid or liquid surface. The degree of volatilization can be generally
related to Henry's constant of the compound: a compound with a high Henry's
constant has a higher volatilization potential than one with a low Henry's
constant.

The model presented in this note provides an estimate of the mass of
PCBs lost from an in-lake and an upland CDF. PCB was the only compound con-
sidered because of its regulatory significance and to simplify development of
the models. It is anticipated that other semivolatile and volatile compounds
such as PAHs will be modeled in the future for sediments contaminated with
these substances.

Chemical equilibrium principles are used in this note to determine the
transfer of the VOCs between various phases. In the case of VOCs associated
with sediment, three phases of matter are involved. The first phase includes
the solid particles which constitute the sediment and have both organic matter
and mineral matter comprising the particles. The two other primary phases

include air and water. With respect to dredging, VOCs can enter the air from either the water or sediment surfaces. for volatilization to occur from the water surface, the VOC must first desorb from the suspended solids phase and diffuse through the water before emitted into the air.

MODEL PURPOSE

PCB volatilization models developed by Thibodeaux (1987) were adopted by the Chicago District to local conditions as part of the preparation of the Draft Environmental Impact Statement (DEIS) for Indiana Harbor and Canal Maintenance Dredging and Disposal Activities, Lake County, Indiana. The models estimate the mass flux of PCBs form a proposed CDF by volatilization from dredged material. Two scenarios were considered: The first assumes that the dredged materials are placed in an in-lake CDF, while the second assumes placement in an upland CDF.

Volatilization is complicated and can involve a number of transfer pathways. In order to quantify volatilization of contaminants to air, the major sources, pathways, and external parameters which affect the transfer must be addresses. Lab and field verification of critical transfer coefficients are lacking, and hence a complete quantification of PCB volatilization for all activities associated with a dredging operation is impossible. Therefore, the models were used as an indication of the relative significance of volatilization when compared to other loss pathways (such as leachate, seepage, plant, and animal uptake) for various operational schemes. In this manner, potential PCB mass flux for different placement options can be estimated, and viable options can be evaluated against each other and the no action plan.

MODEL ASSUMPTIONS

Theoretical chemodynamic models for organic pollutants in dredged material have been developed to estimate potential emission rates of PCBs to the air (Thibodeaux 1989). Although these models have not been verified experimentally for dredged material, studies of pesticide volatilization from soils, VOC emissions during refinery waste landfarming, and VOC emissions from hazardous waste lagoons indicate that theoretical chemodynamic models, when properly formulated, provide realistic estimated of VOC volatilization (Thibodeaux and Hwang 1982; Thibodeaux and Becker 1982; Thibodeaux, Parker, and Heck 1984; Eklund, Nelson, and Wetherhold 1987). It should be noted that input to the model is highly dependent on the physical aspects of the particular CDF, the placement method, and the amount of time for a particular filling operation, as well as the lifetime of the CDF.

The equation used to calculate flux from exposed sediments describes chemical movement in the unsaturated pore spaces near the exposed surface. Sediments are initially in a semisaturated state, but surface layers soon will approximate the unsaturated situation. This initial transient state is not accounted state is not accounted for by the model. Also, wetting and drying cycles generated by rainfall were not considered.

The major emission locales for a CDF and its inherent operations are dredging and transporting, submerged sediments (ponded zone), exposed sediments void of vegetation, and sediments with vegetative cover.

Because of complexities involved and the lack of sufficient theory, this evaluation considers only the submerged sediments and the exposed void of vegetation locales as emission sources for PCB flux.

MODEL FORMULATION

Submerged Dredged Material
(Pond Volatilization) Algorithms

The pathway for volatilization in the case of submerged dredged material involves desorption from the suspended solids phase, diffusion through the water, and transport through the air-water interface. Assuming a constant suspended solids concentration, the steady-state flux of an organic chemical through the air-water interface is given by the following equation:*

$$n_A = {}^1K'_{A2} \left[\frac{W_A}{K_d + 1/\rho_{32}} - \rho_{A2}^{**} \right] \left(\frac{1}{1,000} \right) \tag{1}$$

where

n_A = flux of A through air-water interface, mg A/cm^2 hr
A = organic chemical of interest
${}^1K'_{A2}$ = overall liquid-phase mass transfer coefficient, cm/hr
W_A = concentration of A in the original bed sediment, mg/kg
K_d = sediment-water distribution coefficient for A, L/kg
ρ_{32} = concentration of suspended solids, kg/L
ρ_{A2}^{**} = hypothetical concentration in water for air side concentration of A, mg/L

With respect to the overall liquid-phase mass transfer coefficient, when the emission rate is liquid-phase resistance controlled, as it is for hydrophobic organics, ${}^1K'_{A2}$ depends on wind speed and molecular diffusivity of A in water and can be estimated using the following equation (Lunney, Springer, and Thibodeaux 1985):

$$^1K'_{A2} = 19.6V_x^{2.23}D_{A2}^{2/3} \tag{2}$$

where

V_x = wind speed, mph
D_{A2} = molecular diffusivity of A in water, cm^2/sec

If the diffusivity of A in water is not known, it can be estimated using the following equation (Thibodeaux 1979):

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* Environmental Laboratory. 1988 (20 July). Information on the Volatilization of Organic Pollutants from Dredged Material, Memorandum, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

$$D_{A2} = D_{B2}(M_B/M_A)^{0.6} \tag{3}$$

where

D_{B2} — molecular diffusivity of B in water, cm^2/sec
B — model organic chemical of known molecular diffusivity
M_B — molecular weight of B
M_A — molecular weight of A

The quantity $W_A/(K_d + {}^1/\rho_{32})$ is the dissolved concentration of A in the pond water and can be thought of as the dissolved concentration of A at the air-water interface. The difference between it and ρ_{A2}^{**} is the driving force which cause the flux of A into the air.

The value of ρ_{A2}^{**} is derived from the existing concentration of A in the air. This value is very small compared to the water concentration and therefore, if assumed to be zero, would have little effect on the driving force. This conservative assumption maximizes volatilization.

Equilibrium partitioning uses the relative chemical solubilities of hydrophobic organic compounds (like PCBs) in sediment and water to estimate the concentrations of the compound in these two media at equilibrium. PCBs are poorly soluble in water and have a high affinity for sediments, particularly those with much organic matter. The ratio of PCB concentrations in sediment and water at equilibrium is referred to as K_d . This partitioning coefficient (K_d) can be calculated from chemical properties of the contaminant (PCB) and information about the total organic content (TOC) of the sediment or through a number of laboratory procedures. The K_d for PCBs in the Indiana Harbor sediments was determined through sequential batch leach testing and column leach testing by the U.S. Army Engineer Waterways Experiment Station (WES) as 256,000 L/kg (Environmental Laboratory 1987).

Equation 1 is applicable as long as the suspended solids concentration is not reduced to identically zero. In a CDF, the suspended solids concentration usually decreases when filling operations are discontinued, but never goes to zero because of resuspension. When the suspended solids concentration is very low and cannot be reliably estimates, flux may be better estimated using the following equation (Thibodeaux 1979):

$$N_A = {}^1K_{A2}'(\rho_{A2} - \rho_{A2}^{**}) \tag{4}$$

where

ρ^{A2} — bulk liquid dissolved concentration of A, g/cm^3
ρ_{A2}^{**} — hypothetical concentration in water for air side concentration of A, g/cm^3

Exposed Dredged Material Algorithms

The volatilization pathway for exposed dredged material incorporates a number of steps. Although sediments are placed in a semisaturated state,

water and VOCs become quickly depleted from the surface layer, and continuing losses come from the pore spaces within the dredged material beneath the surface. At this point, VOC emission is dredged material-side vapor phase diffusion controlled. The emission pathway involves desorption from particle surfaces into a water film surrounding the particles, diffusion through the water film, desorption from the water film into the pore gas, and diffusion through the pore gas prior to emerging into the atmosphere. This last step is apparently the limiting step in soil systems (Dupont 1986), and this condition is thought to apply to the top layers of dredged material in a CDF (Thibodeaux 1989). Ficks second law, with an effective diffusivity that accounts for tortuosity of the diffusion path and other factors that affect diffusion, is an appropriate mathematical model. Because of the depth of the dredged material and the relatively flat surface, a semi-infinite solution to Ficks second law can be applied without serious error. (The semi-infinite solution is conservative; that is, flux is maximized). The instantaneous flux is given by

$$
n_{A,t} = \left[\frac{D_{A3}\left(E_1 = \frac{K_d \rho_B}{H}\right)}{\pi t} \right]^{1/2} \left[\frac{W_A H}{1{,}000 K_d} - \rho_{A1i} \right]
\tag{5}
$$

where

$n_{A,t}$ = instantaneous flux of A through dredged material-air interface at time t, mg A/cm^2/sec

D_{A3} = effective diffusivity, cm^2/sec

E_1 = air-filled porosity, dimensionless

ρ_B = bulk density of dredged material, kg/L

H = Henry's law constant, dimensionless

t = time since initial exposure, sec

ρ_{A1i} = background concentration in air at dredged material surface, usually assumed to be zero, mg/cm^3

The average flux over a given time t is given by

$$
\bar{n}_A = \frac{\int_0^t n_A \, dt}{\int_0^t dt}
\tag{6}
$$

It can be shown that

$$
\bar{n}_A = 2 n_{A,t}
\tag{7}
$$

Equation 7 is an idealized diffusion transport model that describes chemical movement in the unsaturated pore spaces near the surface of exposed

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dredged material. It does not account for the development of cracks as the dredged material dewaters by evaporative drying.

Effective diffusivity is a constant diffusion coefficient that characterized the movement of chemical A as a vapor within the porous solid. It is one parameter for which there is no information available. To calculate the flux, it is therefore necessary to estimate D_{A3} . As an approximation, tortuosity can be accounted for using the equation below (Thibodeaux 1987):

$$D_{A3} = \frac{D_{A1}\left[E_1^{10/3}\right]}{E^2}$$ (8)

where

D_{A1} = molecular diffusivity of chemical A in air, cm^2/sec
E = total porosity, dimensionless

Henry's law constant (H) applies for dilute solutions of chemicals in air and water. It is an equilibrium partition coefficient for chemical A between the air and water phase. Henry's law constant can be estimated using the equation below (Dilling 1977):

$$H = 16.04\left[\frac{P_A^o M_A}{T \rho_{A2}^*}\right]$$ (9)

where

P_A^o = vapor pressure of A as pure solute, mm Hg
T = temperature, deg K
ρ_{A2}^* = solubility of A in pure water, mg/L

The background concentration ρ_{A1i} in air has an analogous meaning to ρ_{A2}^{**} and is also assumed to be zero. This conservative assumption maximizes volatilization.

RESULTS

Table 1 shows the maximum annual simulated PCB loss for three contaminant transfer pathways. The data presented in the table represent loss of PCB occurring in the first year after disposal of the highest contaminated sediment. Table 2 shown the input parameters used to estimate PCB volatile losses. Estimated PCB volatilization losses from an upland cdf were considerably higher than estimated losses from an in-lake CDF, because over the filling life of the CDF, the exposed surface area in an in-lake CDF is much lower than for an upland CDF. During most of the filling, the dredged material is placed and remains submerged.

TABLE 1. ESTIMATED (WORST CASE) ANNUAL PCB LOSS (LB)

In-Lake CDF			Upland CDF		
Seepage*	Leachate**	Volatile	Seepage*	Leachate**	Volatile
0.0001	0.001	2	0.0001	0.001	8

 * Mass of PCB loss estimated through dike wall or CDF bottom.
** Mass of PCB loss estimated to be collected and treated as leachate.

INTERPRETATION OF RESULTS

The results indicate that volatilization of VOCs is a significant con-taminant transfer pathway. Also, PCB mass flux is less when the sediments are maintained in a submerged state because of the hydrophobic nature of PCBs. The flux is highly dependent on two factors--the exposure time of the sedi-ments and the surface area of the sediments. The exposure time for submerged sediments encompasses the entire time a pond is in contact with PCB-contami-nated sediments. However, the rate of volatilization is directly related to the concentration of PCBs varies over time with the highest rate during an active filling operation. The surface area is that area of the pond which is in direct contact with the air and is dependent on the volume of dredged mate-rial being placed and the volume of material already placed within the CDF.

The exposure time for exposed sediments encompasses the time in which unsaturated sediments are in direct contact with the air, while the surface area is that area which is in direct contact at any given time.

Laboratory analysis has recently been completed by WES on New Bedford Harbor sediments in order to determine the volatile emission rates of PCBs from freshly placed drying sediments.* This experiment was conducted under laminar conditions, excluding the effects of wind. Laminar flow represents an overall simplified condition but does support the analyses presented in this note.

In summary, the approach taken in model formulation was conservative in nature in hat it simulated a worst-case scenario. For instance, the exposed sediments were assumed to be completely void of vegetation throughout the life of the CDF. However, from past experience a vegetative cover will form over the exposed sediments over time. No quantitative theory predicts the effects of vegetation on flux, but it is anticipated that the vegetation cover should reduce the flux rate. Also, the surface area of exposed sediments was simu-lated as a layer covering the entire cell (only for upland CDFs). Realisti-cally, the deposited sediments would flow outward, but probably not far enough to cover the entire cell of an upland CDF. Finally, the suspended and dis-solved solids concentrations in the ponded areas were based on conservative

* Environmental Laboratory. 1989 (April). "Laboratory Assessment of Vola-tilization from New Bedford Harbor Sediment," Memorandum, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

TABLE 2.   INPUT PARAMETERS FOR PCB VOLATILIZATION MODELS

Parameter	Description	Value
	Assumed Values	
K_d	Sediment·water distribution coefficient	256,000 L/kg
W_A	PCB sediment concentration	
	1. Backlog sediment (zone 1)	38 mg/kg
	2. Backlog sediment (zone 2)	6 mg/kg
	3. Long-term maintenance sediment	2 mg/kg
ρ_{32}	Suspended solids concentration	
	1. Within 1C0-ft radius of disposal	100 mg/L
	2. Away from disposal area	10-50 mg/L
ρ_{A2}	Dissolved PCB concentration	5-60 mg/L
M_A	Composite molecular weight of PCB	300
ρ_B	Bulk density of sediment	1.2 mg/kg
D_{A2}	Molecular diffusivity of PCB in water	4.2-06 cm^2/sec
D_{A1}	Molecular diffusivity of PCB in air	0.049 cm^2/sec
P_A^o	Vapor pressure of PCB are pure solute	4.94-04 mm Hg*
ρ_{A2}^*	Solubility of PCB in pure water	0.054 mg/L*
E	Total porosity	0.70
E_1	Air-filled porosity	0.30
V_x	Mean wind velocity	8-12 mph
	Calculated Values	
$^1K_{A2}'$	Mean overall liquid phase mass transfer coefficient	0.78 cm/hr
D_{A3}	Mean effective diffusitity	1.63-03 cm^2/sec
H	Mean Henry's law constant	0.156

* Value used for Aroclor 1248.

estimates. For the reasons stated above, the actual PCB mass flux from a CDF could be substantially lower than what is predicted by the model simulation.

CONCLUSIONS

Theoretical models must be tested against and adjusted to both laboratory and field data prior to their acceptance and widespread use as predictive tools. Preliminary model calculations can be made for the submerged sediment locale and the exposed sediment locale void of vegetation. However, some aspects are based on very simple equations, and further development is needed. Laboratory and field testing must be performed to build a higher degree of confidence in the predictive capability of the PCB volatilization models. A substantial amount of work in laboratory/field testing and verification needs to be completed before any conclusive results can be made on PCB flux simulation from an active CDF.

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SEA BLUE PLAN: A CASE STUDY ON PORT OF AMAGASAKI-NISHINOMIYA-ASHIYA

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ABSTRACT

A case study of the SEA BLUE PLAN was held in the canal area of Amagasaki, Prot of Amagasaki-Nishinomiya-Ashiya. Recently, industrial factories are retreating from the reclaimed area of the canal area of Amagasaki leaving the land unused. Meanwhile, citizens desires a pleasant environment in the water-front area. In response to the request, the utilization of the waterfront for leisure and relaxation not just transportation and industry was considered. We proposed six measures for environmental improvement: 1. Dilution and diffusion by river water conveyance. 2. Dilution and diffusion by sea water conveyance. 3. Water purification by porous bed contact purification method. 4. Water purification by living filter. 5. Dredging and sand-capping. 6. Retrieval of floating garbage. By using these measures with some creative ideas, the water and sediment quality in the canal area will be improved and further, a pleasant coastal environment will be realized in Amagasaki canal area.

BACKGROUND OF STARTING CASE STUDY

The Port of Amagasaki-Nishinomiya-Ashiya had been threatened by storm surges and ocean waves caused by typhoons since the port is located at the innermost part of the Osaka Bay. Under these circumstances, Amagasaki Lock was built in 1955 because of typhoon Jane which struck in 1950. Since then, the lock has been playing a very important role of protecting the citizens from disasters and in harbor facility activities which support the industrial city of Amagasaki.

On the other hand, the lock has shut off the seawater flows into the Amagasaki canal area located in the inner side of the lock. The water and seabed of the area became contaminated because of the wastewater from homes and factories which flows into the area causing environmental problems to the adjacent areas.

To solve this problem, dredging of the canal was started to purify the water, but not enough was done to improve environmental contamination of the

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surrounding areas. Some measures are still needed for environmental improvement.

In adjacent areas of the canal area, a couple of projects have been commenced, such as the Phoenix Project and the coastal road construction work. Amagasaki Lock also is under improvement and for completion in 1995. Besides that, Amagasaki City is planning the redevelopment of the southern coastal area of the city for the 21st century. Thus, steps to solve environmental problems and promote development are on the discussion table.

For these reasons, the central government, Hyogo Prefecture, and Amagasaki City jointly conducted a survey to study the present state of the environment, canal utilization, and surrounding areas. In this study, they considered utilization methods, facilities, and project methods which fit the characteristics of the area. This survey on the active use of the canal waterways identified specific methods to make the area pleasant and appealing for the citizens and the users of harbor facilities.

On the other hand, the government and Hyogo Prefecture jointly carried out the Sea Blue Technology Survey on how to purify the canal water in respect to technical methods, suitably for surrounding areas, facilities, and project methods. A part of the study applied, and its result shall be reported in the following pages.

PROCEDURE OF CASE STUDY

The survey for the Sea Blue Plan was carried out with the following procedure taking the existing major plan and related plans in the canal area into consideration.

Comprehension of the Present
Situation of the Canal Area in Question

By surveying the site or by perusing literature, the condition of the natural environment such as marine phenomenon, quality of water and sediments, and the social environment was confirmed. The relevant plans in action were also reviewed by checking existing materials and data.

Organizing and Identifying
Problems of the Present Situation

The needs of the area in question need to be grasped by comparing them with the reality of the present environment. Thus, the problems can be sorted out and identified.

Reviewing of Basic Concept

Setting of the aim to be accomplished for environmental improvement and its utilization consider the conformity with the existing major plan and related plans. Then, the purification methods to apply to this plan will be discussed.

The aim to be accomplished should be one which is easily understood by the average citizen. Basically, the words used in the plan should appeal to the five human senses in stages of touching, viewing, and so forth. In the

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quantitative evaluation of purification results, of course, environmental indices such as COD, SS, etc., are to be used; however, such technical terms should be transplanted into simple daily words corresponding to the five senses.

Reviewing of Basic Plan

In accordance with the basic concept. the detail of the facilities including the layout will be presented. Furthermore, the budget for execution and probable effect of the environmental improvement will be discussed.

Problems to be Settled
Before Implementation

Sorting out and identifying problems were necessary for the accomplishment of the plan.

CASE STUDY ON PORT OF AMAGASAKI-NISHINOMIYA-ASHIYA

Comprehension of the Present
Situation of the Canal Area in Question

Topography and History of
the City as an Industrial City

Amagasaki City of Hyogo Prefecture is located at the innermost end of Osaka Bay, in the central part of Japan (Figure 1). Its area is approximately 50 km^2 and the population is approximately 500,000. It is commercial and industrial city. Its eastern border is shared with Osaka City, the second biggest city of Japan. Amagasaki City, situated on the alluvium deposits carried down by the river, has many lowlands and the highest part of the city is merely 20 m above sea level. Land of 0 m above sea level occupies one-third of the city.

Amagasaki City made its start as a modern industrial city after the Amagasaki Spinning Factory began operation in 1891. Following the Russo-Japanese War (1904-05), glass and steel related factories started operation, thus turning Amagasaki into a base for heavy-chemical industries. After World War II, it became the center of the Hanshin Industrial Area during the rapid economic growth of Japan which started around 1955. Because of this reason, the coastal areas of the city became exclusively industrial areas. However, current changes of industrial structure in Japan have made smokestack industries such as steel and chemicals retreat from the city. Thus, utilization of former industrial land had to be discussed.

From around 1931, reclamation of the coastal areas was carried out in step with the rapid growth as an industrial city at that time. In these reclaimed areas in the southern part of the city. navigational canals run vertically and horizontally (Figure 2).

Present Situation of Canal Area

These canals still operate for the transportation of materials, while most of the waterways in Japan lost their essential functions. In addition,
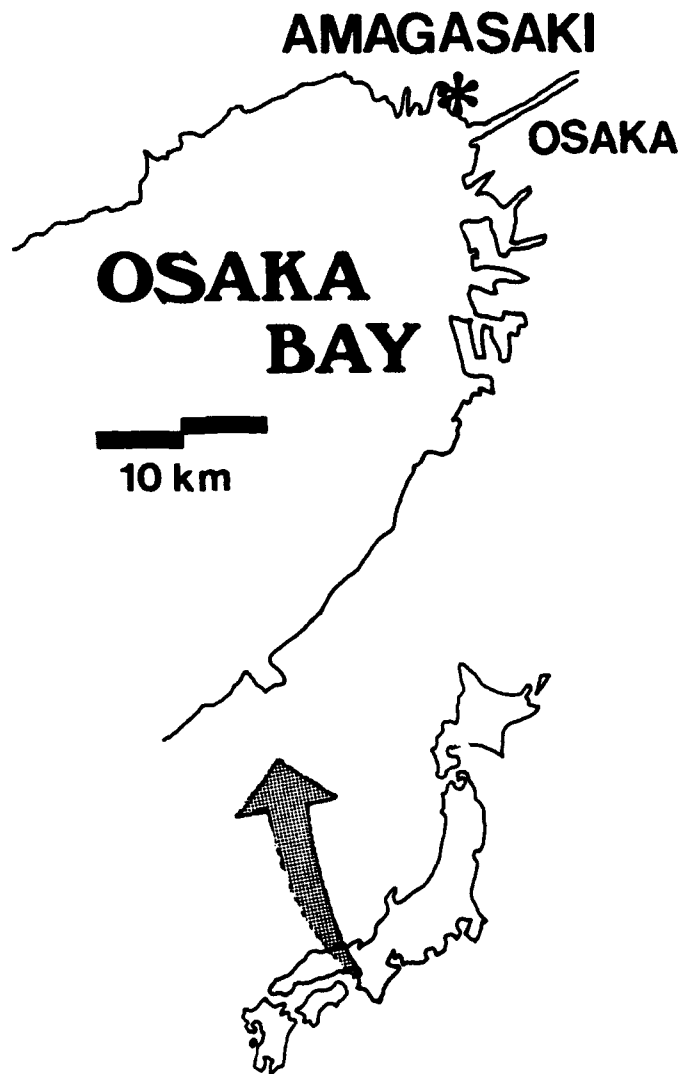
Figure 1. Location of Amagasaki City

they function as disaster prevention facilities, i.e., as retarding basins to store water during heavy rains.

The lock and gates were made at the border line between the canal and the sea in order to maintain a fixed sea level for navigation and also to prevent whole city from being flooded. Water in the canals stays still except when the water level is lower than OP + 0.60 m or higher than 1.35 m. Consequently, there is no flow-in and flow-out of water most of the time. Partially because of the above fact and also to the flow-in of turbid water from the upstream area of the river, contamination of the canal water is proceeding rapidly.
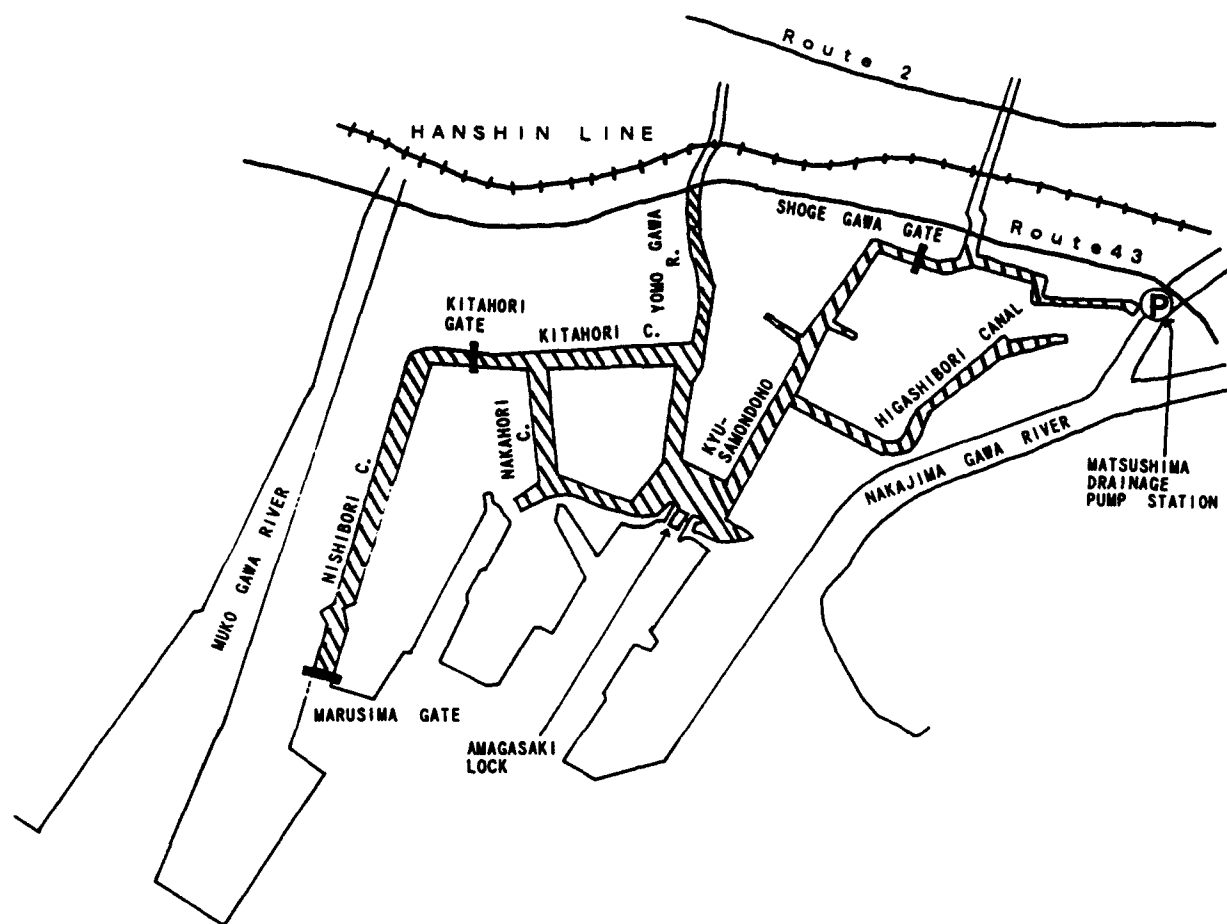
Figure 2. Canal area in Amagasaki

Organizing and Identifying the
Problems of the Present Situation

New Forms of Utili-
zation for the Canal Area

As described previously, industrial factories are retreating from the reclaimed area of the canal leaving the land unused. Meanwhile, citizens dc:ires a pleasant environmental in the waterfront areas. In response to the request, the utilization of the waterfront for leisure and relaxation, not for just transportation and industry, was considered. With this background, reutilization of the Amagasaki canal area came to the table for discussion.

Several bodies such as Hyogo Prefecture, Amagasaki City, and the prot management body have made reutilization plans for the canal area and/or the waterfront. As of 1990, there are five such related plans. The Sea Blue Plan shall be reviewed so it does not conflict with these plans. The five plans deal basically with the following: (a) upgrading prot facilities, (b) activating the canal area, (c) setting up a desirable waterfront environment, (d) activating industry in the reclaimed area, and (e) locating waste disposal for the surrounding area. The characteristics common to all these plans is that

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one of the functions of the canal and harbor area would be the provision of a pleasant environment for sue by the people in the area.

Present Problems
and Future Challenges

However, to realize the utilization of the waterfront as a leisure place, many problems still remain to be solved. Such problems are the purification of water and sediments, its function as hydrophilic space, coexistence with industrial facilities, linkage with other plans, its function as a disaster prevention facility, and regulations or laws which hamper the realization of the plan.

The contamination of the water in the canal, checked with indices of dissolved oxygen (DO), biological oxygen demand (BOD), sulfide density, suspended solids (SS), color of water, and pollutant sedimentations, has progressed and is especially serious at the river mouth. The main cause of the contamination of water is the flow-in of polluted water from rivers, and the closed environment of the canals makes the situation worse. Flow-in water from the river is expected to be reduces when the sewage improvement project is completed in 1992. However, this project will not be taken into consideration in the Sea Blue Plan; in other words, the pollutant load from the rivers will be assumed.

On the other hand, purification of water can be done by making good use of differences in tidal level, but this method is impossible since the difference is merely 10 cm. If this method is chosen, electric-powered pumps should be adopted for moving canal water.

In order to make the canal, which had been used for industrial facility activities, a leisure place, problems still remain unsolved, such as the layout and shapes of existing structures and inaccessibility. Another problem is that no green exists on the southern reclaimed land.

The canal, at the same time, should keep its original function as an industrial facility. Conjunction between industrial facilities and leisure place is the important matter in this plan. However, contradictions will arise, if citizens can easily access the canal, since loading work at the area will be frequently disturbed. Even though new structures will be built for leisure purposes, it may not always be convenient for industrial use. At present, this area is restricted for only industrial use so that structures for leisure would also be restricted to some extent.

The canal area will have to fulfill the three functions of industry, disaster prevention, and leisure place. The water drainage pump station and lock which have been discharging excess water in the canal after a typhoon or heavy rain should be maintained. The lock has been the only facility exchanging the water in and out of the canal, and this exchange should continue. Basically, the canal will still remain as a closed water area like it is now.

Reviewing of Basic Concept

Based on the previously described conditions, the method of how to develop the canal area into a pleasant coastal environment will be explained herein.

According to the flowchart on Figure 3, first, targets for improving water and sediment environment (indicated by the five human senses) are set. Second, the canal area is divided into zones for the creation of a pleasant environment. third, measures on how to improve the water and sediment environment are established, and lastly more specific measures to create a pleasant are established. In any of the measures taken, the existing functions of the canal will not be distributed.

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┌─────────────────────────────┐
│ Setting targets for improving│
│ water & sediment environment │
└─────────────────────────────┘
                ↓
┌─────────────────────────────┐
│    Zoning of the canal area  │
└─────────────────────────────┘
                ↓
┌─────────────────────────────┐
│    Establishing measures to  │
│    improve water & sediment  │
│         environment          │
└─────────────────────────────┘
                ↓
┌─────────────────────────────┐
│    Establishing measures to  │
│    create a pleasant coastal │
│         environment          │
└─────────────────────────────┘
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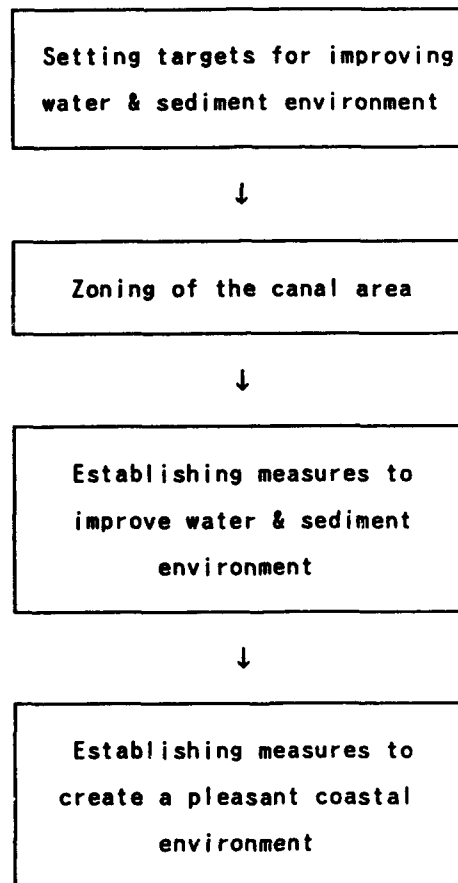
Figure 3.   Flowchart for
            review of basic
            concept

Zoning of the Canal Area for a Pleasant Coastal Environment

In order to create a pleasant coastal environment which is full of diversity, the area will be divided into four areas (Figure 4, Table 1). As for zoning, the zones in the existing major plan were referred.

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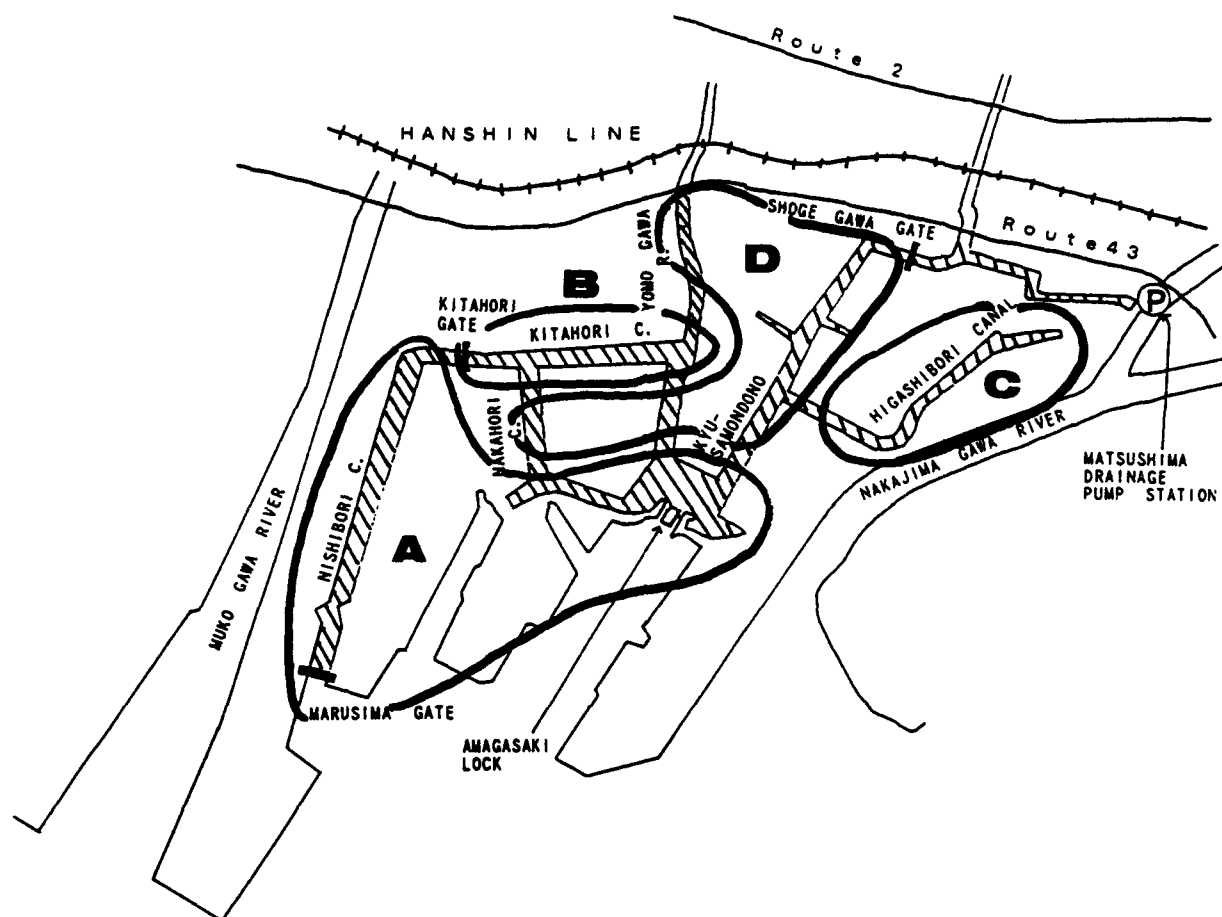
Figure 4. Zoning of the canal area for a pleasant coastal environment

TABLE 1. TARGET OF IMPROVEMENT OF EACH ZONE
AS A PLEASANT COASTAL ENVIRONMENT

ZONE	CANALS INCLUDED	TARGETS OF IMPROVEMENT
A	Nishihori Canal Ogimachi Canal Lock	viewing level
B	Kitahori Canal	touching level
C	Higashihori Canal	touching level
D	Yomo-gawa River Nakahori Canal Kyu-Samondono-gawa River	viewing level

Target of Water and
Sediments Environment Improvement

The target of the improvement shall be at the level suitable for touching and viewing, although that level will differ depending on the zone. COD will be adopted for checking the purification degree of the touching level of water. According to the report of the Ministry of Construction, water quality suitable for playing at the beach is below COD 5 mg/l. Thus, water in the canal shall be purified to this level. From the correlation between COD and transparency, COD is 8 mg/l when the transparency is approximately 1 m. The transparency of water in the canal area is almost the same as this figure, and it means no further improvement is needed in respect to transparency. Rather, the amount of floating garbage is adopted as the criterion for the pleasant viewing level.

Thus, the target of improvement for viewing and touching, respectively, is to lower COD to below 5 mg/l and to reduce floating garbages.

Ideas for Water and Sediment
Environment Improvement and the
Creation of a Pleasant Coastal Environment

In general, there are various methods for water and sediment environment improvement. However, based on the characteristics of the Amagasaki canal area as previously described, the following six methods should be adopted in this plan. Merits and demerits of these methods will be explained herein.

One of the principal ideas of the Sea Blue Plan is not only water and sediment environment improvement but also the addition of functions other than the essential aim, e.g., some way for citizens to enjoy their life in the pleasant coastal environment. As for the Amagasaki canal area, the following points shall be deliberated in the realization of the plan:

a. Recreate a natural waterside.

b. Adopt the natural movement of water.

c. Add artificial water structure in some places.

d. Create an ideal environment in which such species as water plants and animals can live.

The following six ideas to improve water and sediment environment are proposed:

a. River water conveyance.

(1) On the eastern and western sides of the canal area, there exist Nakajima-gawa and Muko Gawa Rivers, respectively. Water of both rivers is rather clean, so water from these rivers shall be taken into the canal area for improvement of canal water through dilution or diffusion. Effective improvement could be anticipated by this method, but the work of laying the pipeline will be rather difficult. Furthermore, the cost of operating pumps will be high if the pipeline covers long distance.

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(2) Meanwhile, man-made streams shall be made along the canal area for creating a pleasant coastal environment, and water taken from the river will be used there. Fountains and waterfalls can be made by utilizing the powerful force of water from the outlet. Illumination can also be adopted for producing a marvelous effect at night.

(3) Utilization of water as previously described is not only producing a pleasant coastal environment but also purifying water by supplying atmospheric oxygen to water since the time in which water comes into contact with atmospheric air is prolonged.

b. Sea water conveyance. Effective purification could be anticipated by taking in seawater with the successive operation of the lock and gates in the canal area. this method of water conveyance will contribute to the creation of a pleasant coastal environment.

c. Porous bed channel.

(1) In the porous bed contact purification method, the biofilm which forms on the surface of gravel will purify seawater when water passes through the gravel.

(2) This method has been put in practice in sewage and river water but never applied at seawater in Japan. The purification facilities become large scale; however, the facilities can be constructed underground, allowing the open space at the surface to be used for multiple purposes. the facilities can also be built into various marine and harbor structures, enabling them to have the additional function of purifying seawater. In any case, some problems still remain unsolved because this method has the defect of clogging up sludge in the channel.

(3) The facility is large in size so that the best way for constructing it shall be underground of an open space in order to use the surface for a park of some other purpose. One way to use the purified water could be to channel it into a man-made stream.

d. Living filter.

(1) The improvement method in which water plants, seagrasses, and seaweed are being used is called a "living filter." This method can take out nutrient salts but not without much difficulty. In respect to improvement, this method is not so highly evaluated since a large area for planting water plants is needed for effective improvement. Besides, there still remains the problem of clearing the withered water plants. The characteristic of this method is to provide us with beautiful scenery and a pleasant environment for birds and other animals.

(2) Here the purification of water is secondary. Rather, the beauty of natural plants can be enjoyed. Also, the effect of

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attracting wild birds and other animals and producing a play area true to nature should be evaluated.

(3) This method plays an important role for human beings rather than prominent improvement, as these water plants offer us spiritual fulfillment by merely growing there. There is also expectation that some new ecology of water plants could be born. It is recommendable to plant them in the man-made stream into which improved water will flow in.

e. Dredging and sand-capping. These methods are very basic or standard ones so that they are the most positive ways for sediments improvement. A large amount of 'hedoro' (polluted sediment) had accumulated at the dead-end part of the canal area. These methods are very effective especially for this kind of area. It is also possible to create new habitats for living creatures through the application of sand-capping materials and methods. A continuous dredging or sand-capping will be required to sustain the improvement effect. If the canal is changed to a habitat of living creatures, citizens who utilize the area and its pleasant coastal space will be comforted.

f. Retrieval of floating garbages. The retrieval of floating garbages is the first thing to be tackles considering the canal area's external appearance. This method is also quickest way for the improvement of the canal. Movable equipment should be used because the accumulation areas of garbage are not always the same. A barge which is equipped with a garbage collecting system is recommendable. The color or shape of the barge should be carefully deliberated so as not to give ill feeling to the citizens who would be enjoying the pleasant coastal atmosphere.

Reviewing of the Basic Plan

The outline of water and sediments improvement plan and conditional values of application are described below.

a. River water conveyance.

(1) Clean river water (COD ca. 3.3 mg/l) will be taken into Zone B (Kitahori Canal) from the Muko-gawa River, which runs through the western side of the canal area, for diluting the turbid water of Zone-B (Figure 5).

(2) It is assumed that the length of pipeline form the water in-take point of Muko-gawa River to the outlet at Kitahori Canal is 930 m, and the quantity of water conveyed is Q = 6.0 m^3/sec. The capacity of the water supplying pump (S) can be calculated by the following formula:

$$S = 9.8 \times Q \times H/n$$

where
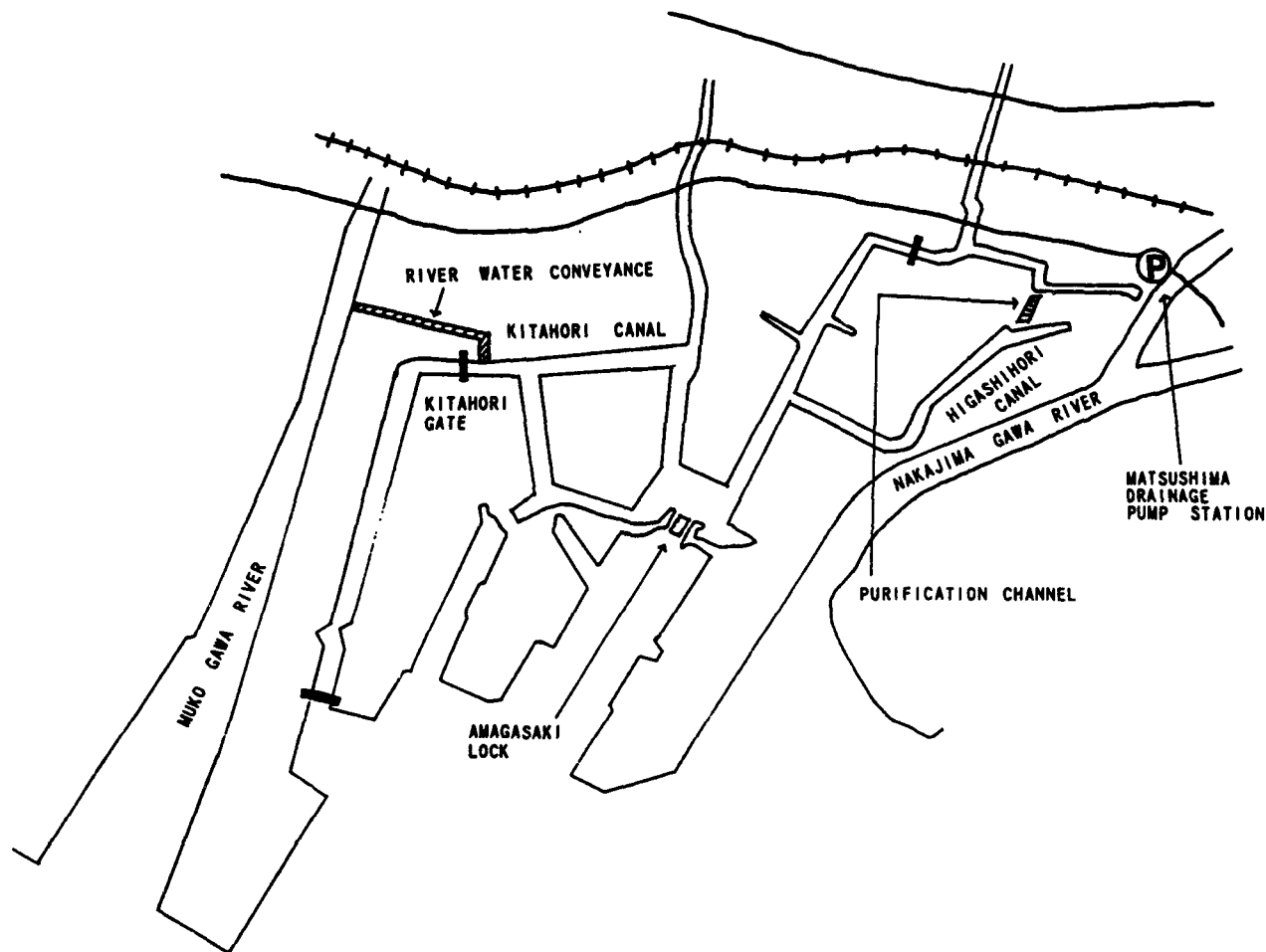
Figure 5. Arrangement of the purification facilities

$$S = \text{capacity of pump}$$
$$Q = \text{rate of discharging}$$
$$H = \text{head loss}$$
$$n = \text{efficiency}$$

then

$$S = 9.8 \times 6.0 \times 12/0.8 = 882$$

Thus, one = 900 kw pump shall be used.

b. **Sea water conveyance.**

(1) Two methods could be considered for seawater conveyance. One of them is to operate the existing lock, gates, and drainage pump station. The other one is the installation of a new pump for water conveyance. In applying the former method. some steps should be taken so as not to allow polluted water from Shoge-gawa River to come into the canal.

(2) As for water conveyance, seawater should be taken in from Kita-hori Gate and should be drained out through the fate by operating the gate and the lock adjusting in accordance with the sea level or water level of the river. To avoid the flow-in of polluted water from Shoge-gawa River, at first the fate of Shoge-gawa River should be closed, then turbid water should be discharged into the Kyu-Samondono-gawa River from Matsushima Drainage Pump Station. Finally, the fate of Shoge-gawa River should be opened to let cleaner water of the canal flow into Shoge-gawa River (Figure 6). Successive operation of these facilities should be carried out three times a week considering the problems of pumping operation and maintenance. That is, full-time operation of the pump is impossible due to the following reasons: (a) the capacity of the pump is too large (15 m^3/sec) to be used for drainage; and (b) operation of the pump is very complicated since a diesel engine is incorporated.

(3) As for the latter method, an exclusive pump (electric-powered 6 m^3/sec) for drainage should be installed at a place close to the Matsushima Drainage Pump Station to ensure full-time operation of pumping. A man-made current should be created for changing the water in the canal by taking in seawater form the Marushima Gate, Kitahori Gate, and also through the lock.

c. **Porous bed channel.**

(1) The porous bed channel was constructed on public lands linking the downstream portion of Shoge-gawa River with the Higashihoro Canal (Figures 5 and 7). The object is purification of water from the Shoge-gawa River; the purified water will then be used for replacing the water in the Higashihori Canal.

(2) The size of the canal is 2 m in depth, 20 m in width, and 100 m in length; 0.18 m^3/sec of turbid water will be purified by placing gravels with a diameter of 100-150 mm (coefficient of permeability is 100 cm/sec, and percentage of void is 35). The retention time of running water in the channel is two hours (flow velocity is 1.4 cm/sec). The channel is divided into four blocks. The length of each block is 25 m. A trench runs through the center of the bottom of the channel to receive sludge accumulated on gravels. The purified water will be temporarily stored in a tank built at downstream of the channel, then will be delivered to the edge of Higashihori Canal by the pump at the edge of the channel (Figure 8).

(3) The disposal of sludge should be taken into account because sludge always remains in the porous bed channel. The sludge will accumulate in the trenches which run along the center of the channel. Sludge should be disposed by underwater pumps three or four times a year. A backwash pipe is also installed, to clear clogging by sludge in the gravel beds.

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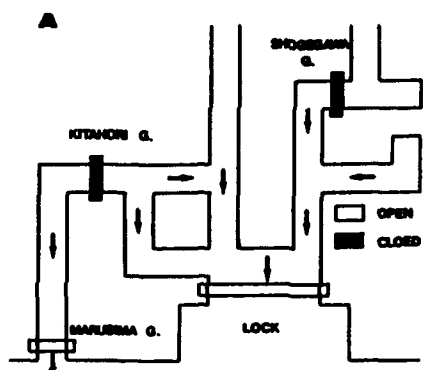
Note: Sea level in the port below
OP + 1.35 m (ebb tide).

B
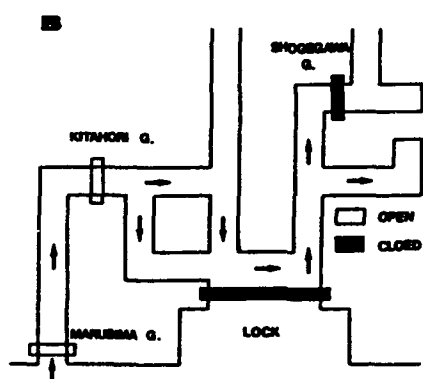
Note: Sea level in the port below
OP + 1.35 m (duration of
rise).

C
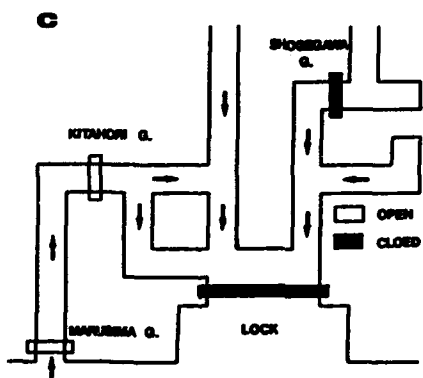
Note: Sea level in the port
OP + 1.35 m.

Figure 6. Water movement in the canal area by the seawater conveyance
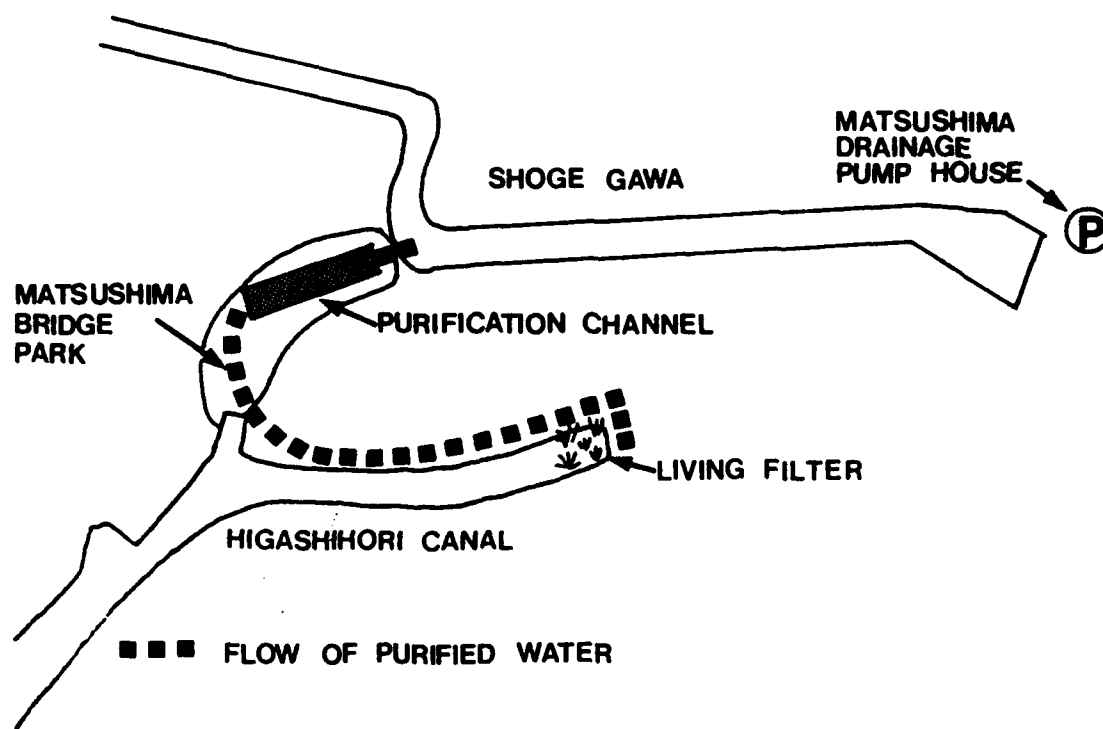
Figure 7.   Construction site of the channel type of purification facility

(4) The removal efficiency of COD and SS applied for this facility
is assumed to be the same figures as the examples of the river
water (30 percent for COD, 80-90 percent for SS), as no actual
data were obtained for seawater. Therefore, an experiment for
collecting such data is needed in the near future.

d. **Living filter.** Water plants such as reeds shall be planted in the
purified water drainage area at the far end of Higashihori Canal.

e. **Dredging and sand-capping.** In the Amagasaki canal area, COD and
sulfides are down to sediment depths of 2 to 3 m. However, dredging
up such sediments is impossible in the canal area due to fear that
the stability of both sides of revetments will collapse. The only
solution is sand-capping. Originally, the purpose of sand-capping
was to prevent the solution of sludge, but recently, its role as
habitat for living creatures has been examined. The thickness of
sand-capping for the purpose of sludge solution prevention is
roughly 30-50 cm. If sand-capping is carried out to promote the
habitation of living creatures, the thickness of sand-capping should
be determined after studying the life history of organisms con-
cerned. For instance, the well-known goby (_Acanthogobius flavi-
manus_) is known to dig 1.5 m holes in the seabed.

f. **Retrieval of floating garbage.** A movable barge equipped with gar-
bage retrieval facilities shall be used considering construction
cost, workability, and suitability to the circumstances (Figure 9).
The size of the barge shall be 8 m wide and 4 m long. Water enters

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平面図　S=1/300

縦断面図　　横：S=1/300
　　　　　　縦：S=1/100

C--C 断面　　B--B 断面　　A--A 断面

D--D 断面

横断面図　S=1/100

E--E 断面
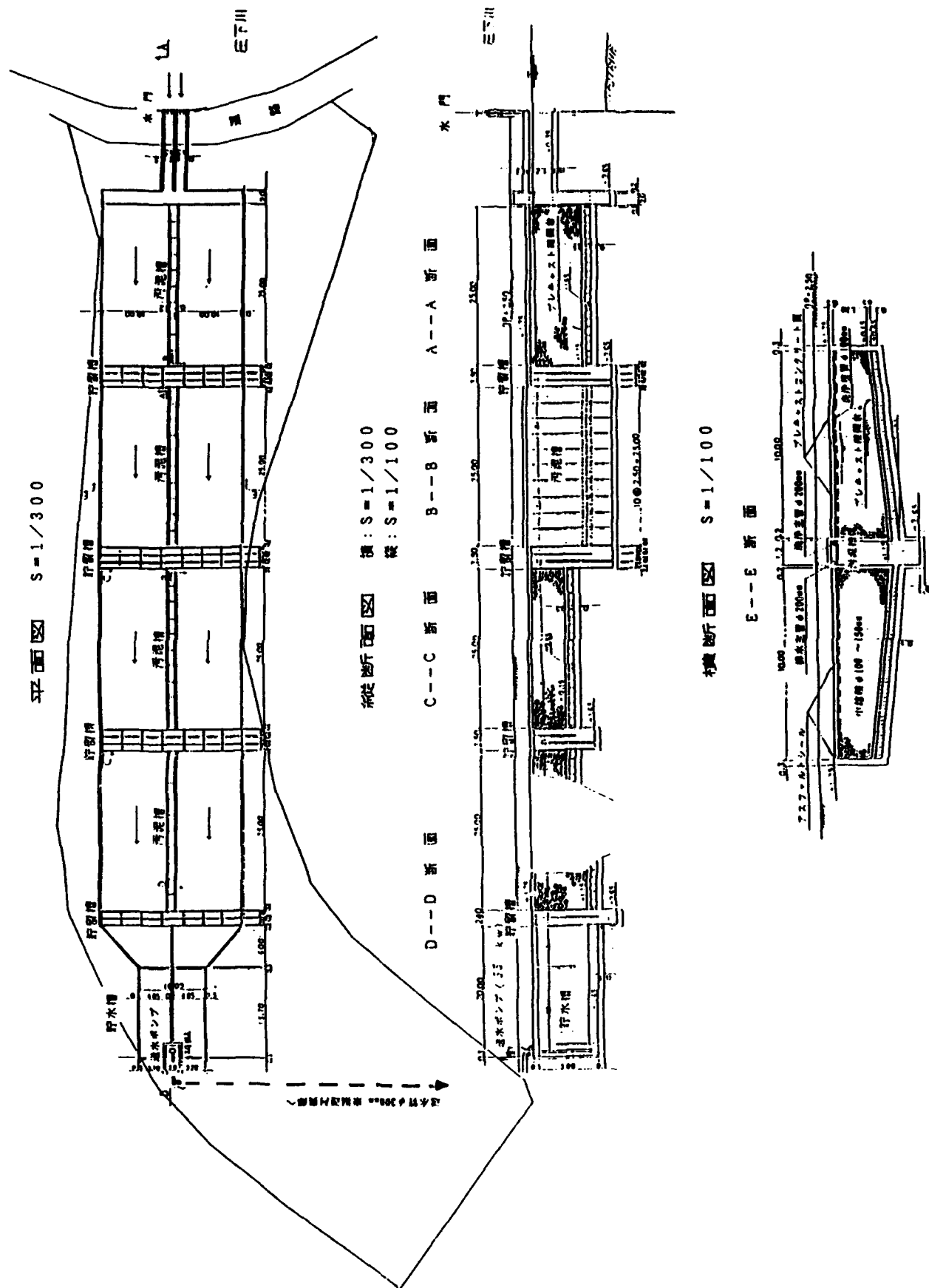
Figure 8.　A ground plan of the channel type of purification facility

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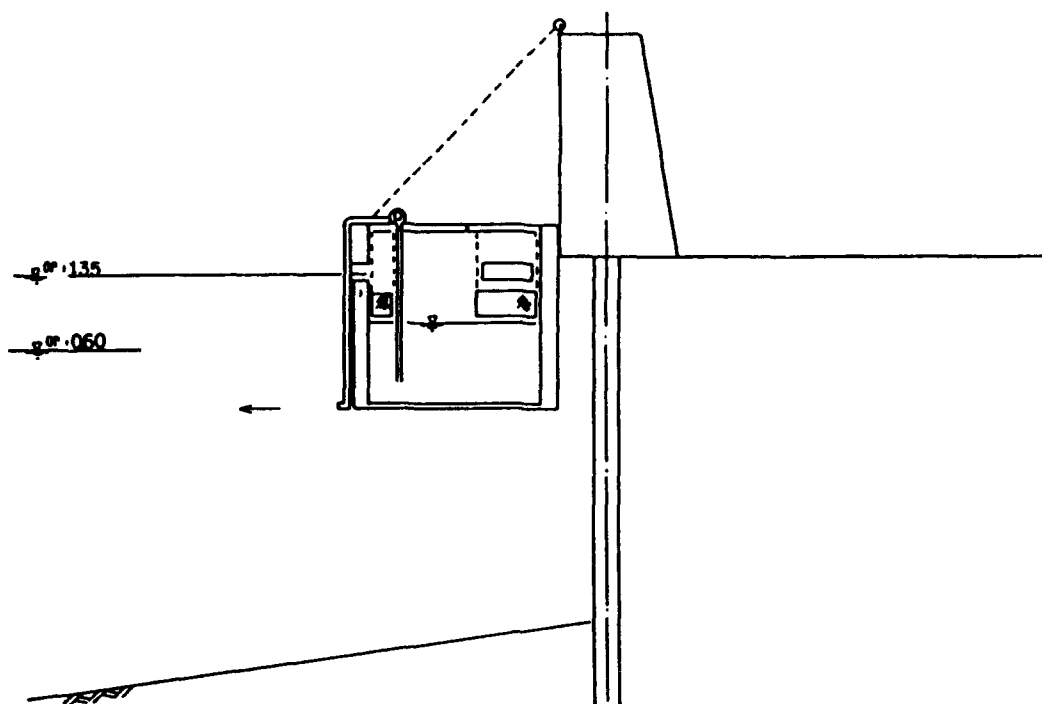
Figure 9. A ground plan of the barge for retrieval of
          floating garbage

a slit in the barge and the garbage on the surface is trapped in a
cage inside the barge while the water flows out into the sea. The
suitable locations for setting the barge are the western side of the
Kitahori Gate, the western side of the lock, the easternmost end of
the lock, and the Higashihori Canal.

Forecast on Water and
Sediment Improvement Effects

The first condition in the calculation was the assumption that COD in
the future will be the same as the present. Although the BOD of the river
water will be greatly reduced after the sewerage improvement works are com-
pleted, the COD will not show as clear a trend of reduction as BOD. The solu-
tion rate from sediment was assumed to be 4.5 mg/m^2/day from the fact that the
amount of COD in the sand-capping material is 0.6 mg/l. The solution rate in
the future after the dredging of the Yomo-gawa River was deemed to be
1,020 mg/m^2/day using the COD content of 136 mg/g in 1-2 m of sediment in the
Yomo-gawa River.

The simulation were carried out to six cases and shown below. Among the
six cases suggested, four methods are combined with the scheduled sewerage
improvement works.

CASE	COMBINATION
CASE 1	Sewerage improvement (under planning)
CASE 2	Sewerage improvement and sand-capping for whole area
CASE 3	Sewerage importance and Muko-gawa River water conveyance
CASE 4	Sewerage improvement and porous bed channel
CASE 5	Sewerage improvement and drainage at Matsushima Drainage Pump House
CASE 6	Sewerage improvement and all four methods

Water purification effect in COD is shown in Table 2. According to the effect forecasting calculation, no further improvement can be expected, when only the sewerage improvement work is completed (CASE 1). Consequently, the methods proposed in this report should be adopted for effective improvement in addition to the sewerage improvement.

TABLE 2. EFFECT ON COD IMPROVEMENT BY THE FORECASTING CALCULATION

(mg/ℓ)

	PRESENT		CASE 1	CASE 2	CASE 3	CASE 4	CASE 5	CASE 6
	OBSERVED	CALC.	1	2	3	4	5	6
a. Shoge-gawa River Shoge R. Bridge	8.5 (4.8 ~ 13.0)	8.6	8.4 (-0.2)	7.3 (-1.3)	8.4 (-0.2)	8.4 (-0.2)	6.7 (-1.9)	5.7 (-3.1)
b. Yomo-gawa River Nakasu Bridge	5.5 (3.9 ~ 7.9)	6.7	6.2 (-0.5)	4.9 (-1.8)	4.6 (-2.1)	6.2 (-0.5)	5.8 (-0.5)	4.0 (-2.7)
c. Lock	6.1 (4.6 ~ 7.7)	5.8	4.9 (-0.3)	4.5 (-1.2)	5.7 (-1.6)	5.0 (-0.4)	4.0 (-1.1)	(-2.1)
d. Nishihori Canal Nishihori Bridge	(2.9 ~ 5.4)	5.0	4.9 (-0.1)	4.9 (-0.1)	4.2 (-0.8)	4.9 (-0.1)	4.6 (-0.4)	3.9 (-1.1)
e. Higashihori Canal Tsukiji-Marushima-machi	——	7.9	7.8 (-0.1)	5.7 (-2.2)	7.4 (-0.5)	7.5 (-0.4)	7.3 (-0.6)	5.0 (-2.9)
Whole Area	——	6.7	6.5 (-0.2)	5.5 (-1.2)	5.8 (-0.9)	6.5 (-0.2)	5.6 (-1.1)	4.4 (-2.3)

Note: Maximum and minimum values are in the parentheses in the column 'observed'. The values in other parentheses show the improvement effect.

The water inflow from Shoge-gawa River should be discharged from Matsu-shima Drainage Pump Station into Kyu-Samondono-gawa-River outside the canal (CASE 5). Then, it is possible to reduce 1.9 mg/l of turbid water and even

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reach to 6.7 mg/l. Besides, sand-capping for the whole area of the canal is also effective. This method can reduce by 1.3 mg/l to 7.3 mg/l. Other methods than the above mentioned are not so effective for purifying the waters from Shoge-gawa River.

As for Yomo-gawa River, the other source of water inflow, taking water in from Muko-gawa River will be effective (CASE 3). This method can reduce by 2.1 mg/l to 4.5 mg/l. The sand-capping for whole area will be also effective. By combining these two methods, Kitahori Canal of Zone-B and Yomo-gawa River of Zone-D will be improved.

For improvement of Zone-A (c,d) water intake from the Muko-gawa River is effective (CASE 3). This method can reduce COD by 1.6 mg/l at the lock and by 0.8 mg/l at Nishihori Canal. Sand-capping (CASE 2) and drainage at the pump station are also effective.

At Higashihori Canal of Zone-C, sand-capping for the whole area is prominently effective (CASE 2). This method can reduce COD by 2.2 mg/l, to 5.7 mg/l. Water intake from Muko-gawa River (CASE 3), porous bed channel (CASE 4), and drainage at the pump station (CASE 5) are also more effective than relying only upon sewerage improvement.

Table 3 shows transparency, which is another index of improvement. The transparency is calculated by the following formula based on the correlation between transparency and COD:

TABLE 3. EFFECT ON SS IMPROVEMENT BY THE FORECASTING CALCULATION

(mg/ℓ)

	PRESENT CALCULATED VALUE	CASE 1	CASE 2	CASE 3	CASE 4	CASE 5	CASE 6
a. Shoge-gawa River Shoge R. Bridge	0.9	0.9 (±0.0)	1.0 (+0.1)	0.9 (±0.0)	0.9 (±0.0)	1.1 (+0.2)	1.2 (+0.3)
b. Yomo-gawa River Nakasu Bridge	1.1	1.2 (+0.1)	1.4 (+0.3)	1.4 (+0.3)	1.2 (+0.1)	1.2 (+0.1)	1.6 (+0.5)
c. Lock	1.2	1.2 (±0.0)	1.4 (+0.2)	1.4 (+0.2)	1.2 (±0.0)	1.3 (+0.1)	1.6 (+0.4)
d. Nishihori Canal Nishihori Bridge	1.3	1.4 (+0.1)	1.4 (+0.1)	1.5 (+0.2)	1.4 (+0.1)	1.4 (+0.1)	1.6 (+0.3)
e. Higashihori Canal Tsukiji-Marushima-machi	1.0	1.0 (±0.0)	1.2 (+0.2)	1.0 (±0.0)	1.0 (±0.0)	1.0 (±0.0)	1.0 (+0.3)
Whole Area	1.1	1.1 (±0.0)	1.3 (+0.2)	1.2 (+0.1)	1.1 (±0.0)	1.2 (+0.1)	1.2 (+0.1)

Note: Values in the parentheses show the improvement effect.

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$$\text{Transparency} = 4.106 \times \text{COD value}^{-0.695}$$

This table shows results of water improvement effect calculation at the same points as the Table 2.

Transparency at the observation points range between 0.9-1.3 m. Judging from this calculation, there is almost no improvement of transparency except with the sewerage improvement (CASE 1). It is shown that the sand-capping method (CASE 2) is the most effective solution of the six cases proposed in this plan. In some areas, drainage from Muko-gawa River showed great improvement (CASE 3). It is possible to realize at least a viewing level with the use of any of these methods.

As noted previously, the sand-capping method has been especially effective. This method can be expected to produce satisfactory results without combining other measures. The sand-capping method is suitable for the canal area because it does not require any large facilities or a bit plot of land. Besides, this method can reestablish habitats of living creatures. However, the project cost is rather high, so it should be carried out step by step according to the priority of work.

Image of Sea Blue
Plan at its Completion

The Sea Blue Plan proposes to create entirely new pleasant coastal environment by implementing measures to improve both water and sediment as well as creative ideas. What kind of pleasant coastal atmosphere will have been created in the canal area of Amagasaki after these six cases are jointly applied for the basic environment improvement?

Zone-A (Nishihori Canal,
Ogimachi Gate, the Lock Area)

A satisfactory viewing level can be achieved by purifying water through seawater dilution and garbage retrieval with barges. The area around the lock shall be open to citizens as a pleasant coastal park. From the park, the daily work of the harbor can be observed (Figure 10).

Zone-B (Kitahori Canal)

The force of water at the outlet is so strong that it should not be discharged directly into the canal; otherwise the outlet water will be mixed with sludge at the canal bottom, increasing the turbidity of the water. In order to avoid this phenomenon, a man-made stream should be constructed on the shoulder of the revetment. The outlet water should be discharged there first to weaken the force of the water. The water which is poured into the man-made stream will flow into the canal with the effect of creating a waterfall. Fountains shall also be constructed using this water power. Citizens can enjoy the various atmospheres produced by the water around this area. Limitation of this area to navigational ships will be helpful in creating this environment (Figure 11).
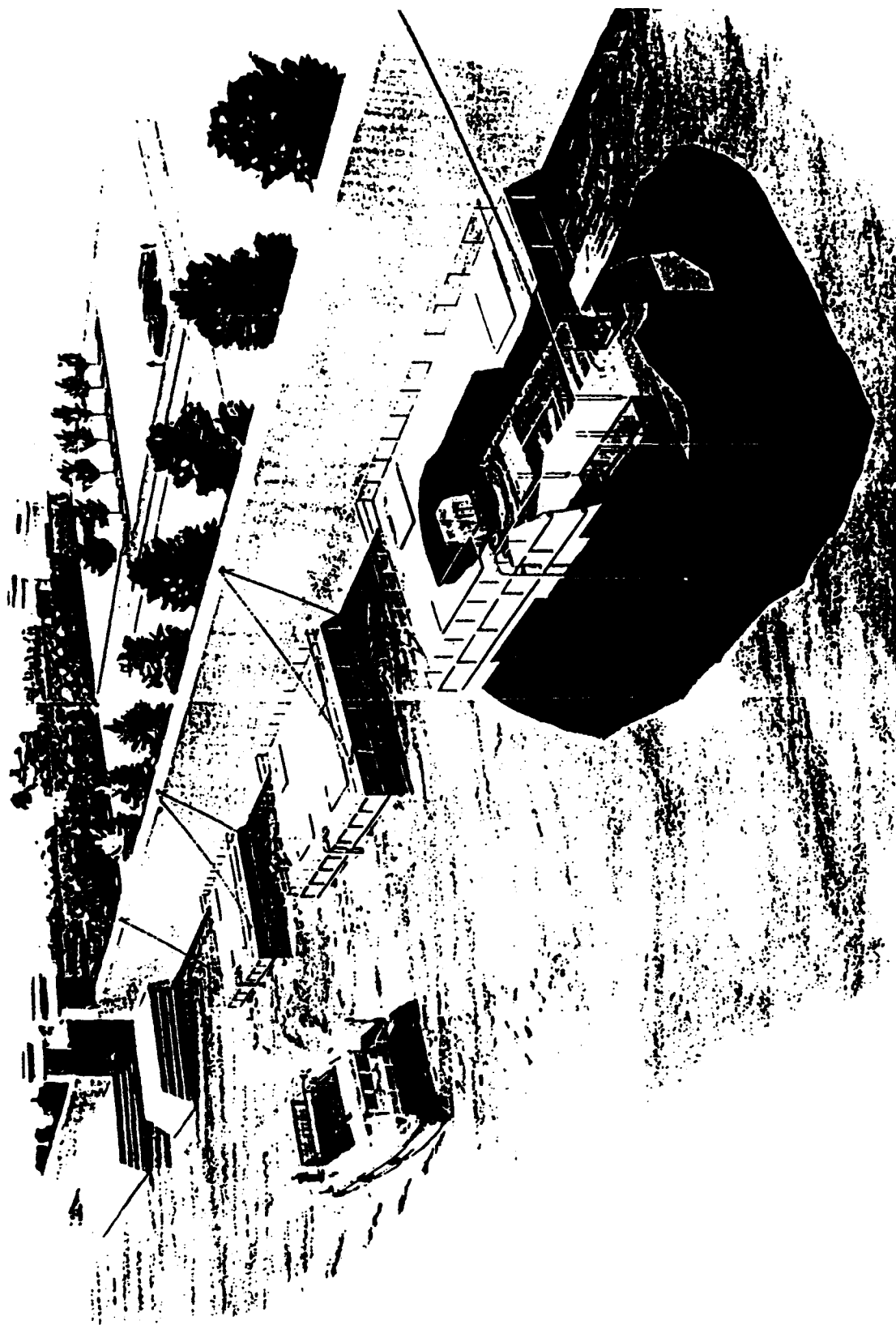
自航式ゴミ回収船とゴミ回収台船

Figure 10. Image of Sea Blue Plan at its completion in the Zone-A

取　　水　　口
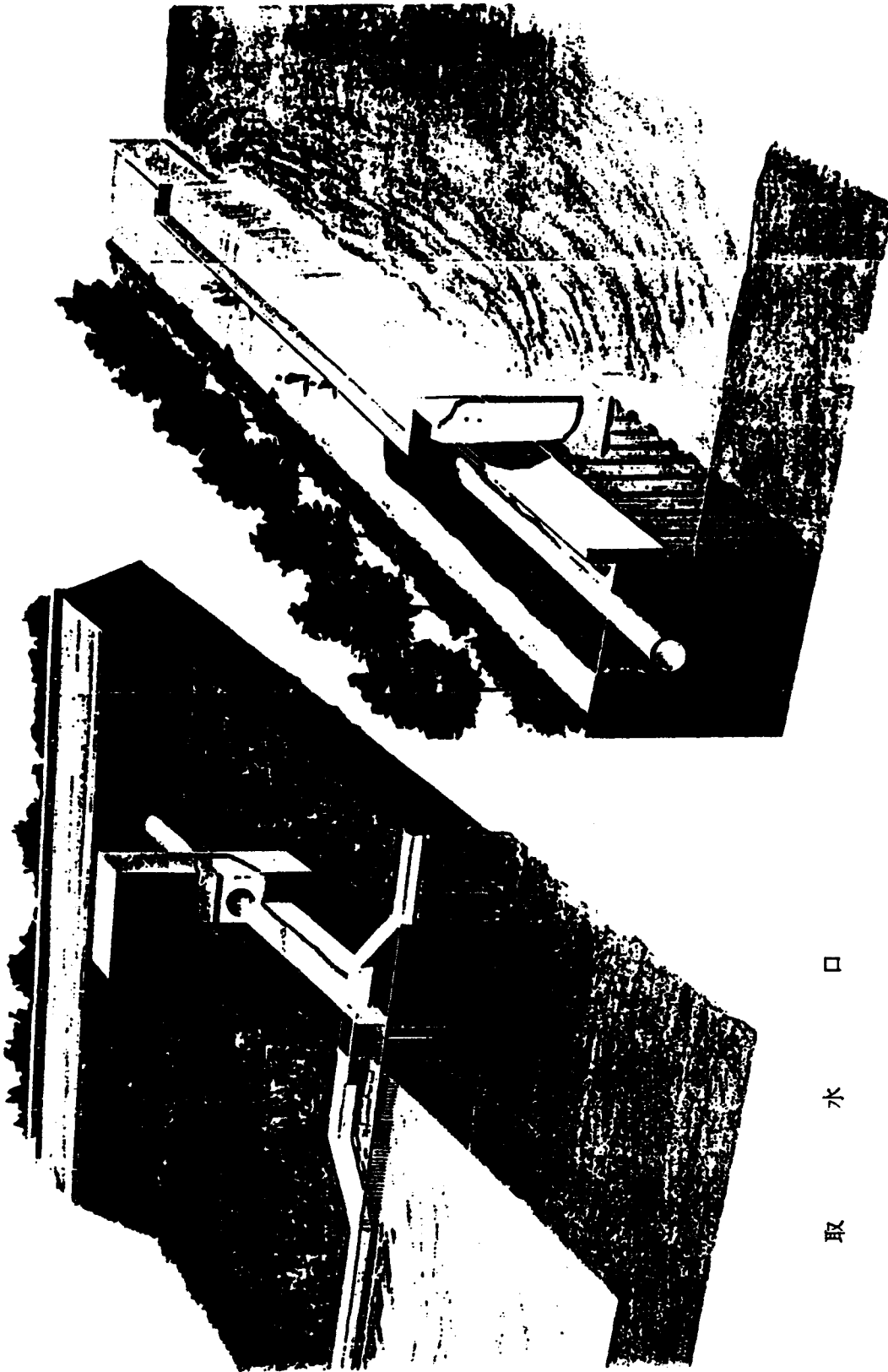
導水を利用した滝

Figure 11.　Image of the Sea Blue Plan at its completion in the Zone-B

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Zone-C (Higashihori Canal)

The porous bed channel shall be constructed underground of the present Matsushima River Park. The water of the Shoge-gawa River will be purified through the channel, then shall be drained at the end of the Higashihori Canal. Living filter will be placed at the water discharge area to increase the purification effect, as well as for a pleasant coastal atmosphere and habitats of living creatures. The habitat of living creatures can also be made by dredging and sand-capping. Water will be purified to a level with which citizens can play (Figure 12).

Zone-D (Yomo-gawa River, Naka-hori Canal, Kyu-Samondono-gawa River)

This area cannot be used exclusively for a pleasant coastal purpose because the navigation of ships takes the priority. However, this area is the introductory part to the canal from the town, so that trees shall be planted to make citizens feel like visiting the canal area.

Problems to be Settled Before Implementation

In starting the project previously described up to this point, there are many problems to be settled.

Setting the Targets for Improvement

The opinions of the citizens must be sufficiently reflected in setting targets for the improvement of water and sediment as well as in the utilization thereafter.

Promotion of Technical Innovations

Among water and sediment improvement methods proposed this time, some of them are already in practice like the sand-capping method, but others are not. However, some have much promise such as the porous bed channel method used in seawater. For solution of this problem, experiments of the porous bed channel in seawater are needed as soon as possible. The Sea Blue Technology Research Group of Japan Sediments Management Association and the Port and Harbor Research Institute of the Ministry of Transport jointly have started the experiment on a project scale since April 1990. Introduction of this experiment is also in the symposium literature.

In the sand-capping method, there is experience in practical use, there are still problems about the kind of sand or a suitable thickness of sand layer, in respect to habitats for living creatures.

Formation of an Implementation System

For the realization of the pleasant coastal improvement proposed this time, several matters such as who will be responsible for the cost of project and who will execute the project still remain unsolved and need to be considered.

In the past, environmental improvement such as harbor and costal improvement has been carried out with the aim of pollution prevention under
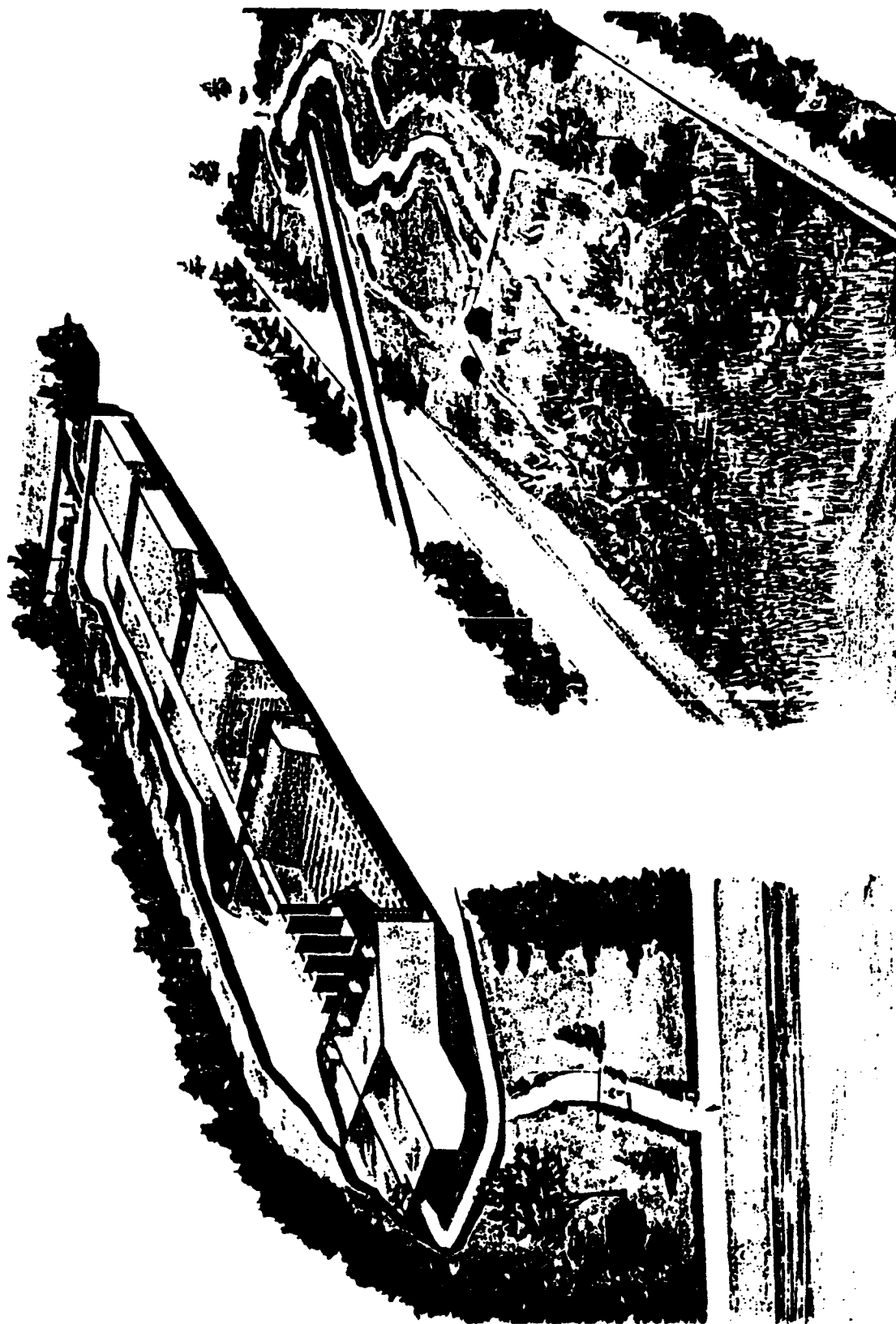
公園地下に埋立された
礫間接触酸化水路

浄化水を利用したせせらぎと
リビング・フィルター

Figure 12.　Image of Sea Blue Plan at its completion in the Zone-C

regime of the Port and Harbor Law and pollution prevention laws. The Sea Blue Plan aims to create a pleasant coastal environment which entails a broader concept than pollution prevention, per se. Therefore, the existing systems may not be sufficient to execute this ground concept, and it may be necessary to consider a new system for the implementation of the plan.

SEA BLUE PLAN: EXPERIMENT OF SEA WATER PURIFICATION BY POROUS BED CONTACT PURIFICATION METHOD

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ABSTRACT

A water purification experiment using channel type of porous bed contact purification method has been conducted since September 1990. This experimental facility is 30 meters long, 6 meters wide, and 1.5 meters in depth, and is separated into six independent channels 1 meter wide. Many kinds of water and sediment quality and organisms were examined and observed. Water qualities such as suspended solids, turbidity, and transparency were exceedingly improved. On the other hand, COD and TOC were not so effectively improved, but about 20 percent of removal efficiencies were gained. Many kinds of organisms were observed in the biofilm and the channels. By means of the built-in channel into the harbor and structures as revetment, breakwater, etc., it is enabling them to have the additional function of purifying sea water.

INTRODUCTION

The Sea Blue Plan, which we have proposed since 1987, is a project to create a new coastal environment through both improvement and utilization of it. In other words, it brings back a blue sea literally. The project is characterized by the following five concepts:

a. Active creation of sea environment. The aim is to treat the sea as an environmental resource whose wonderful value can be utilized to actively create the environment.

b. Close connection between land and sea. The link between land and sea should be strengthened to foster familiarity with the sea environment.

c. Harmonizing environmental improvement and utilization. The plan should promote not only the improvement of the environment but its utilization by citizens at the same time.

d. Appreciation of natural features of the sea. In so doing, the characteristics of the sea, for example, currents, tide, waves, and marine life, are not harmed.

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e. <u>Hybrid technology.</u> This concept involves the combined use of various kinds of relevant technology from low tech to high tech, mainly those which utilize natural energy and/or biorelated technology.

Through the technical research on the Sea Blue Plan, we have reached the conclusion that the porous bed contact purification method is a very effective way for the purification of polluted seawater. This method, however, has been hardly put in practice in seawater so far, although there are some practical examples in river water and/or wastewater treatment process. Then, the Ports and Harbors Bureau (Ministry of Transport), the Port and Harbor Research Institute (Ministry of Transport), and the Sea Blue Technology Research Group have started a study on the porous bed contact purification method since 1990 in order to evaluate the application possibility of this method to costal waters. In this report, we will present a few of the conclusions of the experiment and also show some images of the hybrid facilities utilizing the porous bed contact purification method.

THEORY OF PURIFICATION BY POROUS BED CONTACT METHOD

So-called biofilm is naturally formed on the surface of the gravel and other kinds of bed dipped in the seawater and other natural waters. Biofilm consisted of many kinds of microorganisms. The biological activities of those microorganisms such as feeding and decomposition of food materials purify organic matters in the seawater. Another function of the biofilm is settling and sedimentation of suspended solids in the seawater. Both biological and physicochemical actions of the biofilm contribute to the purification. Those functions are illustrated in Figure 1.

The porous bed contact method is one of the biofilm reactors. Three types of the plant design were adopted, mainly in Japan and other countries. They are the channel type, trickling filter type, and rotating contactor type. In this experiment we adopted the channel type.
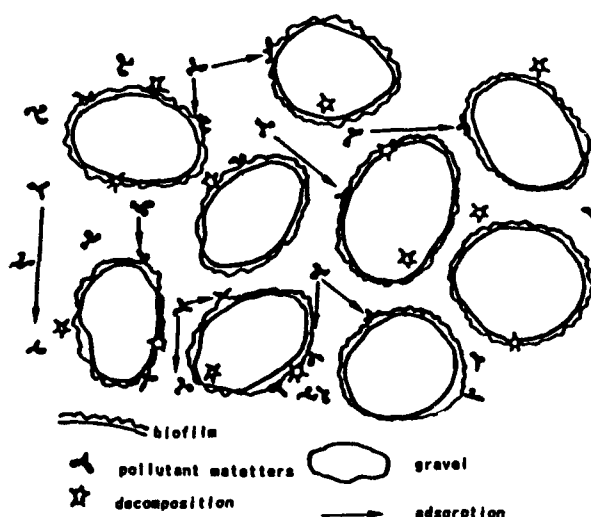
Figure 1. Purification mechanisms of the biofilm
(redrawn after Kasen-Kankyo, Kenkyu-kai, ed. 1985)

Plant

The experimental plant is constructed at the innermost part of the Tokyo Bay which is facing Sunamachi-Kita-Unga Canal (Figure 2). Six independent concrete-made channels, each 30 m long, 1 m wide, and 1.3 m deep, are laterally combined as shown in Figures 3 and 4. It is possible to practice a variety of comparative experiments. Three sizes of gravels (andesite) are used for the experiment. Channels No. 1, 2, 3, and 6 have gravels of mean diameter 100-150 mm; channels No. 4 and 5 have 60-80 mm and 20-30 mm respectively. Gravels are put in the channels up to 1.2 m.
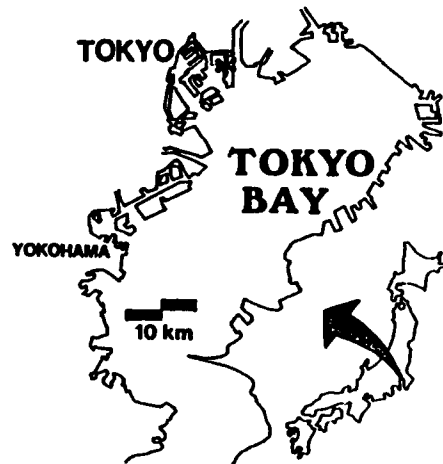
Figure 2. Experimental site
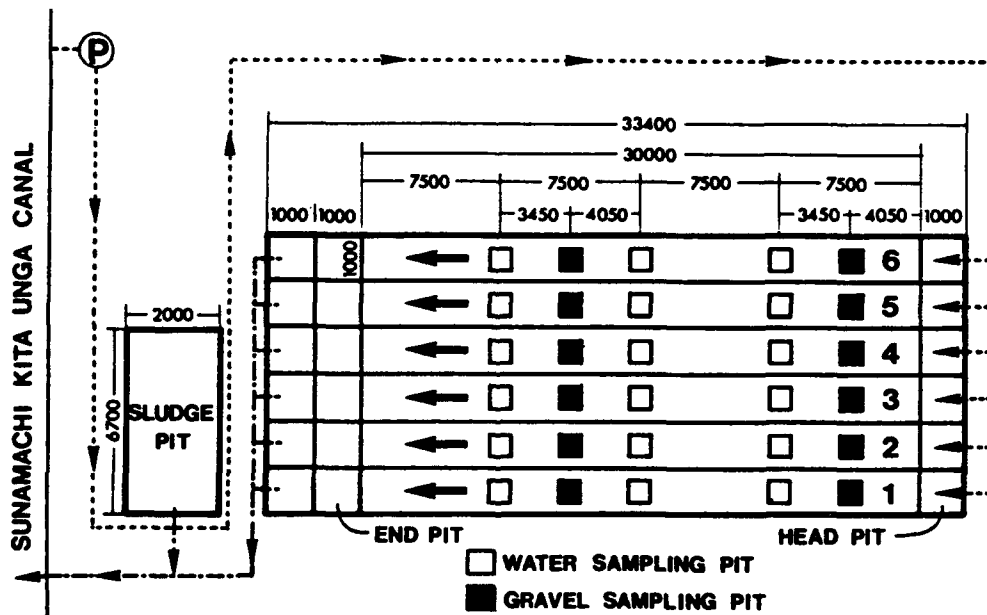
Figure 3. Ground plan of the experimental channel
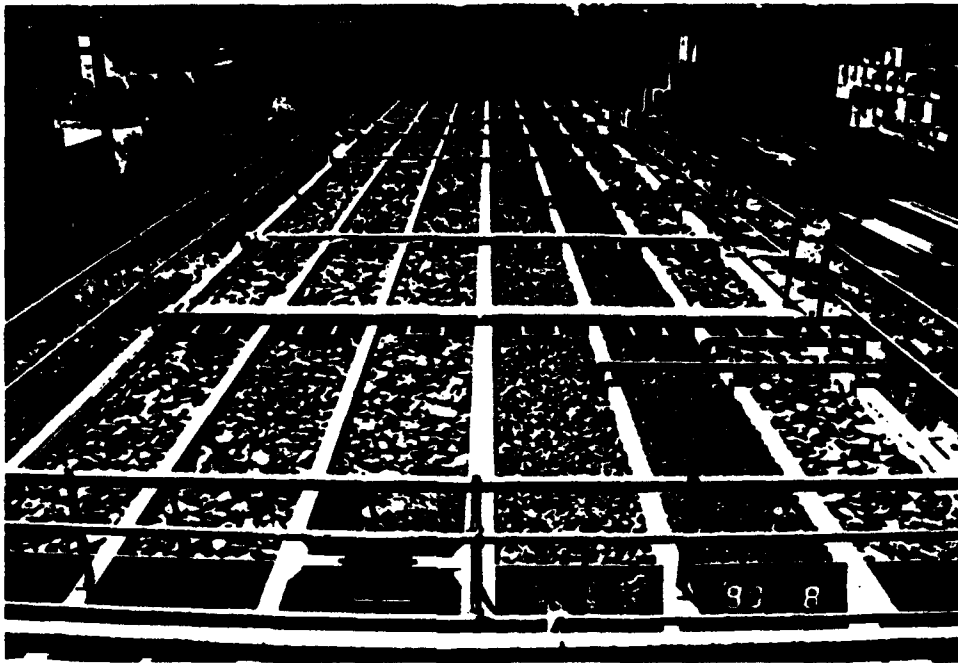
Figure 4. A photo of the experimental channel

The experimental water is pumped up from the Sunamachi-Kita-Unga Canal and directly into the head pit at the upstream end of the channel. The water is running through the channel naturally and drained from the end pit. There are three water-sampling pits (at 7.5, 15, and 22.5 m from the channel head) and two gravel-sampling pits (at 4 and 19 m from the channel head). Pipes for aeration and backwash are arranged on the bottom of channels No. 2-6.

Experimental Conditions

We conducted comparative experiments by setting different conditions for (1) gravel sizes, (2) water velocity (HRT), and (3) presence or absence of aeration (Table 1). The sunlight is cut off by dark plastic sheets placed over the channels to prevent the primary production by photosynthesis.

TABLE 1. EXPERIMENTAL CONDITIONS

Channel	Gravel size (mm)	Aeration	Retention Time (hours)	Fixed flow velocity (cm/sec)
1	100-150	none	4	0.5
2	100-150	none	2	1.0
3	100-150	none	1	2.0
4	60-80	none	2	1.0
5	20-30	none	2	1.0
6	100-150	none	4	0.5

Enough aeration is given in the head-pits of all channels. In channel No. 6, aeration is conducted in the whole length of the channel. In the channels No. 2-5, the backwash by water and air-blown was operated six and a half months after the beginning of the experiment because of clogging of the channel.

After one month of preliminary experiment on the hydraulics of the channel, the purification experiment was started after October 1, 1990. Meanwhile, biological observations have been done four times in this experiment. The first time is November 19, 1990 (two and half months after the beginning of the experiment); the second time, January 30, 1991 (five months); the third time, March 27, 1991 (six and a half months); and the fourth time, June 18, 1991 (nine and a half months).

Observation Items

The following water quality items have been examined to evaluate the water purification effect.

a. **Water quality condition.** The items examined were water temperature, turbidity, transparency, suspended solids (SS), pH, salinity, chemical oxygen demand (T-COD, D-COD), total organic carbon (T-TOC, D-TOC), NH^3-N, NO^2-N, NO^3-N, T-N, PO^4-P, and T-P. [Note: COD is measured after the Japan Industrial Standard (JIS) procedure. This COD expresses oxygen demand by $KMnO_4$, with H_2SO_4 at $100°$ C for 30 minutes.

b. **Condition of biofilm.** The items used for the evaluation were moisture content, Ignition Loss, org-C, Inorg-C, org-N, and Inorg-N.

c. **Condition of sediments.** The items involved in the evaluation were org-C, Inorg-C, org-N, Inorg-N, T-P, sulfide, COD, Ignition Loss, pheophytin, grading composition, and specific gravity.

d. **Organisms.** The items examined for the evaluation were fauna in the biofilm, flora in the biofilm, zooplankton, phytoplankton, benthos, chlorophyll, heterotrophic plate count, and coliform group.

Items such as water temperature, salinity, turbidity, transparency, pH, SS, COD, TOC, and dissolved oxygen (DO) were examined once every two days in the period from October 1 to November 16; once a week in the period from November 26 to March 29, 1991; and twice a week in the period after April. Sample waters were collected at 10 A.M. in the period from October 1 to November 16. From November 26, samplings were conducted corresponding to the retention time of each channel.

RESULTS

Purification Experiment

Water Purification Effect

a. **Suspended solids (SS).** Average SS concentration of influent was 5.7 mg/l, whereas it was 1.8 mg/l in the effluent through the whole period (Table 2). SS was largely removed in the effluent, and high

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TABLE 2. SUSPENDED SOLIDS (SS) CONCENTRATION (MG/ℓ)

Channel No.		Autumn Oct.-Dec.		Winter Jan.-Feb.		Spring 1 Mar.-Apr.		Spring 2 May-June		Whole Period Oct.-June	
		Influent	Effluent	Influent	Effluent	Influent	Effluent	Influent	Effluent	Influent	Effluent
1	Mean	3.69	1.34	5.72	2.14	6.92	1.52	6.72	1.25	5.09	1.44
	Max.	11.00	3.80	8.60	3.00	9.80	2.50	14.40	1.90	14.40	3.80
	Min.	1.40	0.10	3.60	1.50	4.80	1.00	3.60	0.80	1.40	0.10
2	Mean	4.30	1.57	7.43	1.67	8.43	1.86	9.73	5.00	6.33	2.16
	Max.	11.40	2.50	7.80	1.90	15.90	2.60	11.70	8.70	15.90	8.70
	Min.	1.00	0.30	6.90	1.50	4.40	1.30	6.50	2.80	1.00	0.30
3	Mean	3.67	1.67	7.67	3.63	7.83	3.35	6.86	3.60	5.18	2.42
	Max.	7.70	5.00	9.60	4.70	10.90	5.10	13.40	7.70	13.40	7.70
	Min.	1.40	0.40	5.90	2.80	4.80	1.90	4.20	1.60	1.40	0.40
4	Mean	4.21	1.34	6.48	2.18	8.71	2.03	8.22	2.65	6.33	1.90
	Max.	9.50	3.00	10.50	3.50	15.90	3.80	13.10	5.60	15.90	5.60
	Min.	1.00	0.30	1.30	1.60	4.40	0.70	5.20	1.10	1.00	0.30
5	Mean	4.41	1.06	7.30	1.78	8.56	1.26	8.06	1.27	6.45	1.24
	Max.	10.00	2.70	14.20	3.10	15.40	2.80	12.70	3.30	15.40	3.30
	Min.	1.00	0.20	1.10	0.90	4.40	0.40	4.80	0.50	1.00	0.20
6	Mean	3.49	1.07	5.00	4.40	7.13	2.30	6.26	1.00	4.85	1.63
	Max.	8.10	3.40	8.10	6.40	9.60	4.70	9.60	1.30	9.60	6.40
	Min.	1.40	0.30	1.70	2.40	4.60	0.40	3.90	0.60	1.40	0.30
Total Mean		3.90	1.34	6.60	2.63	7.93	2.05	7.64	2.64	5.71	1.80
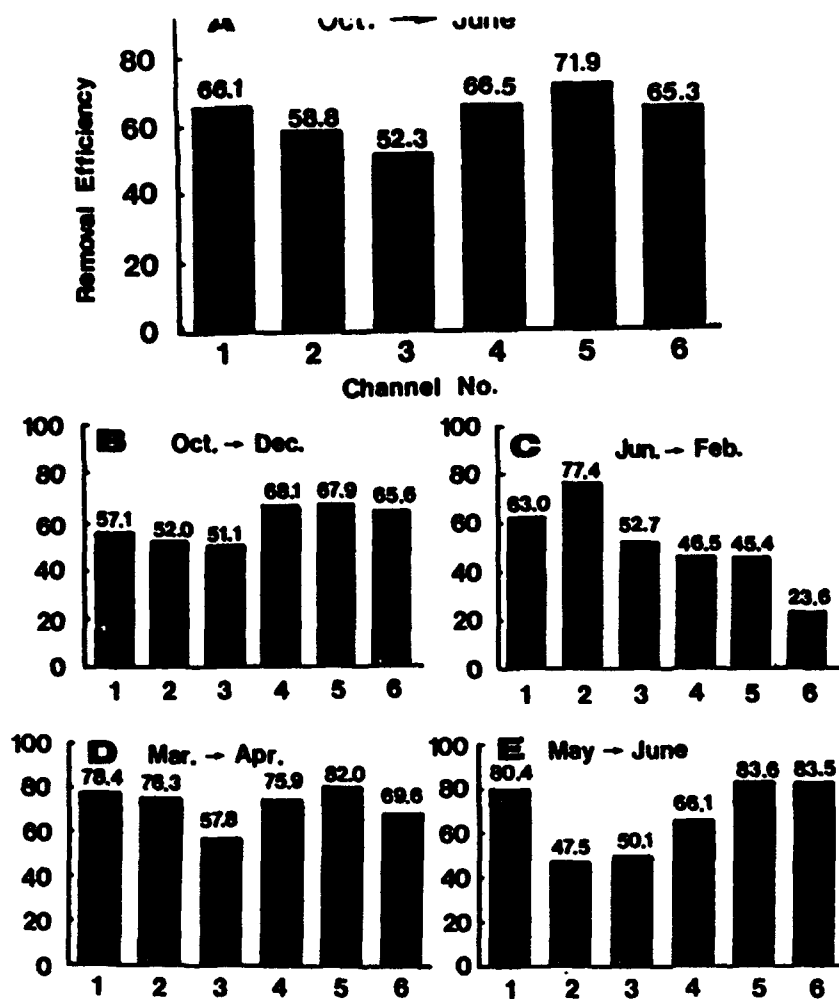
Figure 5. Average removal efficiency of SS (A: whole
experimental period from Oct. 1990 to June
1991; B: autumn/winter period from Oct. to
Dec.; C: middle winter period from Jan. to
Feb.; D: spring period from Mar. to Apr.;
and E: early summer period from May to June)

removal efficiency (52.3 - 71.9 percent in whole period) was gained
(Figure 5).

(1) Effects of each experimental condition on the removal effi-
ciency and mass removed through the whole experimental period
are expressed first. The removal efficiency decreased with the
flow velocity among the channels with larger gravels (No. 1, 2,
3-flow velocity: 0.5, 1.0, 2.0 cm/sec). Thus, the efficiency
of channel No. 1 was 66.1 percent, whereas it was 52.3 percent
in No. 3. However, the removed weight notably increased from
94.1 kg (No. 1) to 259.5 kg (No. 3) as shown in Figure 6.
Among the channels with the same flow velocity (No. 2, 4 and 5
- flow velocity: 1.0 cm/sec), the removal efficiency increased
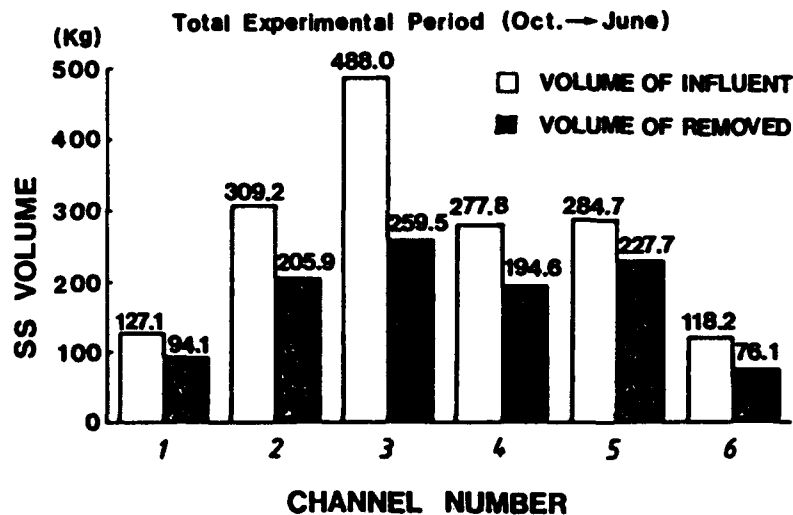
Figure 6. Average removed weight of SS in the whole
experimental period from Oct. 1990 to
June 1991

with the gravel size. The value of the large gravel (100-
150 mm) channel No. 2 was 58.8 percent; the medium gravel (60-
80 mm) channel No. 4 was 66.5 percent; and the small gravel
(20-30 mm) channel No. 5 was 71.9 percent. No clear difference
between channel No. 1 (gravel size: 100-150 mm) with aeration
and channel No. 6 without aeration was recognized.

(2) Some seasonal differences were observed in Figure 5. Chan-
nel No. 3 (v:2.0 cm/sec, gravel size: 100-150 mm) always had
low removal efficiencies and showed large fluctuation. Chan-
nels No. 1 (100-150 mm, v:0.5 cm/sec), No. 4 (60-80 mm, v:1.0
cm/sec), and No. 5 (20-30 mm, v:1.0 cm/sec) each exhibited
similar changing pattern: the lowest values were found in
January 1991, and the values increased again after that. In
channels No. 1 and 2 the pattern almost corresponds to that of
the average SS load in the influent $(0.22-1.37(0.61)g/m^2/day$
from October to December, 1990; $0.61-3.71(1.42)g/m^2/day$ from
January to February, 1991; $0.47-3.77(1.50)g/m^2/day$ from March
to April, 1991; $0.42-3.15(1.37)g/m^2/day$ from May to June).

(3) Figure 7 expresses the relationships between the effect on
improvement of SS and the elapse of the experiment. Until 30
to 40 days after the beginning of the experiment, the removal
weight of SS in the effluent were stable at about 0.2 to
0.3 kg/day. After 30 to 40 days, SS decreased and was stable
at about 0.1 to 0.2 kg/day until 60 to 90 days after the begin-
ning of the experiment. However, SS in the effluent increased
again in the next period (until 150 to 180 days after the
beginning) and was showing some fluctuation. After 150 to
180 days, SS decreased again.

b. Chemical Oxygen Demand (COD). The average total chemical oxygen
demand (T-COD) in influent was 5.03 mg/l and that of soluted

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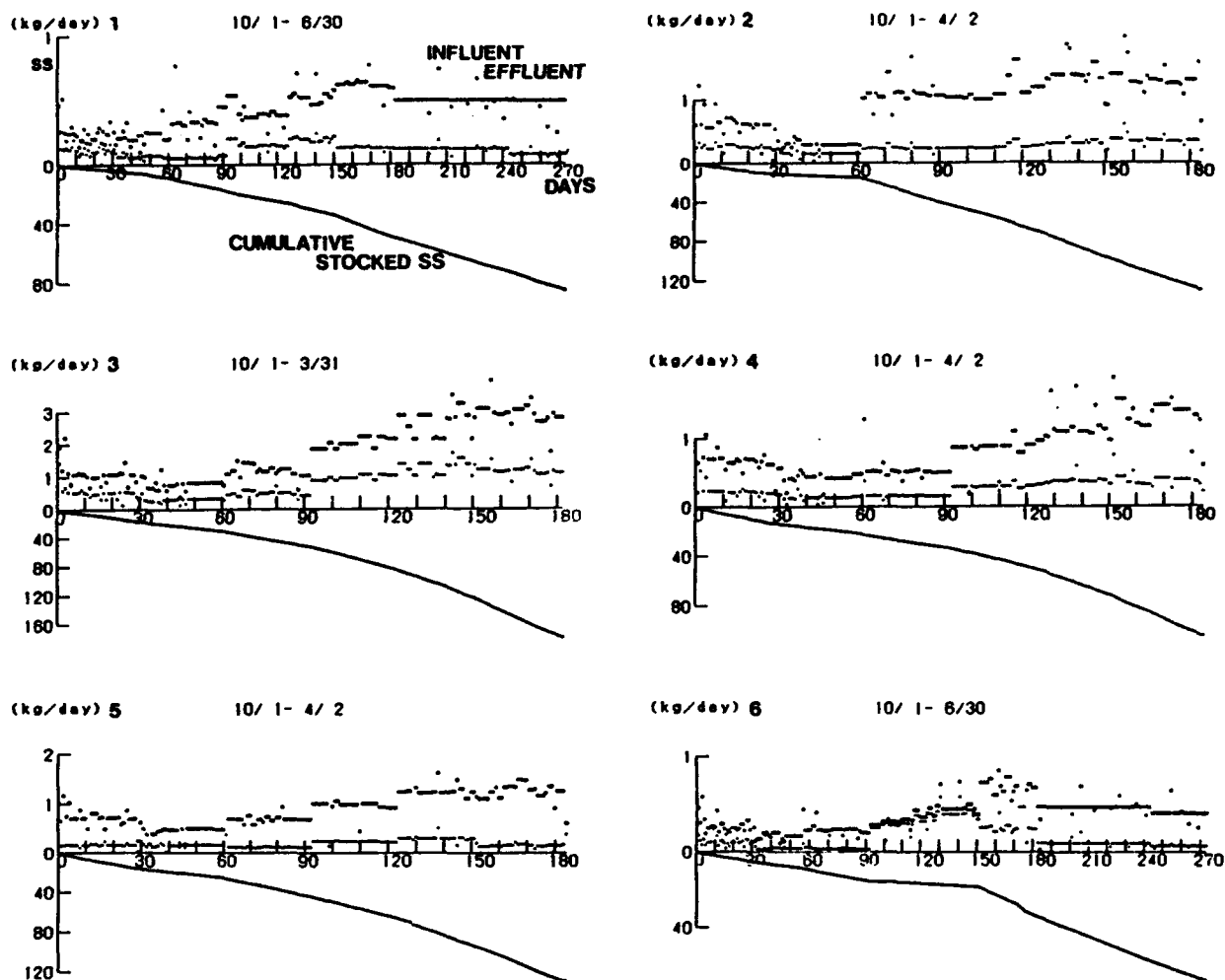
Figure 7. Weight of SS in the influent and effluent and
the cumulative stocked SS

chemical oxygen demand (D-COD) was 4.3 mg/l through the whole period
(Table 3).

(1) The average removal efficiency in the whole period will be
shown first (Figure 8A). The removal efficiency is not so
high, and it is below 20 percent even maximally. Differences
among the channels with different flow velocity (retention
time) (No. 1, 2, 3 - gravel size: 100-150 mm, v:0.5, 1.0,
2.0 cm/sec) are prominent, and the efficiency diminished with
the flow velocity. Thus, the values of channel No. 1 are 9.4
percent in T-COD and 7.5 percent in D-COD; those of channel
NO. 2 are 6.1 percent in T-COD and -2.0 percent in D-COD; and
those of channel No. 3 are -2.5 percent in T-COD and -5.5 per-
cent in D-COD. The efficiency decreased with the gravel size
among the channels with the same flow velocity (No. 2, 4,
5 -v:1.0 cm/sec, gravel size: 100-150, 60-80, 20-30 mm). The
values of the smallest gravel channel No. 5 are 19.3 percent in
T-COD and 15.9 percent in D-COD; those of the medium gravel
channel No. 4 are 13.9 percent in T-COD and 8.5 percent in

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TABLE 3. CHEMICAL OXYGEN DEMAND (COD) CONCENTRATION (MG.ℓ)

Channel No.		Autumn Oct.-Dec.		Winter Jan.-Feb.		Spring 1 Mar.-Apr.		Spring 2 May-June		Whole Period Oct.-June	
		Influent	Effluent	Influent	Effluent	Influent	Effluent	Influent	Effluent	Influent	Effluent
1	Mean	4.78	4.77	4.57	4.05	4.67	3.85	5.53	4.21	4.93	4.34
	Max.	6.80	7.40	6.20	5.40	6.10	4.50	11.30	6.60	11.30	7.40
	Min.	3.10	3.60	3.40	3.10	3.90	2.50	3.90	2.90	3.10	2.50
2	Mean	5.22	4.89	4.57	3.75	4.76	3.74	6.80	7.20	5.27	4.77
	Max.	13.40	7.20	6.00	4.80	5.50	4.30	7.60	9.00	13.40	9.00
	Min.	3.00	2.90	2.70	2.70	3.70	3.20	5.50	4.90	2.70	2.70
3	Mean	4.66	4.89	4.57	4.70	4.59	4.36	6.14	5.96	4.83	4.90
	Max.	6.80	6.00	5.60	5.40	6.00	5.50	9.80	9.30	9.80	9.30
	Min.	3.00	3.80	3.50	4.00	3.50	3.60	4.10	4.30	3.00	3.60
4	Mean	5.22	4.85	4.72	3.40	4.94	3.66	6.21	5.07	5.36	4.47
	Max.	13.40	6.70	6.50	3.80	7.60	6.60	8.90	6.90	13.40	6.90
	Min.	3.40	3.30	3.30	3.10	3.70	2.00	4.50	3.20	2.30	2.00
5	Mean	5.27	5.01	4.03	2.88	4.95	3.05	6.09	4.37	4.86	4.91
	Max.	13.40	8.70	3.60	3.10	7.00	3.80	8.70	8.50	6.80	9.60
	Min.	3.00	2.80	3.00	2.60	3.60	2.20	4.60	2.80	3.10	3.10
6	Mean	4.76	4.38	4.62	3.85	4.81	3.64	4.81	3.89	4.94	4.13
	Max.	6.80	9.60	6.10	4.50	6.60	5.10	6.10	4.90	8.00	9.60
	Min.	3.10	2.90	3.10	2.80	3.20	1.20	3.10	2.40	3.10	1.20
Total Mean		4.99	4.80	4.51	3.77	4.79	3.67	5.93	5.12	5.03	4.59
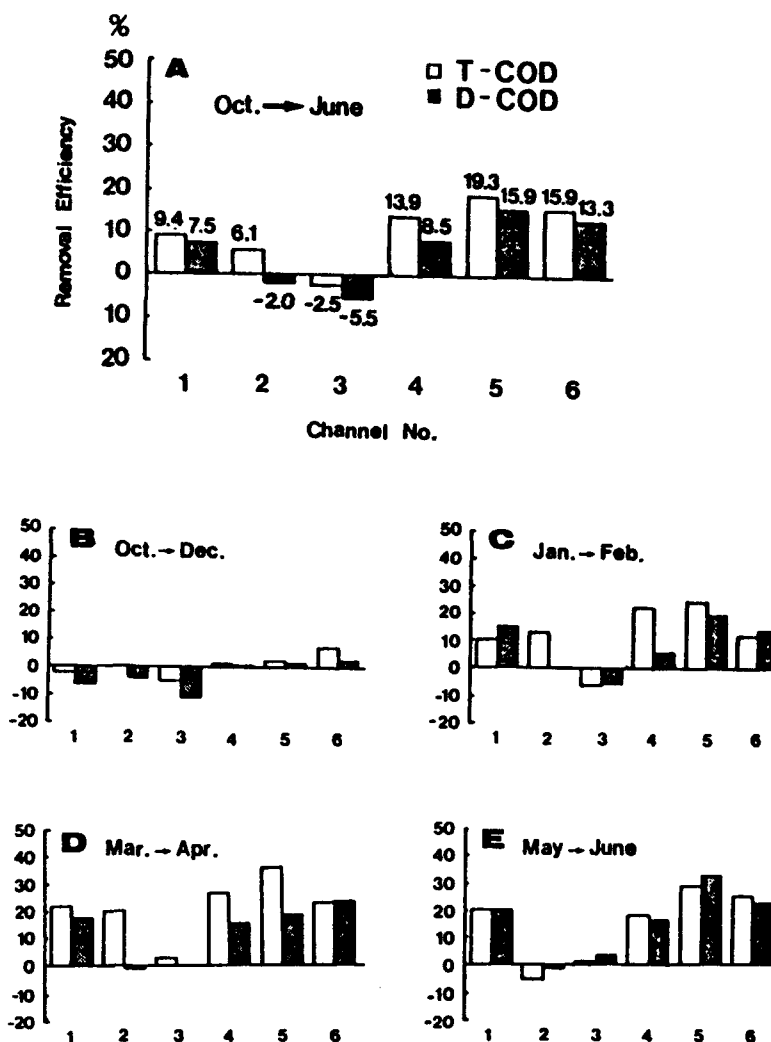
Figure 8.   Average removal efficiency of COD
(A: whole experimental period from
Oct. 1990 to June 1991; B: autumn/
winter period from Oct. to Dec.; C:
middle winter period from Jan. to
Feb.; D: spring period from Mar.
to Apr.; and E: early summer
period from May to June)

D-COD; and those of the largest channel No. 2 are 6.1 percent
in T-COD and 12.0 percent in D_COD. Aeration is effective to
improve efficiency. In channel No. 6 with the aeration, the
efficiencies are 15.9 percent in T-COD and 13.3 percent in
D-COD, whereas in channel No. 1 with no aeration, they are
9.4 percent in T-COD and 7.5 percent in D-COD.

(2)   Some seasonal differences are also recognized in the removal
efficiency (Figure 8B-E). Generally, the removal efficiency of
T-COD had increased to March 1991 and then decreased in June
1991. Namely, channels No. 1, 4, 5, and 6 show almost the same

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changing pattern. In these channels maximum values are beyond 20 percent. In channel No. 5 particularly, the efficiency reaches about 40 percent in March, whereas the efficiency of the channel No. 3 stayed at a very low level. Further, the value of channel No. 2 in the June observation decreased all of a sudden. On the other hand, the removal efficiencies of D-COD have continually increased in all channels. Channels No. 1, 4, 5, and 6 show similar values which are rather high, but channels No. 2 and 3 exhibit extremely low values. The mean COD load in the same season was: 0.65 (Oct.- Dec.), 0.60 (Jan.- Feb.), 1.05 (Mar.- Apr.), and 1.36 g/m²/day (May - June).

c. Total organic carbon (T-TOC, D-TOC). The average T-TOC (Total Organic Carbon) of the influent was 4.87 mg/l (Table 4).

(1) Effects of each experimental condition on the removal efficiency through the whole experimental period and are expressed first (Figure 9A). Average removal efficiencies of T-TOC and D-TOC are lower than 20 percent even in the maximum value. Differences among the channels with different flow velocity (retention time) (No. 1, 2, 3-gravel size: 100-150 mm, v:0.5, 1.0, 2.0 cm/sec) are observed, and the efficiency decreased with the flow velocity. Thus, higher efficiencies are obtained in channel No. 1 (16.4 percent in T-TOC and 9.1 percent in D-TOC). Those of channel No. 2 are 13.1 percent in T-TOC and 5.9 percent in D-TOC, and those of channel No. 3 are 6.9 percent in T-TOC and 8.1 percent in D-TOC. As for the difference of the gravel size (No. 2, 4, 5-v:1.0 cm/sec, gravel size:100-150, 60-80, 20-30 mm), the efficiency decreased with the gravel size. The efficiencies of channel No. 5 with the highest values are 16.8 percent in T-TOC and 10.4 percent in D-TOC. Those of the other two channels are No. 4 with 14.8 percent in T-TOC and 8.1 percent in D-TOC, and No. 2 with 13.1 percent in T-TOC and 5.9 percent in D-TOC. No clear difference between channel No. 6 with the aeration and No. 1 without aeration is recognized. In channel No. 6 the efficiencies are 11.9 percent in T-COD and 4.4 percent in D-TOC, whereas in channel No. 1 they are 16.4 percent in T-TOC and 9.1 percent in D-TOC.

(2) Some seasonal differences are expressed in Figure 9. It seems that the channels are divided into two groups with different changing patterns. In T-TOC, channels No. 1, 3, and 6 have maximum values in the January observation, whereas the maximum values of channels No. 2, 4, and 5 are present in March. In D-TOC, channels No. 1, 3, 4, and 6 have maximum values in January, whereas those of the channels No. 2 and 5 are present in March. The mean TOC load in the same season was: 1.18 (Oct.- Dec.), 0.99 (Jan.- Feb.), 0.84 (Mar.- Apr.), and 1.44 g/cm²/day (May-June).

d. Turbidity. The average turbidity of the influent is 3.5-5.5 deg, and that of the effluent is 1.6-2.0 deg in the total experimental period.

TABLE 4. TOTAL ORGANIC CARBON (TOC) CONCENTRATION (mg/ℓ)

Channel No.		Autumn Oct.-Dec.		Winter Jan.-Feb.		Spring 1 Mar.-Apr.		Spring 2 May-June		Whole Period Oct.-June	
		Influent	Effluent	Influent	Effluent	Influent	Effluent	Influent	Effluent	Influent	Effluent
1	Mean	4.94	4.27	5.57	3.48	3.90	3.22	5.72	4.87	5.07	4.15
	Max.	6.90	6.40	10.30	4.40	5.00	4.40	7.70	7.10	10.30	7.10
	Min.	3.20	2.70	2.70	2.50	3.10	2.10	4.70	3.50	2.70	2.10
2	Mean	4.60	4.51	4.50	3.50	4.35	3.40	7.08	6.20	4.89	4.27
	Max.	5.50	7.90	5.10	4.60	6.40	5.30	8.40	7.40	8.40	7.90
	Min.	2.70	2.40	2.80	3.00	2.50	1.70	6.10	4.50	2.50	1.70
3	Mean	4.76	4.54	5.10	4.02	4.10	3.60	5.46	5.16	4.79	4.36
	Max.	6.90	6.00	7.10	5.60	5.30	4.50	8.10	6.20	8.10	6.20
	Min.	2.80	2.70	3.50	2.70	2.70	2.70	3.70	3.60	2.70	2.70
4	Mean	4.82	4.23	4.42	3.47	4.12	3.17	5.93	5.24	4.88	4.11
	Max.	7.70	5.50	6.20	4.60	6.00	4.10	7.20	7.10	7.70	7.10
	Min.	3.10	2.40	2.70	2.20	2.00	1.60	5.00	4.00	2.00	1.60
5	Mean	4.75	4.18	4.35	3.17	4.48	3.20	5.78	5.07	4.89	4.06
	Max.	7.90	6.70	6.10	3.80	5.40	4.20	7.60	6.20	7.90	6.70
	Min.	2.90	2.70	2.80	2.30	3.20	2.40	4.50	4.00	2.80	2.30
6	Mean	4.78	4.14	4.48	3.68	3.74	3.26	5.36	5.09	4.70	4.13
	Max.	6.90	5.80	5.90	5.30	5.10	4.50	6.90	6.20	6.90	6.20
	Min.	3.10	2.50	3.10	2.30	2.90	2.30	3.90	4.30	2.90	2.30
Total Mean		4.78	4.31	4.74	3.55	4.12	3.31	5.89	5.27	4.87	4.18

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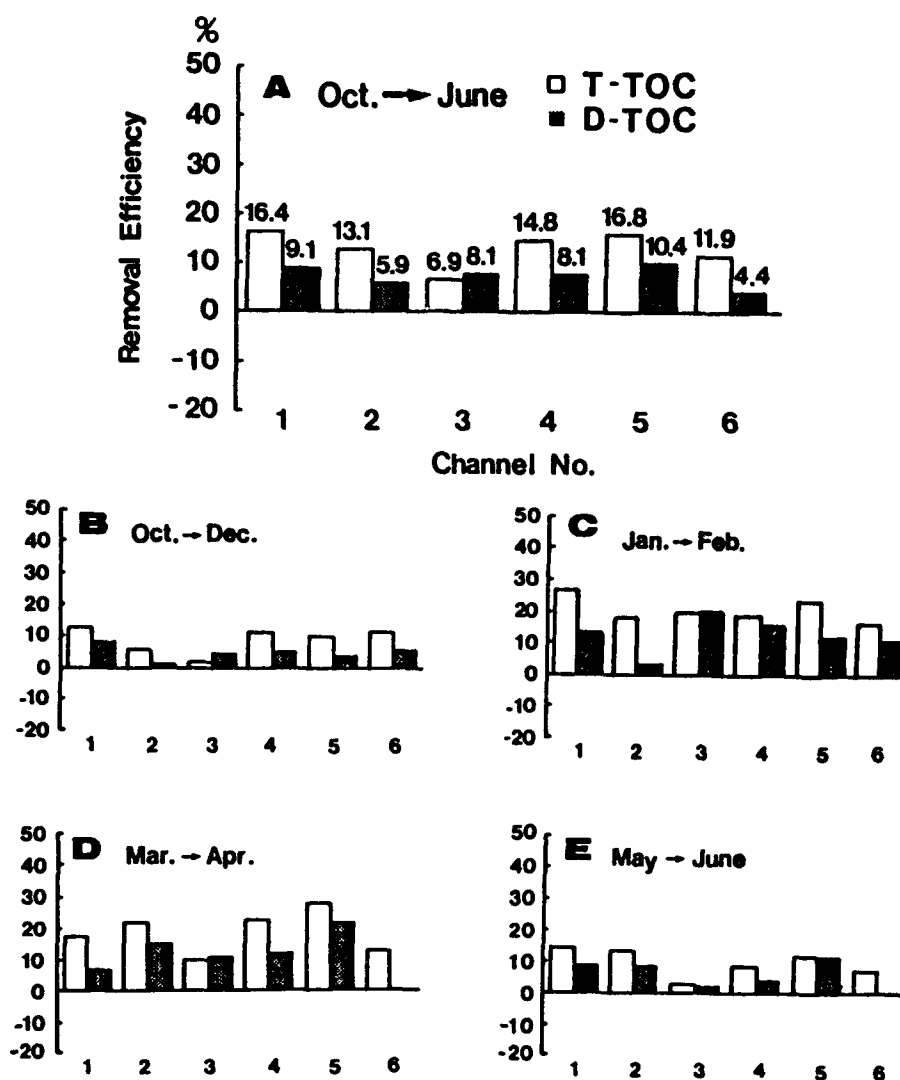
Figure 9. Average removal efficiency of the TOC
(A: whole experimental period from Oct.
1990 to June 1991; B: autumn/winter
period from Oct. to Dec.; C: middle
winter period from Jan. to Feb.; D:
spring period from Mar. to Apr.; and
E: early summer period from May to
June)

e. **Transparency.**

(1) The average transparency of the influent was 40-150 cm (mean
94 cm) during the whole experimental period, although there
were some exceptions (Table 5). We have been using an ordinary
100-cm cylinder and special 150-cm and 200-cm cylinders depend-
ing on the water quality. In many cases (45-89 percent), the
transparency of the treated effluent was over 200 cm.

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TABLE 5. TRANSPARENCY (cm)

Channel No.		Autumn Oct.-Dec.		Winter Jan.-Feb.		Spring 1 Mar.-Apr.		Spring 2 May-June		Whole Period Oct.-June	
		Influent	Effluent	Influent	Effluent	Influent	Effluent	Influent	Effluent	Influent	Effluent
1	Mean	105	138	92	137	82	187	101	192	99	157
	Max.	200	200	200	200	105	200	147	200	200	200
	Min.	39	45	50	100	43	119	30	150	30	40
2	Mean	104	157	118	200	72	187	60	88	93	161
	Max.	200	200	200	200	115	200	101	154	200	200
	Min.	41	72	62	200	44	151	35	38	35	38
3	Mean	101	146	84	158	74	155	78	125	90	147
	Max.	200	200	128	200	105	200	111	200	200	200
	Min.	39	47	55	122	47	68	25	42	25	42
4	Mean	116	150	110	181	67	165	74	158	95	159
	Max.	200	200	180	200	115	200	151	200	200	200
	Min.	48	100	63	160	46	100	35	58	35	58
5	Mean	112	151	108	200	64	200	74	188	92	177
	Max.	200	200	192	200	100	200	139	200	200	200
	Min.	33	100	57	200	44	200	36	99	33	99
6	Mean	102	140	93	128	78	164	89	195	94	155
	Max.	200	200	200	200	99	200	120	200	200	200
	Min.	39	72	57	74	55	121	33	150	33	72
Total Mean		107	147	101	168	73	176	79	158	94	159

(2) Difference of efficiencies among the channels with different
     gravel size is recognized. The efficiency of channel No. 5
     with the small gravel (mean diameter 20-30 mm) is the highest
     throughout the whole experimental period; however, the differ-
     ence between the channels No. 4 and No. 2 with medium and the
     largest gravel (No. 4, 2) is not clear.

(3) In comparing the presence or absence of aeration, the trans-
     parency of the nonaerated channels No. 1-5 is slightly better
     than that of the aerated channel No. 6.

f. Dissolved oxygen (DO). In channel No. 6 in which the aeration has
    been conducted over the entire length, 3-12 mg/1 of DO has been
    sustained during the whole experimental period. In other channels,
    aeration was conducted only at the head-pit. Therefore, DO is
    rapidly consumed by the endogenous respiration of the biofilm and
    the decomposition of the polluted matters. Some examples of the DO
    profile of channels with different gravel size (No. 2, 4, and 5) are
    plotted against channel length in Figure 10. DO rapidly diminished
    in the channel with the smaller gravel.
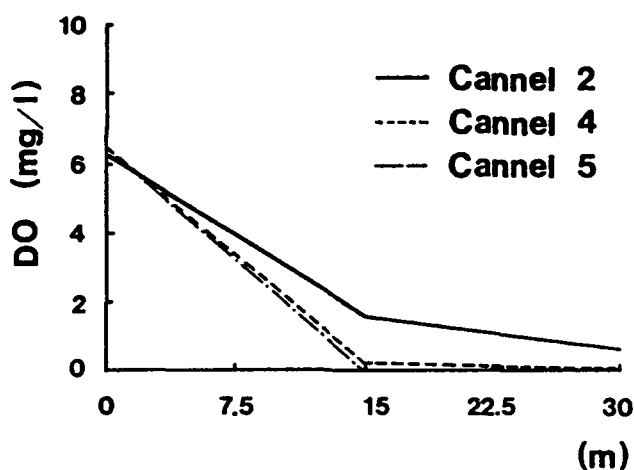
Figure 10. DO profile in the channels with
            different gravel sizes (No. 1, 2, 3)

Relationships Among the Water Quality Indices

     Indices relating to turbidity (SS, transparency, turbidity) have rela-
tively strong interrelationships. The correlation coefficient between SS and
transparency is -0.704, SS and turbidity is 0.639, and transparency and tur-
bidity is -0.725 in the influent during the total experimental period.

     Meanwhile, in the effluent the correlation coefficient between SS and
transparency is -0.692, SS and turbidity is 0.313, and transparency and tur-
bidity is -0.420. The correlation coefficients of the effluent are slightly
smaller than those of the influent. No clear relationships between SS and COD
and SS and TOC in both influent and effluent were recognized.

Organisms in the Channel

More attention has been paid to the biological aspects in the biofilms and channels, because these matters are scarcely known in connection with polluted coastal seawater in spite of the importance of organisms in the biofilm and channels for purification. As for microorganisms inhabiting the biofilm in river water and sewage purification facilities, many authors have repeatedly reported on those aspects (e.g., Hashimoto and Teranishi 1988; Inamori 1989; Inamori et al. 1987; Kuniyasu 1988; Sudo, ed. 1988, 1989; Sudo and Inamori 1989; Tsuda 1982). In the polluted seawater, however, there have only been a few reports (e.g., Otsuki, 1990). Higher classification of the organisms follows by Yamada, ed. (1983).

Microanimals in the Biofilm

a. **Changes of fauna.**

(1) A total of 36 species of microanimals were observed in the biofilms. They are classified into two subkingdoms (Protozoa and Metazoa) and further into six phylla (Protozoa, Rotifera, Nematoda, Annelida, Arthropoda, and Mollusca). The number of species in each phylum is Protozoa 28; Rotifera 3; Arthropoda 2; and Nematoda, Annelida, and Mollusca 1. All species of the phylum Protozoa are included in the class Ciliatea. Three species of the Metazoa were present as larvae: polychaete larvae of Annelida, D-larvae of Mollusca, nauplius larvae of Arthropoda. The dominant five species in each observation are:

(a) Nov. 19, 1990   Total number of individuals: 1,771 N/cm^2
                                  Total number of species: 7 species/cm^2
Carchesium sp. (77.9 percent), *Vorticella* sp. (10.1 percent), *Nematoda* sp. (9.3 percent), *Ciliatea* sp. (1.6 percent), *Dystreria* sp. and *Loxophylum* sp. (0.4 percent)

(b) Jan. 30, 1991   Total number of individuals: 5,115 N/cm^2
                                  Total number of species: 14 species/cm^2
Vorticella sp. (70.7 percent), *Carchesium* sp. (10.3 percent), *Zoothamnium* sp. (3.9 percent), *Ciliatea* sp. (3.7 percent), *Diophyris* sp. (2.7 percent)

(c) Mar. 27, 1991   Total number of individuals: 4,929 N/cm^2
                                  Total number of species: 29 species/cm^2
Zoothamnium sp. (53.5 percent), *Eutintinnus* sp. (9.0 percent), *Helicostomella fusiformis* (7.0 percent), *Vorticella* sp. (6.8 percent), *Tintinnopsis kofoidi* (6.4 percent)

(d) June 18, 1991   Total number of individuals: 1,479 N/cm^2
                                  Total number of species: 18 species/cm^2
Peritrichida sp. (62.5 percent), *Nematoda* sp. (11.4 percent), *Zoothamnium* sp. (5.5 percent), *Helicostomella* sp. (5.1 percent), *Monostyla* sp. (3.9 percent)

(2) The primary dominant species accounts for 53.5-77.9 percent of the total number of individuals. Almost all dominant species were protozoans except *Nematoda* sp. (Nov. 1990, June 1991) and

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Monosytla sp. (Rotifera) (June 1991). All dominant species in the first two observations were freshwater species, whereas some marine species (*Eutintinnus, Helicostomella, Tintinnopsis*) were present in the last two observations. Some of the dominant species are illustrated in Figure 11.
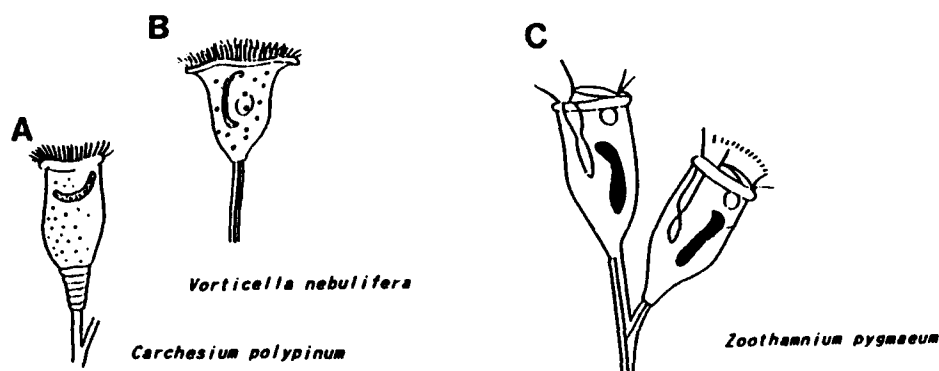
Figure 11. Some of dominant microanimal species in the biofilms - A: *Carchesium polypinum*, B: *Vorticella Nebulifera*, and C: *Zoothamnium pygmaeum* (A & B: after Mizuno 1990; C: after Sudo & Inamori 1989)

b. **Changes of the number of individuals.** Number of individuals increased with flow velocity (Figure 12). Thus, among the channels No. 1, 2, and 3 (gravel size: 100-150 mm, v:0.5, 1.0, 2.0 cm/sec), channel No. 3 had the maximum number in both upper and lower part of the channel. No clear differences were found in the channels with different gravel sizes (No. 2, 4, 5-v: 1 cm/sec; gravel size: 100-150, 60-80, 20-30 mm). Aeration was not so influential on the number of individuals. In the upper part of the channel, the number in channel No. 6 with aeration was slightly larger than that of channel No. 1, but the reverse tendency was recognized in the lower part. In the same channel, the microanimals in the upper part always outnumbered the lower part except No. 3.

c. **Changes of the dry weight of the biofilm.** In the upper part of channels No. 1, 2, 4 and 6, the dry weight (mg/100 cm^2) increased with season but decreased in channels No. 3 and 5, whereas there were no clear tendencies in the lower part. Effect of the flow velocity was recognized between channels No. 1 and 3 (gravel diameter: 100-150 m; v:0.5, 2.0 cm/sec). The dry weight of channel No. 3 was larger than that of channel No. 1. The dry weight decreased with the gravel size in the upper part of the channel in No. 2, 4, 5 (v:1 cm/sec; gravel diameter: 100-150, 60-80, 20-30 mm), but the reverse tendency was found in the lower part. No distinct difference due to aeration was found between channels No. 1 and 6 (Figure 13). In the same channel, the dry weight in the upper part was larger than that of the lower part.

Nov. 19, 1990

Jan. 30, 1991

Mar. 27, 1991

June 18, 1991

■ UPPER ☐ LOWER
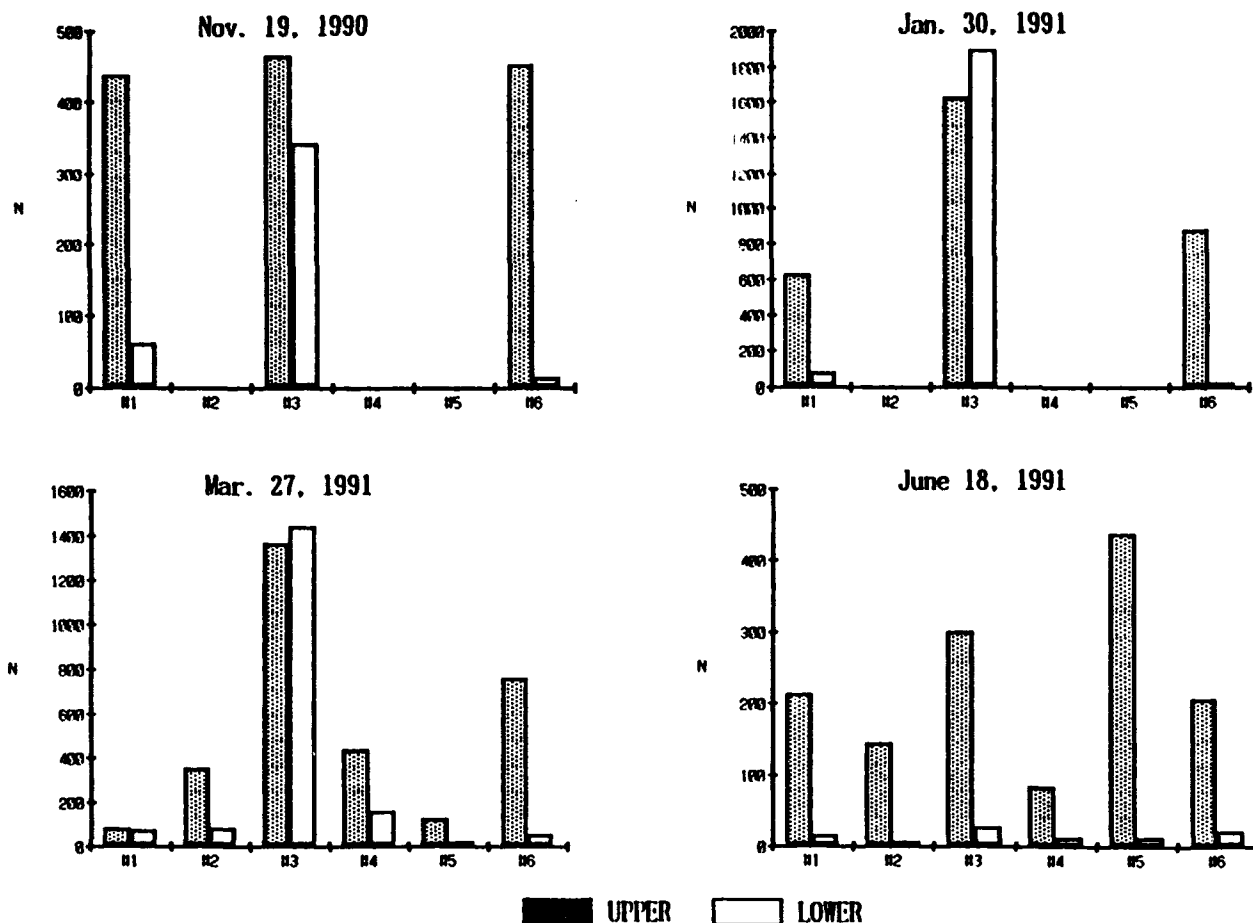
Figure 12. Changes of the number of individuals of the
microanimals (N/cm^2) in the biofilms

Microalgae in the biofilm

    a. Changes of flora.

        (1) A total of 61 species of microalgae were observed. They are
largely classified into phylla Cyanophyta, Dinophyta, Chromo-
phyta, Euglenophyta and Chlorophyta. The Chromophyta occupied
52 species. Of the 52 species of the Chromophyta, 48 are spe-
cies of the class Bacillariophyceae (diatoms). The dominant
five species in each observation are:

        (a) Nov. 19, 1990   Total number of cells: 2,466 cells/1
                                 Total number of species: 18 species/1
        Aphanothece sp. (96.4 percent), *Oscillatoria* spp.
        (1.7 percent), *Skeletonema costatum* (1.1 percent), *Navi-
cula* spp. (0.1 percent)

        (b) Jan. 30, 1991   Total number of cells: 2,069 cells/1
                                 Total number of species: 27 species/1

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Skeletonema costatum (49.0 percent), *Navicula* spp.
(20.9 percent), *Rhizosolenia setigera* (6.4 percent),
Nitzchia spp. (4.3 percent), *Cymbella* sp. (2.9 percent)

(c) Mar. 27, 1991   Total number of cells: 251,047 cells/l
                       Total number of species: 32 species/l
Skeletonema costatum (93.2 percent), *Rhizosolenia setigera*
(4.5 percent), *Navicula* spp. (0.7 percent), *Nitzschia* spp.
(0.5 percent), *Chaetoceros* sp. (0.4 percent)
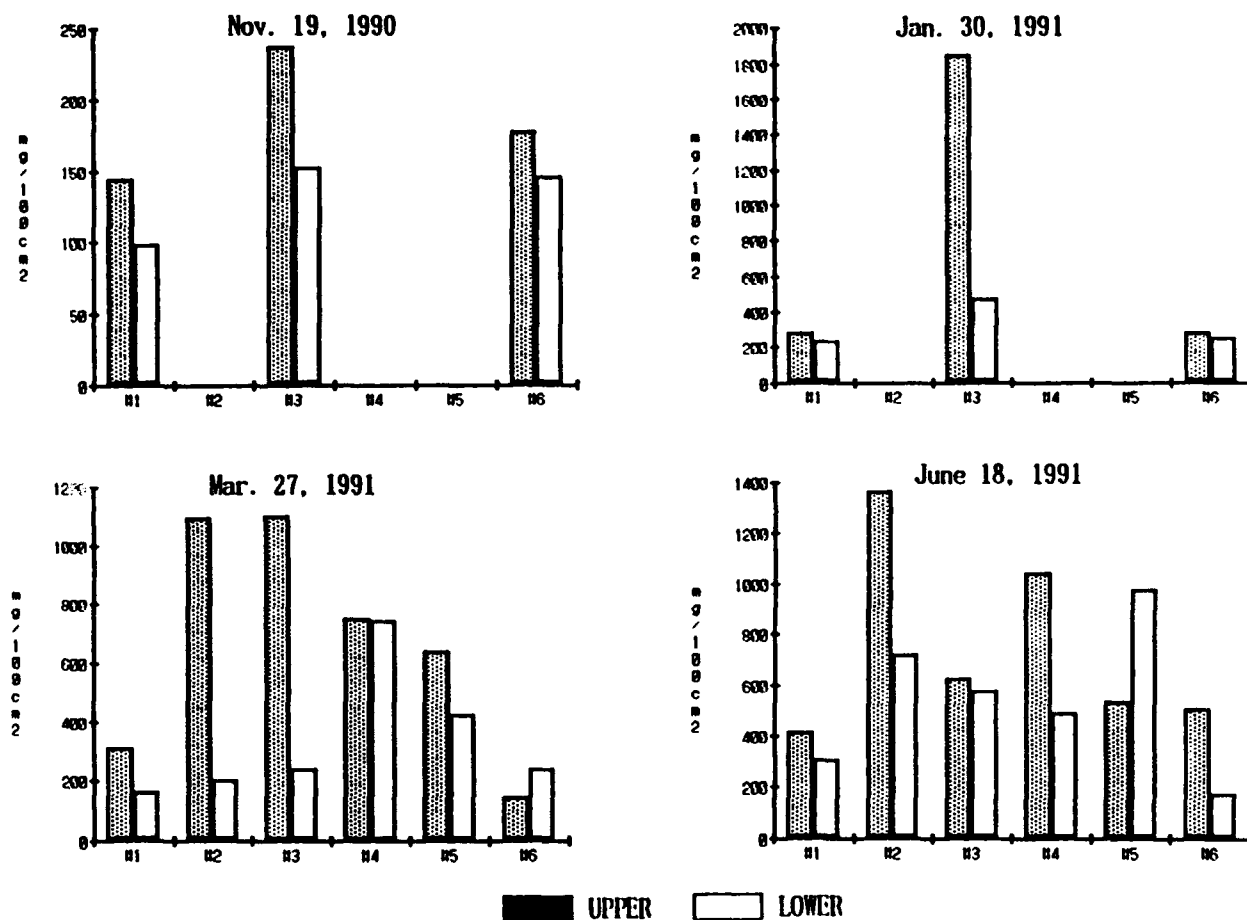
Figure 13.   Changes of the dry weight (mg/100 cm^2)
             of the biofilm

(d) June 18, 1991   Total number of cells: 14,643 cells/l
                      Total number of species: 21 species/l
Skeletonema costatum (87.0 percent), *Rhizosolenia setigera*
(4.4 percent), *Navicula* spp. (3.3 percent), *Melosira num-
muloides* (2.2 percent), *Nitzschia* spp. (1.2 percent)

(2) The primary dominant species accounts for 87.0-96.4 percent of
     the total number of cells except the January observation when
     the proportion of dominance was 49.0 percent. *Skeletonema
     costatum* and *Navicula* spp. were present in all seasons as domi-
     nant species. Particularly, *S. costatum* primarily dominated in

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January, March, and June observations. All dominant species are marine inhabiting. Some of the dominant species are illustrated in Figure 14.
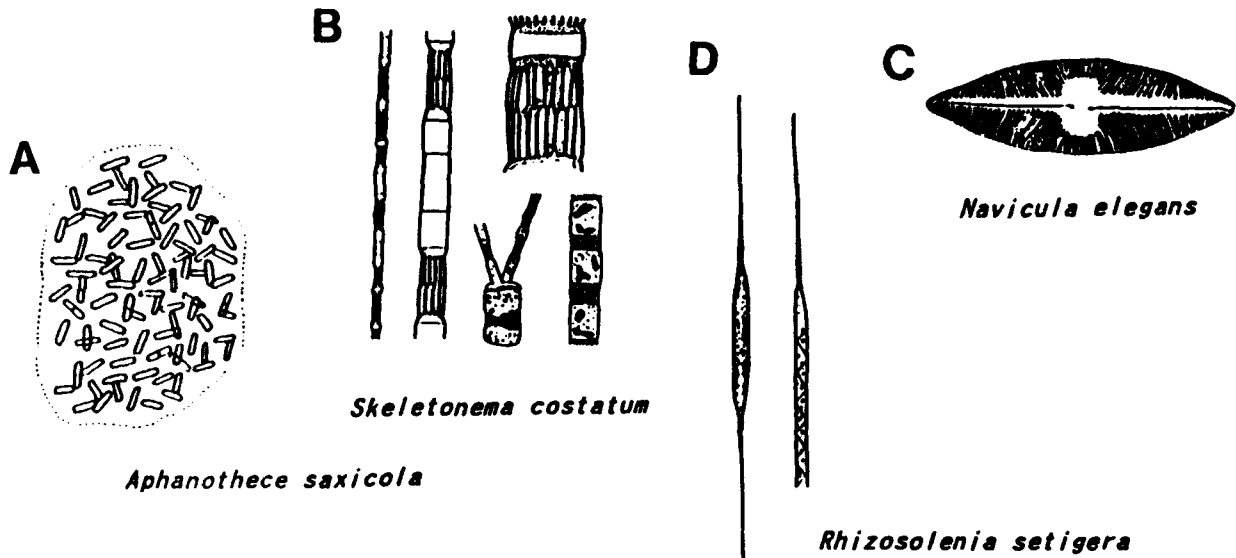
Figure 14. Some of dominant microplant species in the biofilms
A: *Aphaenothece saxicola*, B: *Skeletonema costatum*,
C: *Navicula elegans*, and D: *Rhizosolenia setigera*
(after Mizuno 1990)

b. **Changes of the number of cells.** The number of cells increased with flow velocity in the channels No. 1, 2, and 3 (gravel size: 100-150 mm; v:0.5, 1.0, 2.0 cm/sec) as shown in Figure 15. Effects of the gravel sizes and the aeration were not recognized.

Zooplankton

a. **Changes of fauna.**

(1) A total of 55 zooplankton species were observed. They are firstly classified into two subkingdoms, Protozoa and Metazoa. The former has only one phylum Protozoa. But the latter is further classified into five phylla (Rotifera, Nematoda, Annelida, Arthropoda, Mullusca). The protozoans and metazoans are different in their body plan and body sizes. As for the body plan, the former is unicellular and the latter is multicellular. The body sizes of the protozoans are 30-500 μm, and those of the metazoans are 300 μm-1.5 mm in the species which were collected in the present study. The number of species in each phylum is: Protozoa 38, Arthropoda 7, Rotifera 6, Mollusca 2, and Nematoda and Annelida 1. All species except one (*Amoeba*) are included in the class Ciliatea. Five species of metazoans are larval forms: polychaete larvae of Annelida, nauplius larvae of Copepoda and Cirripedia (Arthropoda), D-larvae and Umbonium larvae of Mollusca. The dominant five species in each observation are:

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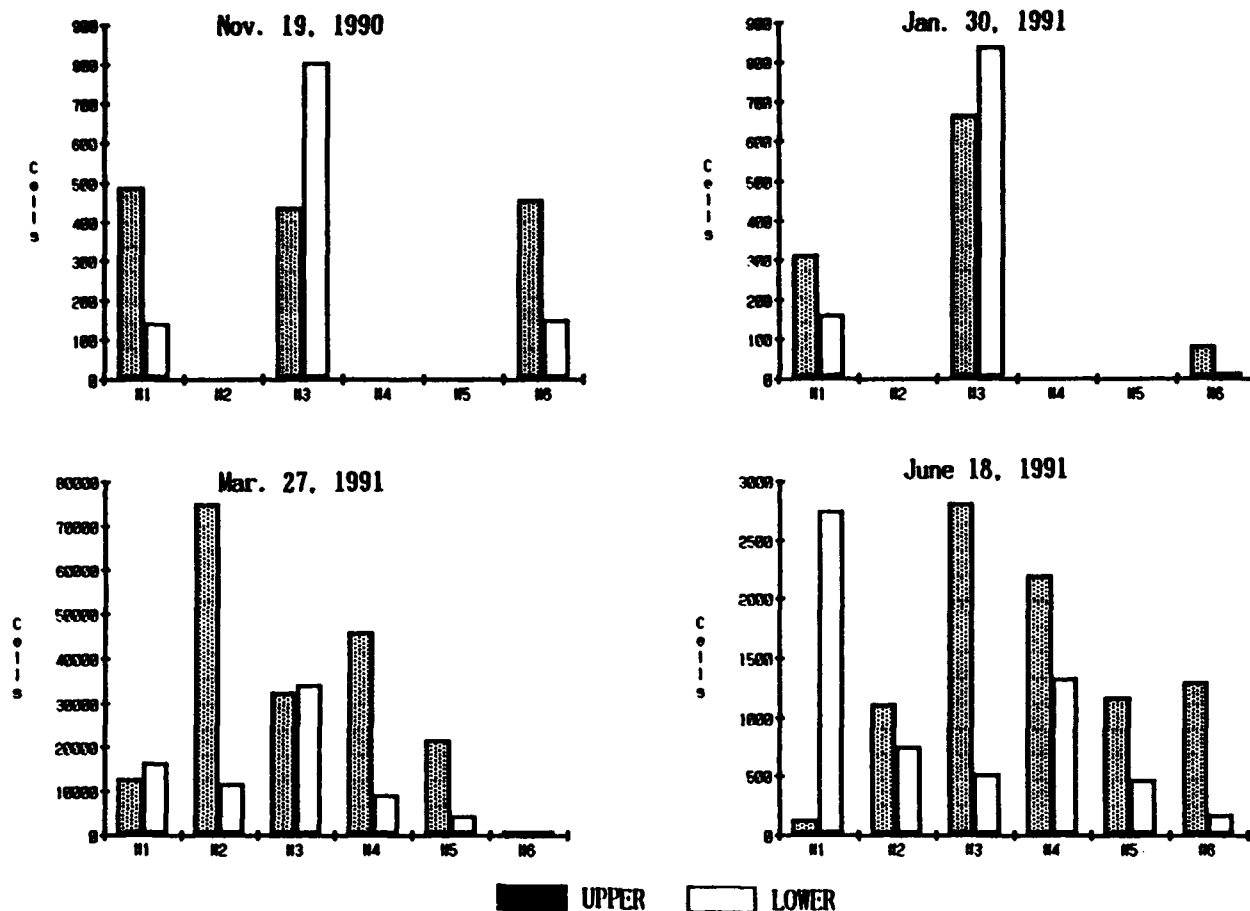
Figure 15.   Changes of the number of cells of the microplants
             (cells/ℓ) in the biofilm

(a)   Nov. 19, 1990   Total number of individuals: 534 N/1
                          Total number of species: 18 species/1
      Tintinnopsis beroidea (30.3 percent), *Strombidium* spp.
      (14.6 percent), *Dystreria* spp. (13.5 percent), nauplius
      larvae of Copepoda (11.2 percent), *Monostyla* sp.
      (10.1 percent)

(b)   Jan. 30, 1991   Total number of individuals: 1,020 N/1
                          Total number of species: 16 species/1
      Tintinnopsis beroidea (30.5 percent), *Strombidium* spp.
      (17.4 percent), *Carchesium* spp. (13.2 percent), *Strombili-
      dium* spp. (10.0 percent), *Didinium natusum* (8.8 percent)

(c)   Mar. 27, 1991   Total number of individuals: 6,564 N/1
                          Total number of species: 23 species/1
      Strombilidium spp. (69.8 percent), *Zoothamnium* spp.
      (6.4 percent), *Eutintinnus rectus* (5.7 percent), *Eutintin-
      nus turris* (2.7 percent), *Helicostomella fusiformis*
      (2.4 percent)

(d)   June 18, 1991   Total number of individuals: 1,380 N/1
                          Total number of species: 17 species/1

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Peritrichida sp. (25.2 percent), *Tintinnopsis beroidea*
(22.6 percent), nauplius larvae of Copepoda (13.0
percent), *Monostyla* sp. (10.4 percent), *Helicostomella
longa* (7.8 percent)

(2) Proportion of dominance (25.2-69.8 percent) is rather low com-
pared with other microorganisms. The most dominant species are
protozoan except two metazoans (nauplius larvae of Copepoda and
Monostyla of Rotifera). Both marine and freshwater species are
included in the dominant species: marine - *Tintinnopsis*, *Heli-
costomella*, *Eutintinnus*; and freshwater - *Strombidium*, *Strom-
bilidium*, *Carchesium*, *Pidinium*, *Zoothamnium*, *Monosytla*. Some
of the dominant species are illustrated in Figure 16.
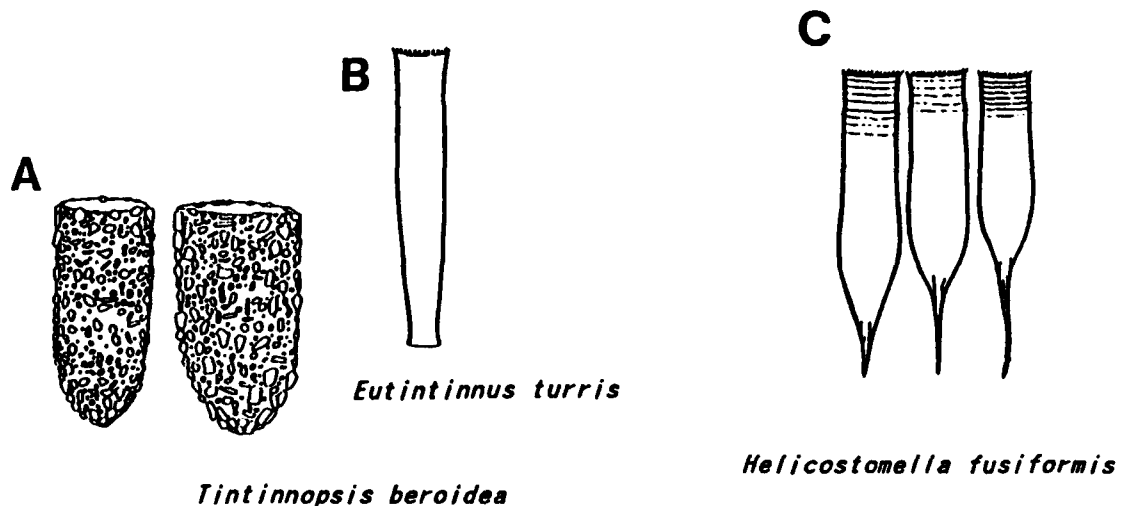
Figure 16. Some of the dominant zooplanktons - A: *Tintinnopsis
beroidea*, B: *Eutintinnus turris*, and C: *Helicosto-
mella fosmis*, (after Minuno 1990)

b. <u>Decreasing tendencies of the number of species and individuals.</u> In
some cases, species which were not present in the influent were
observed in the channel. Those species not observed in the influent
are omitted here.

(1) Figure 17 expresses the differences of the removal efficiencies
on the number of individuals among channels. The removal effi-
ciency reduced with flow velocity. Among channels No. 1, 2 and
3 (gravel diameter: 100-150 mm; v:0.5, 1.0, 2.0 cm/sec), the
highest value was obtained in channel No. 1. The efficiency
diminished with gravel size, and the highest value was obtained
in channel No. 5 which has 20 to 30-mm-diam gravels. A low
efficiency value was expressed in channel No. 6 with aeration
compared with channel No. 1 without aeration.

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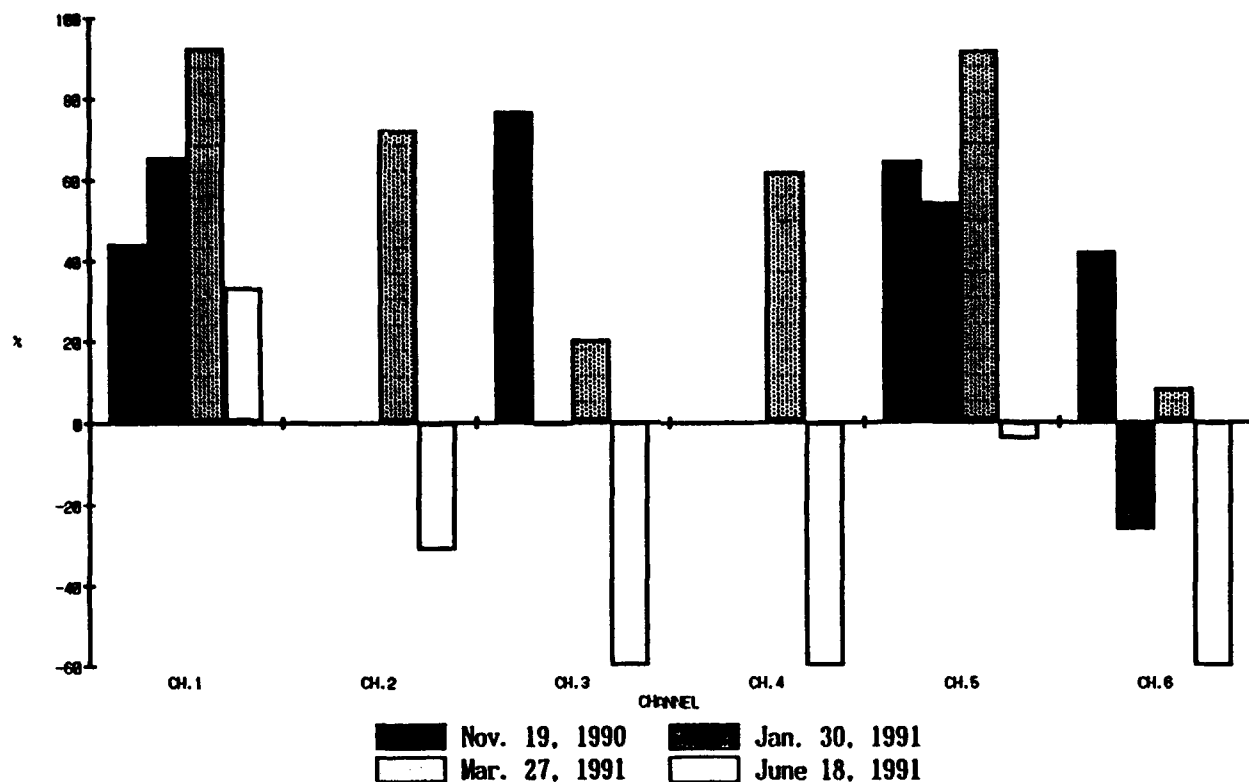
Figure 17. Removal efficiency of the zooplankton

(2) Secondly, the differences in the removal efficiencies between
the protozoans and metazoans are compared (Figure 18) because
these two groups are different in body size. The efficiency
decreased with flow velocity in both protozoan and metazoan
(No. 1, 2, 3) and with gravels size (No. 2, 4, 5). In No. 6
with aeration, the value was lower than channel No. 1 without
aeration. No consistent difference was recognized between the
protozoans and metazoans, although some tendencies were recog-
nized during certain months. That is, the efficiency was high
in the protozoans and low in the metazoans in November; no
clear difference was found between them in March; and the value
was high in the metazoans and low in the protozoans in the
January and June observations.

Phytoplankton

a. Changes of flora.

(1) A total of 59 species of phytoplankton were observed. They are
largely classified into phylla Cyanophyta, Dinophyta, Chromo-
phyta, Euglenophyta, and Chlorophyta. The number of species in
each phylum is: Chromophyta 44, Dinophyta 11, Euglenophyta 2,
and Cyanophyta and Chlorophyta 1. Forty-one species of the
Chromophyta are included in the class Bacillariophyceae (dia-
toms). The dominant five species in each observation are:

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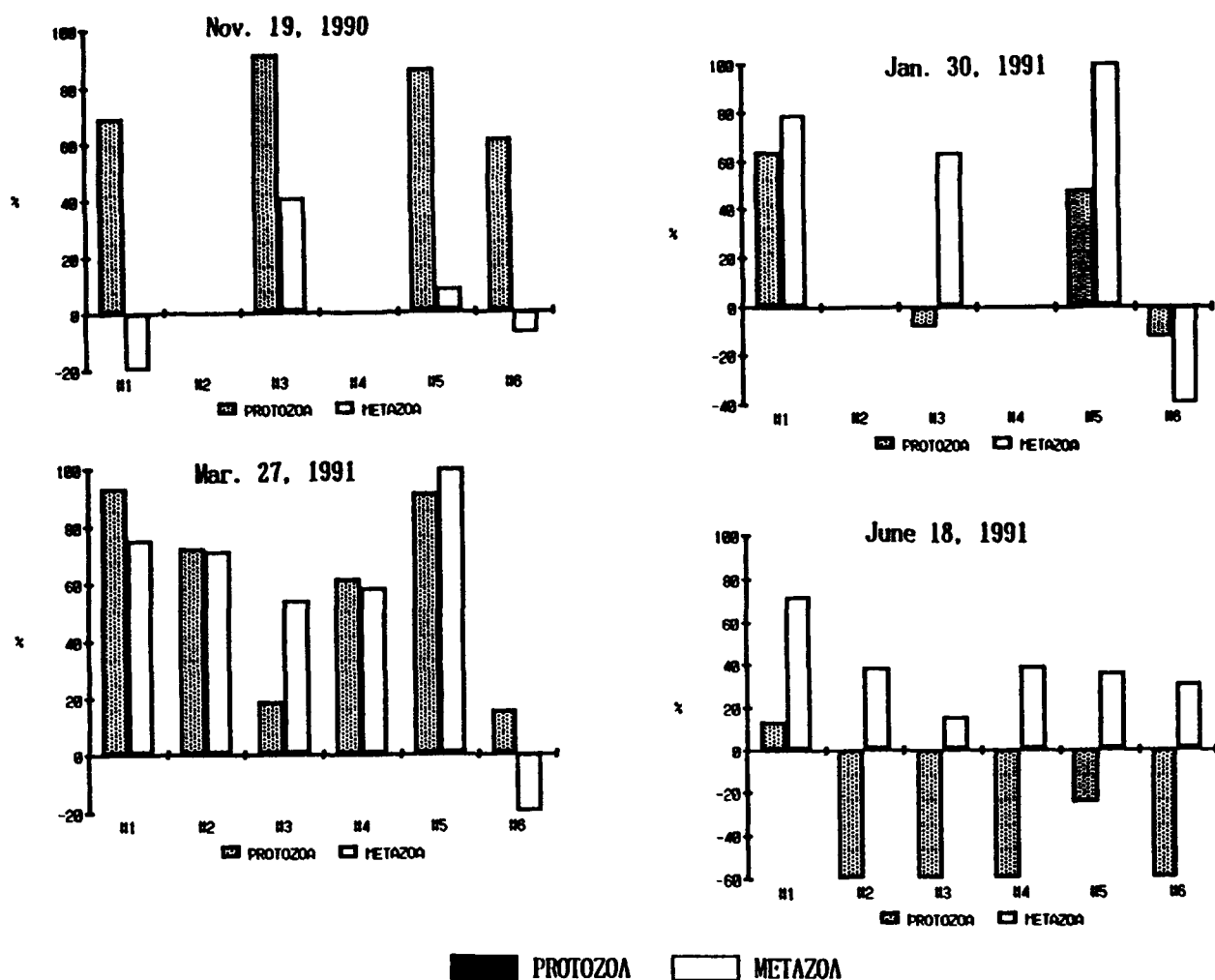
Figure 18. Differences in removal efficiency between the
protozoans and metazoans in the zooplankton

(a) Nov. 19, 1990   Total number of cells: 1,241,600
cells/l
Total number of species: 14 species/l
Skeletonema costatum (82.7 percent), *Euglenophyceae* sp.
(13.1 percent), *Nitzschia* spp. (2.1 percent), *Cymbella* sp.
(1.3 percent), *Navicula* spp. (0.5 percent)

(b) Jan. 30, 1991   Total number of cells: 890,400 cells/l
Total number of species: 30 species/l
Skeletonema costatum (76.9 percent), *Rhizosolenia setigera*
(12.9 percent), *Navicula* spp. (4.3 percent), *Cyclotella*
spp. (1.1 percent), *Nitzschia* sp. cf. *pungens*
(0.7 percent)

(c) Mar. 27, 1991   Total number of cells: 1,945,360
cells/l
Total number of species: 29 species/l
Skeletonema costatum (93.4 percent), *Rhabdonema arcuatum*
(2.6 percent), *Nitzschia* sp. (0.6 percent), *Navicula* spp.
(0.5 percent), *Chaetoceros didymum* (0.4 percent)

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(d)   June 18, 1991   Total number of cells: 7,960,736
                          cells/l
                          Total number of species: 18 species/l
      Skeletonema costatum (99.7 percent), *Navicula* spp.
      (0.1 percent), *Amphiprora* sp. (0.04 percent), *Cyclotella*
      spp. (0.04 percent), *Melosira numuloides* (0.04 percent)

(2)   The primary dominant species accounts for 76.9-99.7 percent of
      the total number of cells. Only one freshwater species (*Cym-
      bella*) was observed in the dominant species in the November
      observation. The habitat of the other species is marine.

b. <u>Decreasing tendencies of the number of species and cells.</u> In some
cases, species which were not present in the influent were observed
in the channel. Those species not observed in the influent are
omitted here. Figure 19 shows the difference in the removal effi-
ciency on the number of cells among the channels. The removal effi-
ciency decreased with flow velocity. In channels No. 1, 2, and 3
(gravel diameter: 100-150 mm; v:0.5, 1.0, 2.0 cm/sec), the highest
efficiency was obtained in channel No. 1. The efficiency declined
with gravel size, and the highest value was obtained in channel
No. 5 which has 20 to 30-mm-diam gravels. A low value of the effi-
ciency was expressed in channel No. 6 with aeration compared with
channel No. 1 without aeration.

■ Nov. 19, 1990   ▨ Jan. 30, 1991
▢ Mar. 27, 1991   ▢ June 18, 1991
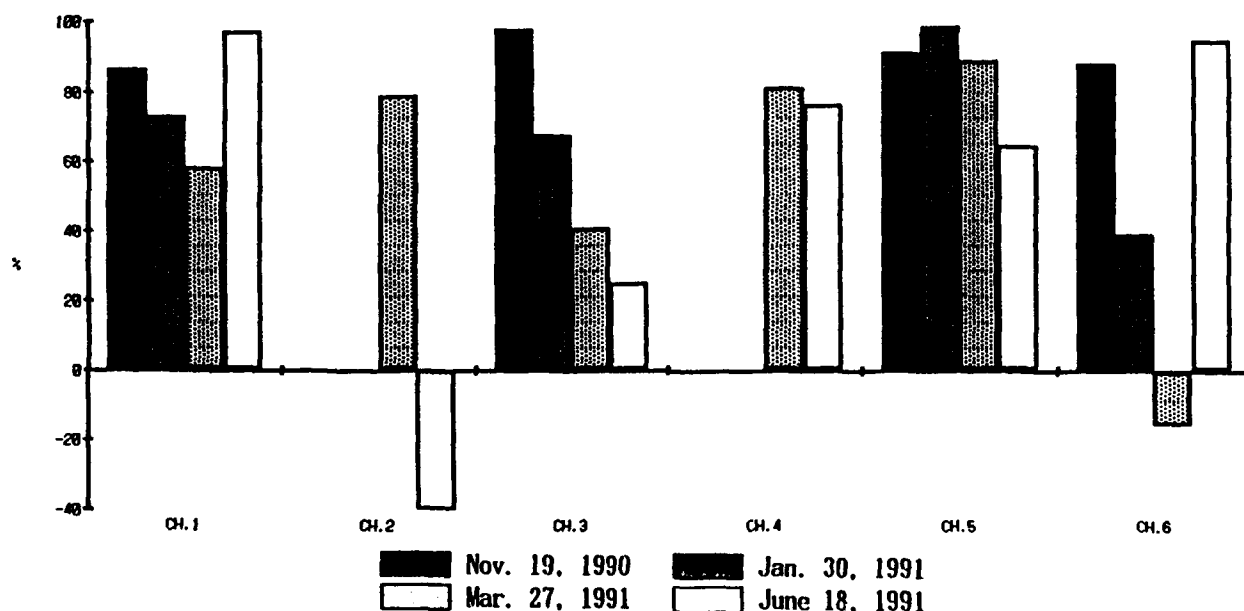
Figure 19. Removal efficiency of the phytoplankton

Large Sessile Animals

Other than the above microorganisms, many kinds of large size sessile
and benthic animals were observed in the biofilm, in the pipes, and on the
channel walls (Figure 20).

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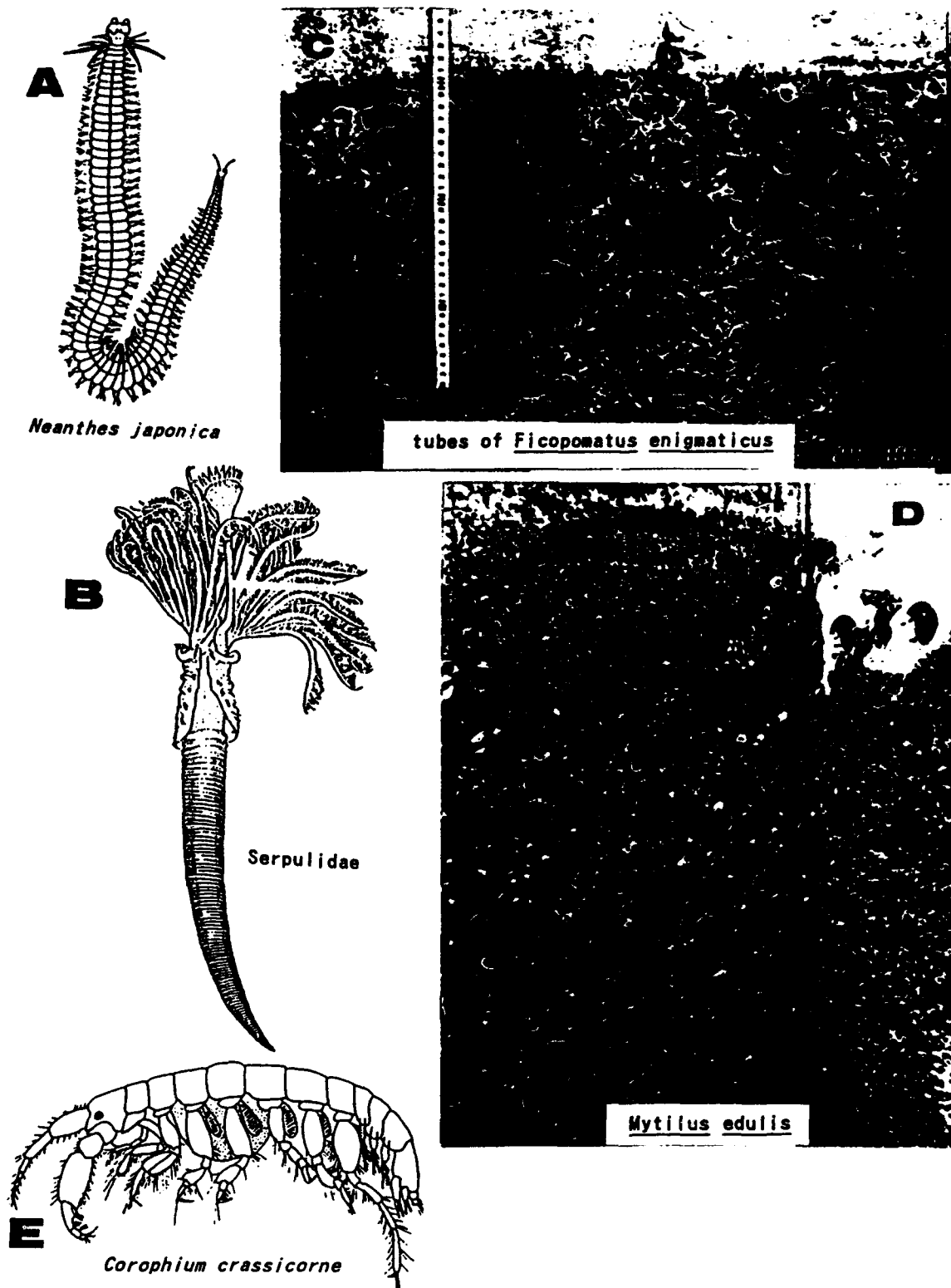
Figure 20. Some of representative sessile animals observed on the gravels and channel walls - A: a nereid *Neanthes japonica*, B: a species of *Serpulidae*, C: a serula *Ficopomatus enigmaticus* on the channel wall, D: a bivalve *Mytilus edulis* on the wall of the head pit, and E: an amphipod *Corophium crassicorne*, (A: after Akiyama & Matsuda 1974; B: after Fuchaku-Seibutsu Kenkyukai 1986; D: after Shiino 1969)

a. Phylum Cnidaria
   Hydroida sp.

b. Phylum Annelida, Class Polychaeta, Order Errantia
   Neanthes japonica
   Neanthes succinea
   Hesionidae sp.
   Capitella sp.

c. Phylum Annelida, Class Polychaeta, Order Sedentaria
   Ficopomatus enigmaticus
   Hydroides ezoensis
   Polydora sp.

d. Phylum Mollusca, Class Pelecypoda, Order Dysodonta
   Mytilus edulis
   Musculus senhousia
   Limnoperna fortunei kikuchii

e. Phylum Arthropoda, Class Crustacea, Order Thoracica
   Balanus improvisus

f. Phylum Arthropoda, Class Crustacea, Order Amphipoda
   Anisogammarus sp.
   Corophium sp.

Coliform Groups and Heterotrophic Plate Number

Both the coliform groups and heterotrophic plate number reduced in the effluent (Table 6). The number of the coliform groups in the influent ranged from 490 to 27,000 (mean 13,623) MPN/100 ml, but those in the effluent ranged from 17 to 3,300 (mean 1,101) MPN/100 ml. On the other hand, the number of the heterotrophic plate in the influent ranged from 1,600 to 67,000 (mean 88,900) CFU/ml, but those in the effluent ranged from 70 to 34,000 (mean 5,287) CFU/ml.

The removal efficiency of the coliform group among channels was affected only by the presence or absence of the aeration. In channel No. 1 (not aerated) and No. 6 (aerated), high removal efficiency was found in channel No. 6. Average removal efficiency was 80.6 - 99.7 percent. However, on January observation the value in channel No. 1 was 44.9 percent.

Meantime, the removal efficiency of the heterotrophic plate number shows the same tendency as the coliform group. Average removal efficiency was not so constant as compared with the coliform group, but removal efficiencies of over 80 percent were shown in some cases.

Chlorophyll *a*

Chlorophyll *a* in the influent ranged from 3.9 to 32.5 μg/l (min: Jan. 1991; max: June 1991), but in the effluent was about 2 μg/l (Table 7). No particular tendencies according to differences in the experimental conditions were found.

TABLE 6. NUMBER OF THE COLIFORM GROUPS AND THE HETEROTROPHIC PLATE
NUMBER AND THEIR REMOVAL EFFICIENCIES

Coliform Group (MPN/100 ml)

	INFLUENT	#1	#2	#3	#4	#5	#6
Nov. 1990	27000	1300		3300		2400	2200
Jan. 1991	490	270		33		17	17
Mar. 1991	10000	700	490	1300	330	330	33
June 1991	17000	1300	3300	1700	1300	1000	700

Removal Efficiency (%)

	#1	#2	#3	#4	#5	#6
Nov. 1990	95.2		87.8		91.1	91.1
Jan. 1991	44.9		93.3		96.5	96.5
Mar. 1991	93	95.1	87	96.7	96.7	99.7
June 1991	92.4	80.6	90	92.4	94.1	95.9

Heterotrophic Plate Count (CFU/ml)

	INFLUENT	#1	#2	#3	#4	#5	#6
Nov. 1990	67000	8000		8400		34000	26000
Jan. 1991	1600	350		320		230	180
Mar. 1991	3300	2700	720	140	70	370	250
June 1991	17000	5500	1300	12000	1700	220	3300

Removal Efficiency (%)

	#1	#2	#3	#4	#5	#6
Nov. 1990	88.1		87.5		49.3	61.2
Jan. 1991	78.1		80		85.6	88.8
Mar. 1991	18.2	78.2	95.8	97.9	88.8	92.4
June 1991	67.6	92.4	29.4	90	98.7	80.6

TABLE 7. CHLOROPHYLL *a* AND ITS REMOVAL EFFICIENCY

CHLOROPHYLL *a* (μg/l)

	INFLUENT	#1	#2	#3	#4	#5	#6
Nov. 1990	9.5	1.4		0.4		0.6	1.3
Jan. 1991	3.9	1.3		1.7		0.2	2.5
Mar. 1991	7	1.3	1.4	1.7	0.6	0.6	2.8
June 1991	32.5	1.3	5.9	5.4	3.9	3.4	3

REMOVAL EFFICIENCY (%)

	#1	#2	#3	#4	#5	#6
Nov. 1990	85.2		95.8		93.7	83.6
Jan. 1991	66.7		56.4		94.9	35.9
Mar. 1991	81.4	80	75.7	91.4	91.4	60
June 1991	96	81.8	83.4	88	89.5	90.8

DISCUSSION

Purification Effects of the Experimental Channels

Nakamura and Sakai (1987) divided 220 days of river water purification experiment into four subperiods according to the purification effect on SS. The first is the first stable period (0 to 40th day) when very good purification proceeded; the second is the transition period (40 to 90th day) when the water quality of the effluent is affected by the purification process; the

third is the instable period (90 to 150th day) when the values of influent and effluent are sometimes reversed; and the fourth is the stable period (150 to 220th day) when good purification is proceeding.

A pattern similar to above is also recognized in our experiment. From the relationship between the improvement effect of SS and the elapsing time of the experiment (Figure 7), it is assumed that there are four subperiods in the whole experimental period:

a. 1st Period: 0 to 30-40th day
Sufficient purification effect is not yet attained.

b. 2nd Period: 30-40th to 60-90th day
Stable purification is proceeding.

c. 3rd Period: 60-90th to 150-180th day
Unstable period.

d. 4th Period: after 150-180th day
Stable purification is proceeding again.

The removal efficiency of BOD in river and sewage waters is generally in the range from 50 to 90 percent (e.g., Inamori et al. 1990, Kiriku et al. 1984, Nakamura and Sakai 1987; Osanai 1990; Sekiyama et al. 1987; Tsuchiya and Izumi 1983, 1984); and that of COD is in the range from 20 to 50 percent (e.g., Osanai 1990; Sekiyama et al. 1987; Tsuchiya and Izumi 1983, 1984). Meanwhile, the removal efficiency of COD in the seawater is about 15 percent (Otsuki 1990) and 27 to 38 percent (Tazawa et al. 1991), although only a few examples are available. In the present experiment, the average removal efficiency of COD through the whole experimental period is below 20 percent (Figure 8A). This value is somewhat lower than those of the previous experiments, but some channels exceed 20 percent and even 30 percent depending on season.

The removal efficiency is largely affected by the gravel size. Thus, the efficiencies of the smallest gravel channel (#5) is always the highest. However, small gravel is ineffective, or sometimes has adverse effects on the normal orientation of the channel. Actually, the operation of channel #5 was suspended on September 1991 because of the clogging of the channel despite several backwash attempts.

The removal efficiency of SS decreased with flow velocity. Meanwhile, the removed weight increased with the flow velocity.

Although no clear improvements are recognized in SS by aeration, the aeration will be effective on COD in the season with high polluted load. On the other hand, aeration promotes resuspension of biofilm from the gravel, and it caused low transparency in channel No. 6, particularly during the low temperature period with little suspended solids (Table 2). This result means that the aeration is not effective or is rather conversely effective on improvement of the transparency during the low temperature period. The above purification effects of the experiment are summarized in Table 8.

TABLE 8. SUMMARY OF THE PURIFICATION EFFECTS OF THE CHANNEL

	Gravel Size			Flow Velocity (HRT)			Aeration	
	large	medium	small	fast (short)	medium	slow (long)	done	none
SS								
SS Removal Efficiency	::	::	::	::	::	::	::	::
SS Removed Mass	::	::	::				::	::
COD				x				
Clogging Prevention			x	x				x
No. of Individuals of Microanimals in Biofilm	?	?	?	many		few	many	few
No. of Individuals of Microplants in Biofilm	?	?	?	many		few	?	?
Dry Weight of Biofilm	?	?	?	much		little	?	?
Removal Efficiency of Zooplankton							x	
Removal Efficiency of Phytoplankton								
Removal Efficiency of Coliform Group	?	?	?	?	?	?	?	
Removal Efficiency of Heterotrophic Plate Count	?	?	?	?	?	?		
Removal Efficiency of Chlorophyll	?	?	?	?	?	?		?

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Microorganisms in the Channel

In general, the number of species and individuals increases with time with some fluctuation (succession). Finally, the ecological succession reaches a stable biotic community (climax) which is in equilibrium with the existing environmental condition.

In this experiment, the number of microorganism species in the biofilm and the plankton increased toward spring (Mar. 1991) and reduced toward early summer (June 1991) (Figure 21). This figure also shows the changes of SS load in the influent. There is a good correspondence between the number of species and the SS load changes. In the microanimals in the biofilms, if we consider SS as a food source for the organisms, such correspondence between SS and the number of species may be illustrated by niche expansion because of the food (quantity and quality) supply. Further, the number of species in each organism group is similar to each other despite different sampling unit. The maximum difference is 16 in January observation.
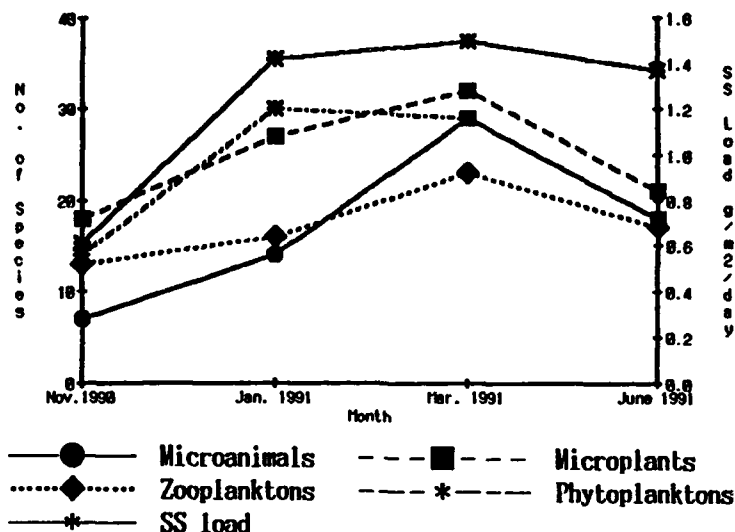
Figure 21. Seasonal changes of the microorganisms in
the channel and SS load in the influent

The following relationships among the number of species, the number of individuals, and the dry weight of the biofilm are obtained.

a. The relationship between the number of species and individuals are seen to be below a certain level. Thus, their relationship is confined to the shadowed area in Figure 22.

b. The relationship between the dry weight and the number of individuals is seen to be below a certain level. Thus, their relationship is confined to the shadowed area in Figure 23. The maximum number of individuals present in the area may be below 600 mg/100 cm^2 of DW. In the area above 600 mg/100 cm^2, the number of individuals may be below 500/cm^2.

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Figure 22. Relationship between the number of species and individuals of the microanimals in the biofilm

Figure 23. Relationship between the dry weight of the biofilm and the number of individuals of the microanimals in the biofilm

c. The number of species increases with dry weight up to 600 g/100 cm^2, but it is maintained at 10-12 species afterwards (Figure 24).

Some speculations can be made from the above relationships. There is a carrying capacity corresponding to a particular number of species. The number of individuals is maintained below that level of carrying capa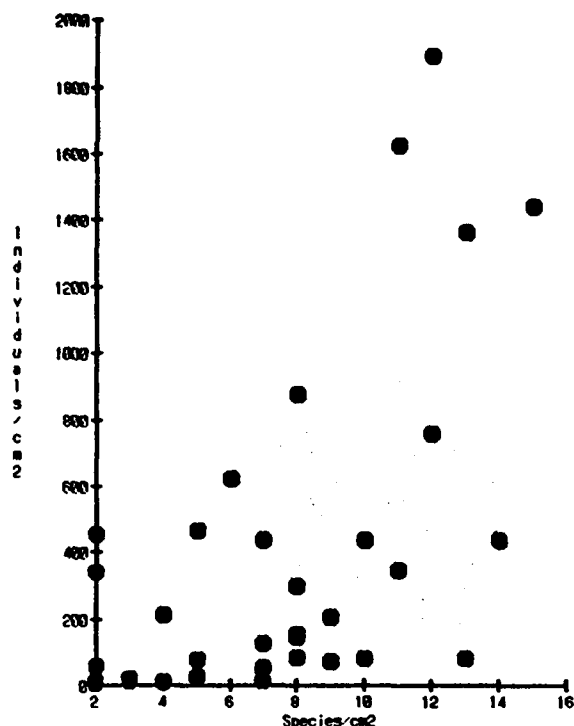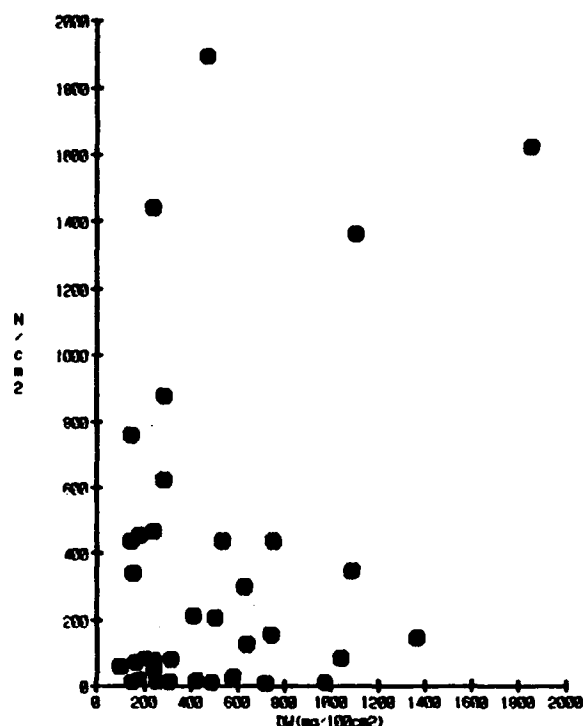city. The number of species and individuals is dependent on the space (represented by the dry weight) below a certain level, but both are independent of the dry weight above that level. That is, if the microorganisms in this experimental channel are contributing to purification, surplus biofilm over 600 mg/100 cm^2 may contribute to the clogging of the channel or humus production. By the way, the removal efficiencies of the channels which have over 600-mg/100 cm^2 biofilm (No. 3 in Jan. 1991; No. 2 and 3 in Mar. 1991; and No. 2 in June 1991) are relatively low, although there are some exceptions (Figure 8).

The relationship between the number of species and the population density (N/dry weight mg/cm^2) is expressed next (Figure 25). It seems that there are three kinds of relationships. That is, group-A in the figure has a proportional relationship; the density is keeping below a certain density level in group-B; and group-C is a special case consisting of only two species. In group-A, the proportion of the primary dominant species is higher than 60 percent. The number of microanimal species is also affected by the dominance proportion of the primary dominant species (Figure 26). Thus, the number of species in the biofilm declines with the dominance proportion.
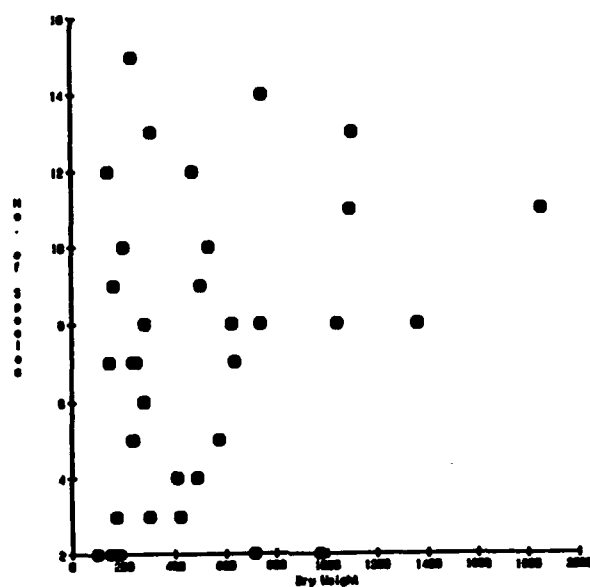
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Figure 24. Relationship between the
dry weight of the biofilm
and the number of species
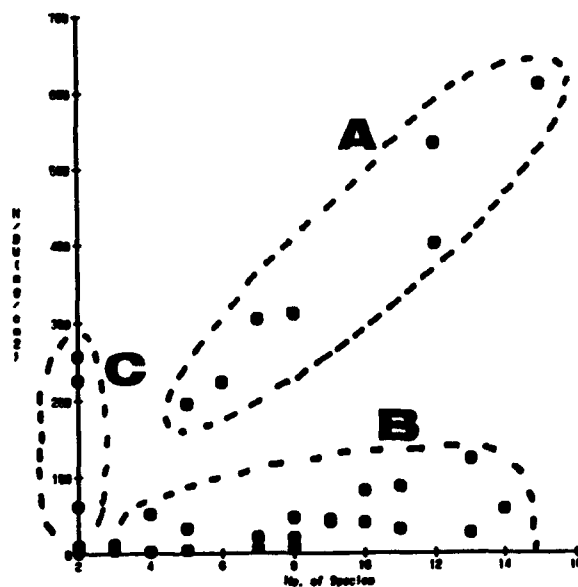of the microanimals in
the biofilm

Figure 25. Relationship between the
number of species and the
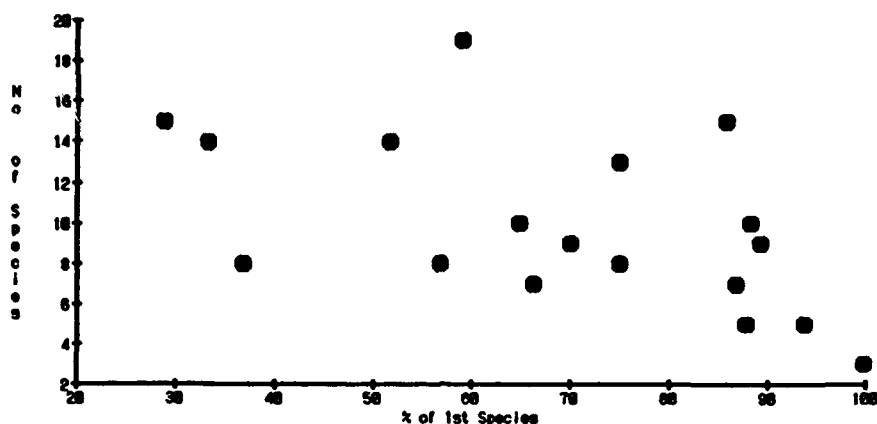population density (N/dry
weight mg/cm^2)

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Figure 26. Relationships between the proportion of dominance
of the primary dominant microanimal species in the biofilm
and the number of species in the biofilm

Figure 27 illustrates the pattern of succession of the dominant species
found in the biofilms. In case of microanimals (Figure 27A), the freshwater
species, *Carchesium, Vorticella* and *Zoothamnium*, have been mostly dominant one
after another. Marine Ciliata like *Eutintinnus* and *Tintinnopsis* increased in
March 1991, though their dominance proportion was low. Further, the metazoans
(*Nematoda, Monosytla*) have maintained constant but low proportion through the
whole experimental period. On the other hand, alternation of the primary
dominant species seen in the microanimals is not recognized in the microalgae
in the biofilm (Figure 27B). Although *Aphanothece* occupied an overall major-
ity in November 1990, only *Skeletonema costatum* is the primary dominant spe-
cies after that.

Comparisons with biological aspects in the wastewater treatment plant
will be discussed as follows. It is however, necessary to pay attention to
the interpretation, because there is a great difference between seawater and
freshwater.

We may know some of the purificatory conditions in the present experi-
mental channel from the biofilm. In the condition when the proper pollutant
load is supplied sand the purification is proceeding smoothly, such Cilita as
Carchesium, Zoothamnium, Epistylis, Opercularia, etc., are dominantly present
in the biofilm in the wastewater plant (Kuniyasu 1988, Sudo, ed. 1988). Among
them, *Zoothamnium* and *Carchesium* also dominantly appeared in the present
channels.

The color of the biofilm is also a good index for the degree of the
proper pollutant load. In the wastewater, gray-brownish biofilm indicates
proper load, and brownish biofilm shows a rather small load (Inamori 1989).
In our observations, the color of the biofilm is generally brownish. By the
way, mean pollutant load of T-COD in the whole experimental period was
0.9 g/m^2/day and that of T-TOC was 1.11 g/m^2/day.

Role of micrometazoans in water purification and sludge reduction has
been repeatedly emphasized (Inamori 1989; Inamori et al. 1987, 1989; Sudo,
ed., 1988), because clogging of the channel is the most troublesome problem in
the maintenance of channel-type facilities, and there is no effective sludge

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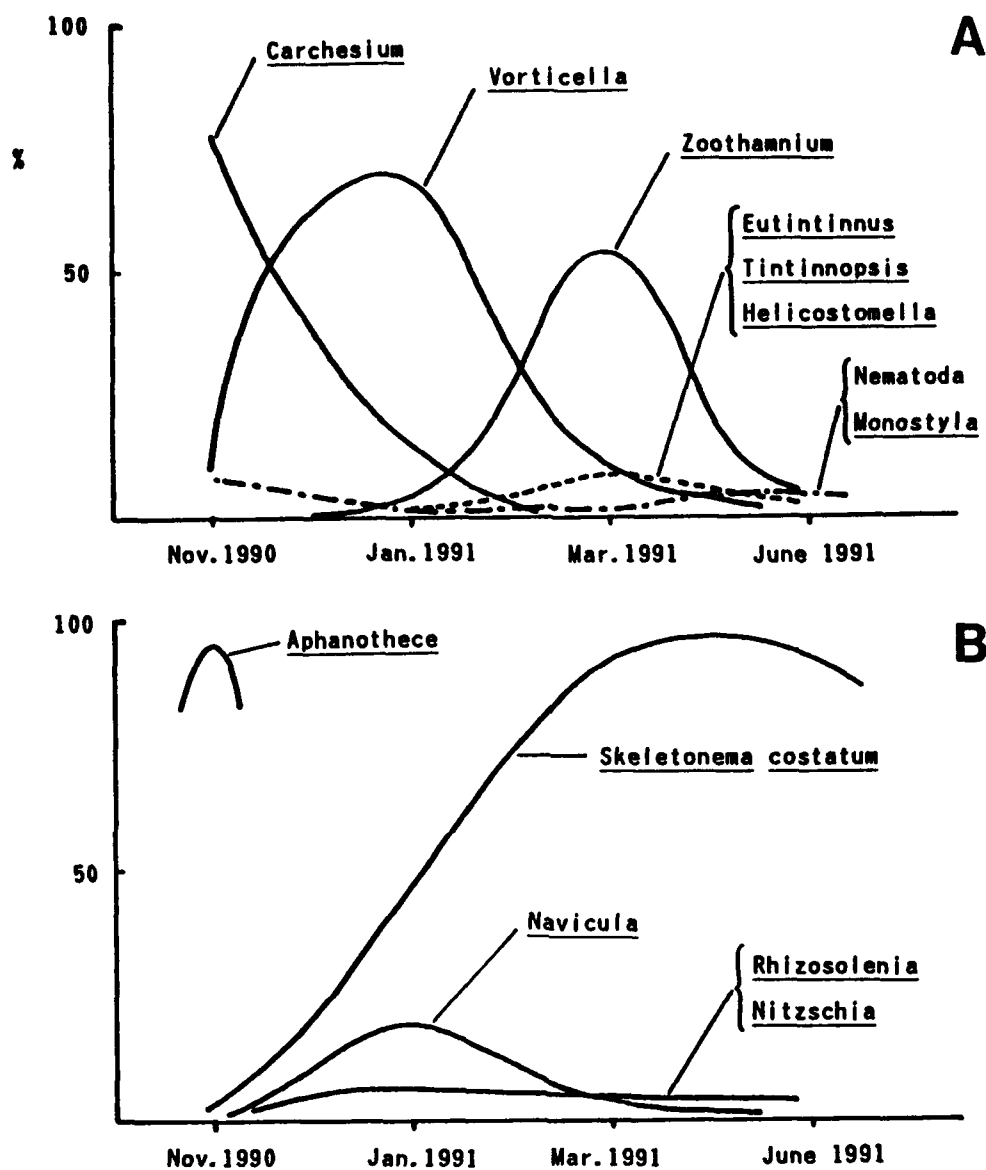
Figure 27. Succession of the dominant microorganisms
in the biofilm (A: microanimals, B: microplants)

reduction method. Of the many kinds of microorganisms appearing in the bio-
film, particularly micrometazoans contribute to reducing sludges. In a rich
ecosystem, a long food chain is formed because of the presence of many kinds
of organisms assigned to a variety of trophic levels, and the energy lost by
respiration becomes large. Thus, it leads to sludge reduction. The predation
by micrometazoans has primary importance for sludge reduction, because the
sludge reduction is realized mainly by the predator-prey interaction in the
food chain.

Other than those microorganisms, many kinds of sessile animals were
observed in the biofilms and pipes, and on the channel walls. Although con-
tributions to water and sediment purification by these animals have been
repeatedly mentioned (e.g., Harris 1990; Hosomi 1989; Jorgensen 1990;

Kurihara, ed. 1988; Sano 1982), the mechanism of purification is scarcely known. As for sludge reduction, for example, the snail *Semisulcospira libertina* contributed well to humus reduction in the porous channel, because these snails fed on biofilms (Sano 1982). On the contrary, those sessile or benthic animals may cause a clogging of the channel. In the present experiment, water flow was blocked several times by the attachment of the bivalve *Mytilus edulis* on the porous plate between the head pit and channel. If we grasp their purificatory function and clogging prevention methods, we will be able to develop a new Ecological Purification Method which utilizes the biological self-purificatory function of both biofilms and sessile and benthic animals.

The number of the coliform group is one of the important items in the Environmental Standard on Water Pollution and the bathing suitability at beach resorts. The number in the influent of the present experiment (13,623 MPN/100 ml) was much higher than the standard value (1,000 MPN/100 ml) in level A of the environmental standard and bathing suitability. The number in the influent, however, decreased to 1,101 MPN/100 ml.

Chlorophyll a in the eutrophic sea, e.g. Seto Inland Sea of Japan, was about 3.1 μg/l (1971-72) (Oceanographical Society of Japan, ed. 1985). The value in the influent of the present experiment (mean 13.2 μg/l) exceeds the value in Seto Inland Sea. However, it was improved to 2.0 μg/l, which is slightly lower than the value in Seto Inland Sea from 1963 to 66 when the eutrophication had not progressed to the present level.

The relationships between the experimental conditions and the fauna and flora, dry weight, and removal efficiencies are summarized in Table 8. The number of individuals of microorganisms and the dry weight in the biofilm were not affected by the gravel size, but high values of these items were obtained in the channel with rapid flow velocity. Aeration affected the number of individuals of zooplankton, and high values were shown in the aerated channel. The reason for this tendency may be the survival of the organisms due to the presence of enough oxygen to survive. The relationship between the gravel size to flow velocity and the removal efficiency of the plankton represents the same pattern as the case of SS. Meantime, the adverse effect on the removal efficiency of zooplankton by aeration is found. The reason for this tendency may be the survival of the organisms due to enough oxygen supply. It is necessary to strictly cut off sunlight in order to restrain the multiplication of phytoplankton in the channel.

Future Application of the Porous Bed Contact
Purification Method to the Port and Harbor Facilities

The channel-type porous bed contact purification method used in seawater may be characterized as follows:

a. It can clarify a large quantity of polluted seawater.

b. Clogging of the channel will be delayed in the case of low pollutant load.

c. Organic matter is not so greatly removed.

d. Driving cost is cheap.

The channel-type porous bed contact purification method might be a very effective purification method in harbors and canal areas in the innermost part of a closed bay. We supposed that the channe.-type porous bed contact purification method plant is not so much a genuine purification plant as it is a secondary treatment plant for COD removal from organic contaminated sewage waters, because the above characteristics of the purification channel can be adapted to meet the various conditions in such area.

How do we practically apply this channel to the port and canal area? We propose building the channel into the harbor and marine structures as revetment, breakwater, etc. By these means, they may have the additional function of purifying seawater.

Some example of ideas of the built-in channel are shown in Figures 28 and 29. In the innermost part of the port with the canal network, the channel can be inserted into the sea wall or revetment (Figure 28) or laid under the ground. In polluted inner bays, a small area is closed by the breakwater with the channel in its body. The pollutant seawater is purified while running through the channel, and we will be able to use the closed area for amusement, water leisure, etc. (Figure 29).

SUMMARY

- The channel-type porous bed contact purification method is effective for polluted seawater as well as wastewater. It particularly has an excellent effect on removing SS, decreasing turbidity, and improving transparency. Therefore, the application of this method is for the water which needs visual beauty.

- From the view point of plant maintenance and control, it is practical to use larger gravel (in case of the present experiment 100-150 mm) because of the difficulty of preventing clogging, although the removal efficiency of the channel with the small gravels is larger than that of large gravels.

- The removal efficiency of SS decreased with flow velocity, whereas the mass removed increased. Clogging tends to take place in the channels with a high pollutant load per unit volume.

- Aeration is effective in the removal efficiency of COD.

- Many kinds of organisms are observed in the channels. A new Ecological Purification Method will most likely be developed, if we aptly utilize biological self-purificatory functions of those organisms.

- The condition of biofilms in the present experiment resembles that in the sewage treatment facilities in which smooth treatment is proceeding.

- Gravel size does not affect the number of individuals of micro-organisms in the biofilm and the dry weight of biofilm. However, these values increased with flow velocity.

人工竹笹工法

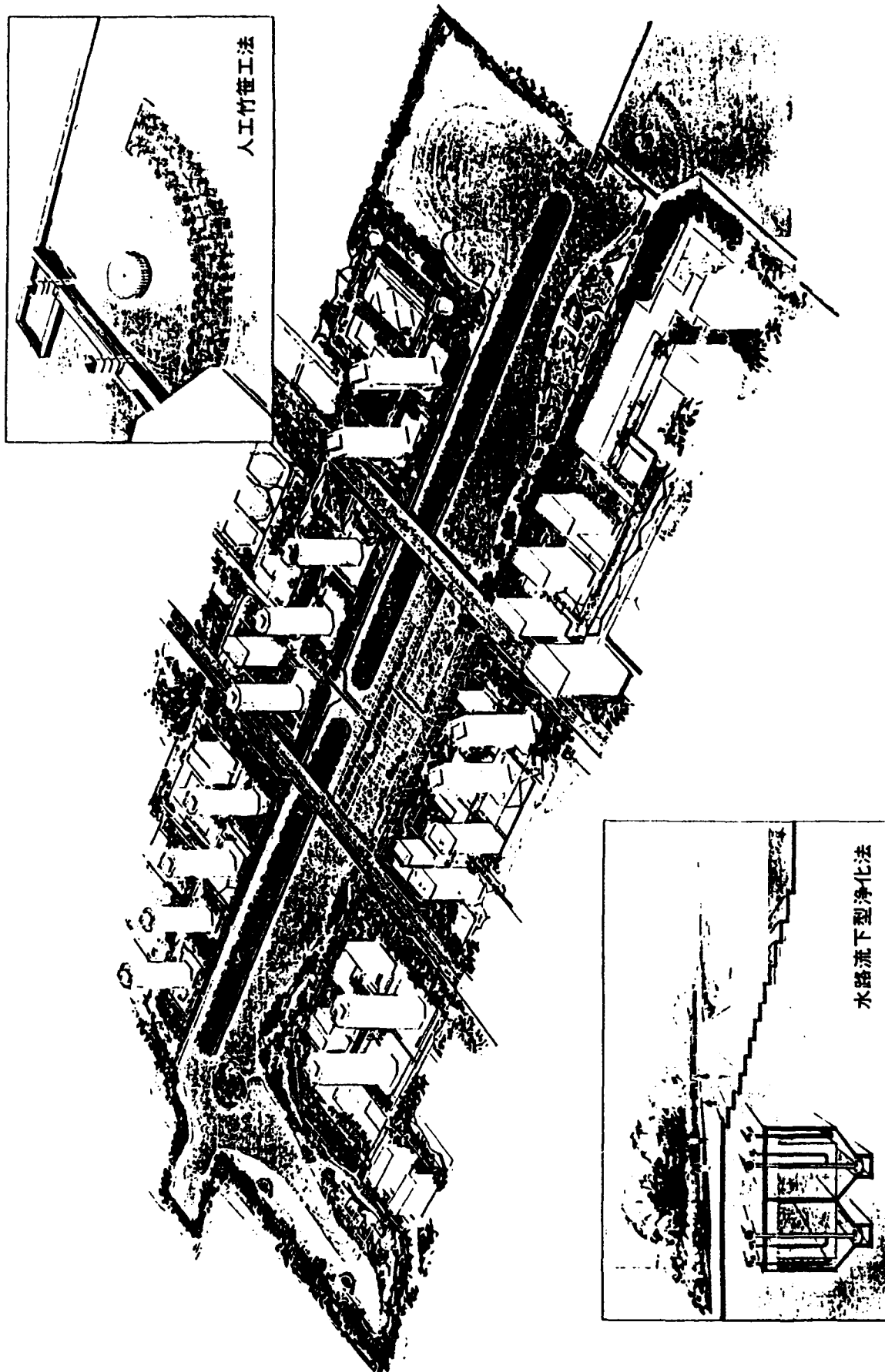水路流下型浄化法

Figure 28. An example of image of application of the channel-type purification facility into the canal area
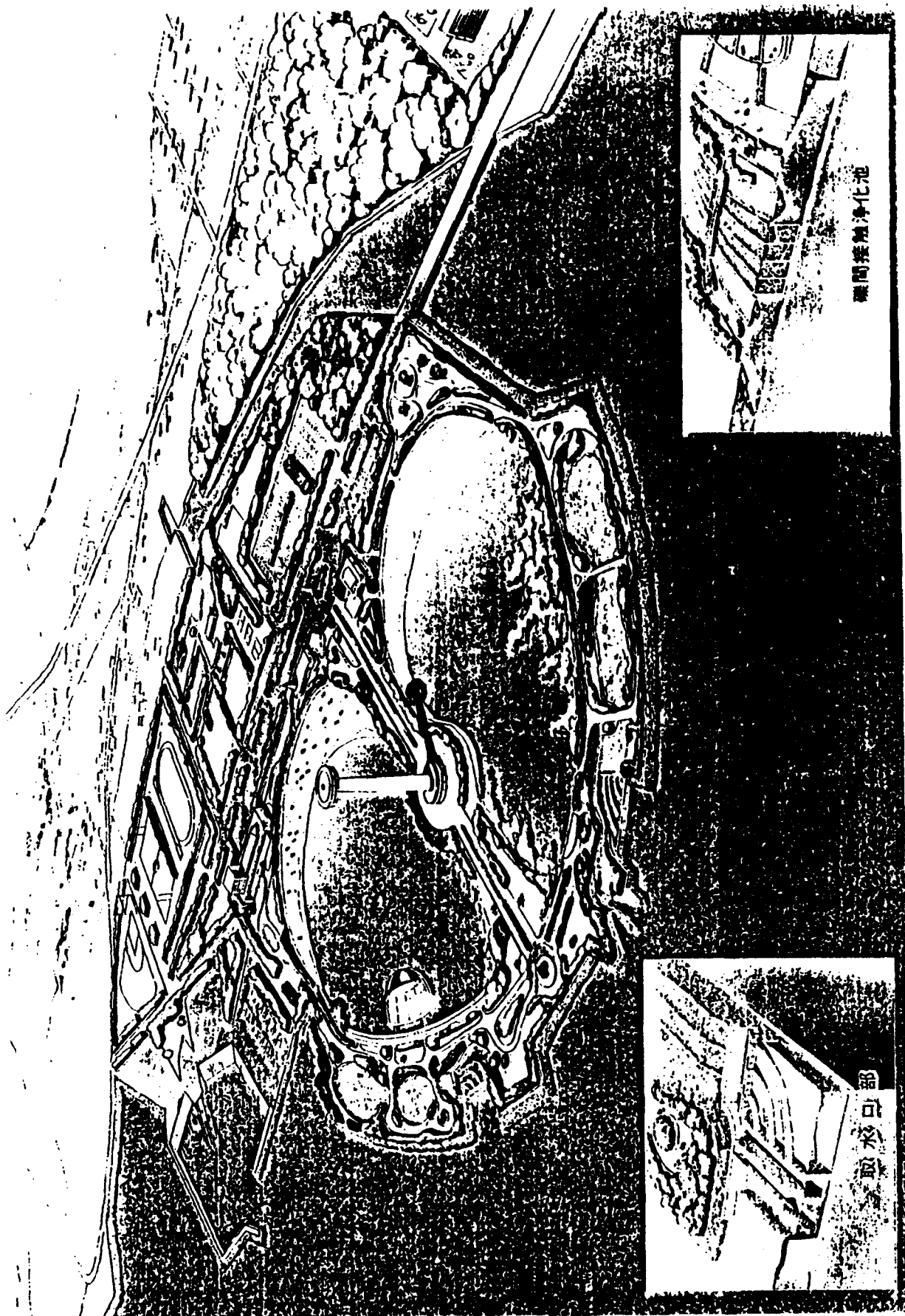
礁間接触浄化池

取水口部

Figure 29. An example of image of application of the lagoon-type purification
facility into the closed inner bay

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- The removal efficiency of planktons shows a similar tendency as that of the SS. Aeration may adversely affect the removal efficiency, because it enhances the survival of the planktons.

- The number of the coliform group decreased to almost the same level as level A of the Environmental Standard.

- Chlorophyll a decreased to the pre-eutrophication level.

- By means of the built-in channels into the harbor and marine structures, they can have the additional function of purifying seawater.

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STABILIZING METHOD BY SOLIDIFICATION FOR DREDGED BOTTOM SEDIMENTS

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ABSTRACT

It is possible to utilize the dredged seabed sediment effectively as excellent material after the proper treatment. Main purpose of the treatment is to eliminate harmful substances and to satisfy the technical requirement from a viewpoint of civil engineering. This paper introduces the solidification technique as a treatment method and usage of its chemical improvement effect. Merits of this technique are mentioned below: 1. Filling can be done on the reclaimed land with sediment. 2. Structures constructed on the sediment will be stable by in situ treating of the sediment. 3. Treated sediment can be used effectively for civil engineering purposes.

INTRODUCTION

According to the recent remarkable development into urbanization, suspended sediments have been accumulated at bottom of rivers, lakes, coves, and bays. These bottom sediments cause serious environmental problems. Usually this problem is solved by dredging the bottom sediment and transporting to a disposal area provided in advance. However, in Japan, it becomes harder to provide the new disposal area.

In this regard, stabilizing the dredged sediments for the purpose of effective use has been recently required as one of the solutions to solve the above situation. The Japan Sediments Management Association has been studying the stabilizing system and method which is shown in Figure 1.

In this paper, typical properties of bottom sediments in Japan are explained first; then the dredging of bottom sediments for the purpose of water clarification is outlined; and finally the recent trend of sediment stabilization by solidification for the effective use is reported.

TYPICAL PROPERTIES OF BOTTOM SEDIMENTS

Bottom sediment (conventionally called "HEDORO" in Japan) is generally defined as the sediment composed of particles that originated in natural or artificial activities and gradually settled on the bottom of lakes, rivers, and seacoast. There are commonly a few typical properties in the bottom sediments in Japan as the following:
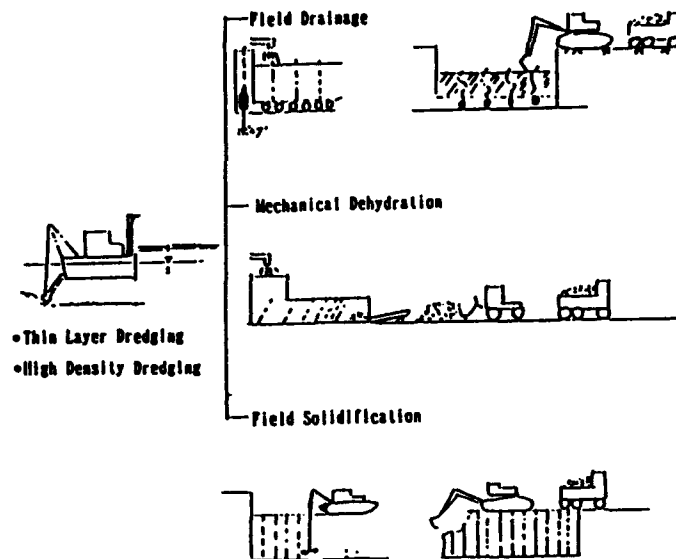
Figure 1. Flow chart of sediment stabilization

a. <u>Very high water content.</u> Water contents of the bottom sediments are mostly 150 percent through 250 percent at the essential part and are often 400 percent through 500 percent at the surface layer. As shown in Figure 2, wet density duly increases as water content increases.

b. <u>Very loose at surface layer.</u> As distributions of water content and wet density at each depth are shown in Figure 3, the 20- through 30-cm-thick layer from the surface deposits in a particularly loose condition. Bottom sediment has little sand in grain distribution and is almost full of silt and clay.

c. <u>High organic content.</u> Organic content is generally identified by ignition loss. As shown in Figure 4, chemical oxygen demand (COD) value is reported to be linearly proportional to ignition loss.

d. <u>Bad odor.</u> Organic matters are decomposed anaerobically by the action of bacteria, and then they are changed into sulfate gas such as hydrogen sulfate and mercaptan. Among such badly smelled odorants, hydrogen sulfate gas is generally more uncomfortable. An example of measurement of the generated gas and sulfate content in the bottom sediment at a canal in Japan is shown in Figure 5, and medical influences on human body by two kinds of gas are shown in Table 1.

e. <u>Heavy metal content with high possibility of dissolving into water.</u> According to a report, the tendency shown in Table 2 considered that most of the bottom sediments commonly contain some heavy metals even
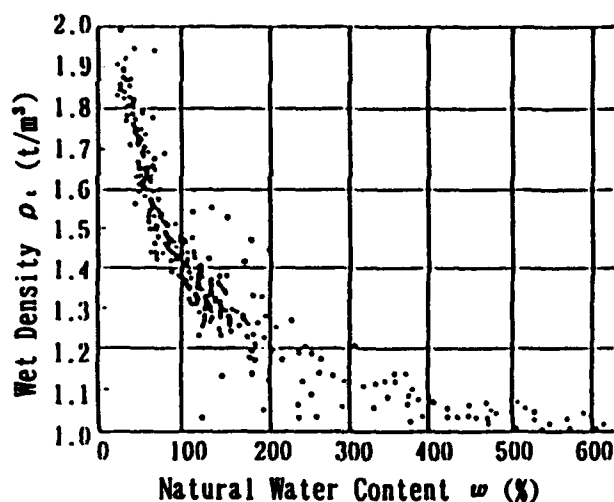
Figure 2. Relationship between natural water content and wet density
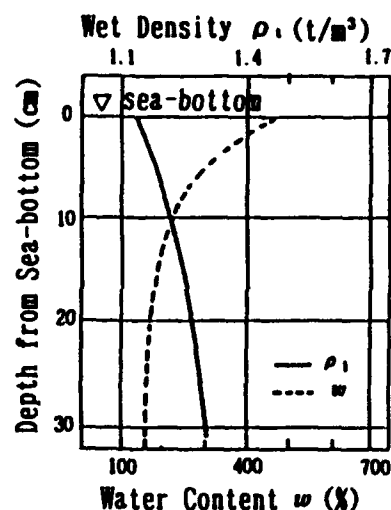
Figure 3. Typical distribution of water content and wet density at bottom sediment
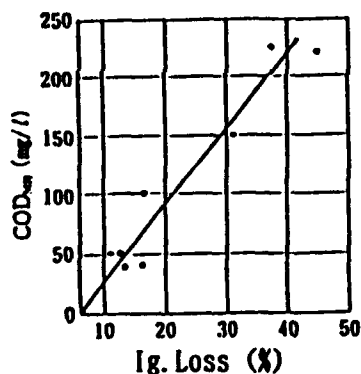
Figure 4. Relationship between ignition loss and COD
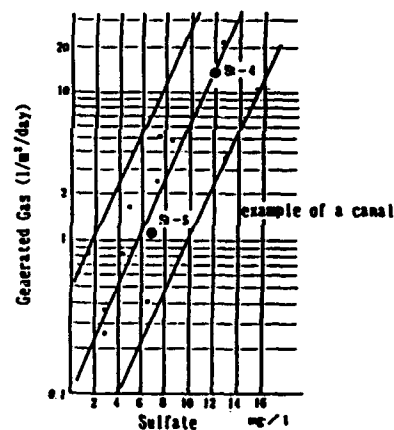
Figure 5. Relationship between sulfate content and generated gas

though chemicals and the quantities contained differ from each other. The dissolved quantities of toxic materials out of the sediment that go into water are legally regulated by the government of Japan. Therefore, the quantities must be strictly controlled to be less than the regulated values on the disposal and stabilization of bottom sediments. The regulated values are shown in Table 3.

TABLE 1. MEDICAL INFLUENCE OF H_2S GAS AND NH_3 GAS ON HUMAN'S BODY

Hydrogen Sulfate (H_2S) Gas			Ammonia (NH_3) Gas		
Density		Influence	Density		Influence
ppm	mg/ℓ		ppm	mg/ℓ	
70-110	0.1~0.15	Some influence after long time	53	0.035	To be able to catch smell
100-150	0.14~0.21	Influence after several hours	85	0.06	To be able to bear for 6 hours without remark-able poisoning
170-260	0.24~0.36	To be able to bear for 0.5 - 1.0 hour without poisoning	100	0.07	To be poisoned after many hours work
360-500	0.5~0.7	To be dangerous after breathing for 0.5 - 1.0 hour	300~500	0.2~0.35	To be able to bear for 0.5 - 1.0 hour work
420-600	0.6	To be dead soon or later after breathing for 0.5 - 1.0 hour	408	0.3	To be clearly stimulative
850-1000	1.2~2.8	Instantaneous death	698	0.5	To be stimulative on throat with cough
1000-3000	1.4~4.2	Instantaneous death	1620	1.2	To be stimulative on throat with cough
			2150~3900	1.5~2.7	To be dead soon after breathing for 0.5 - 1.0 hour
			3600~6500	2.5 ~4.5	Death within 0.5 - 1.0 hour
			5000~10,000	3.5 ~7.0	mostly instanta-neous death

f. **Many kinds of rubbish in sediments.** Depending on the situation and their background, the bottom sediments are mingled with various kinds and sizes of rubbish, such as garbages, metal scraps, dungs, trashes of paper, textile, rubber, constructional wastes, carcasses, plastics, waste oil, and other dusts.

The general properties of bottom sediments just explained above, showed much variety even at the same place. In this regard, survey and investigation of bottom sediment must be multi-itemized.

EXAMPLE OF WATER CLARIFICATION BY DREDGING WORK

The result of water clarification by dredging bottom sediment at the lake is analyzed by Japan Sediments Management Association (1991) and is reported here. Newspapers in Japan stated that: "Once COD value, as an index of current environmental evaluation, was 12 mg/l in annual average between 1980 and 1981. The value was listed on the worst environmental rank out of all lakes in Japan for two years co ously. But COD in 1990 has recorded the minimum value indicating 6.3 m₤ the inlet of the lake and 7.7 mg/l at

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TABLE 2. EXAMPLES OF HEAVY METAL CONTENT IN BOTTOM SEDIMENTS

Way of Disposal	Inland Reclamation	Off-shore Abandonment		Coastal Reclamation	Specified Method	Analysis etc.
Kind of Waste		(1) Slag (2) Non-soluble inorganic sediment (3) Incinerated sediment including Hg	(1) Organic sediment (2) Soluble inorganic sediment	(1) Bottom sediment etc. (2) Sea-bed soil	Method	List of Identification
Toxic Substance	Regulated Value (Dissolvment Test)	Regulated Value (Dissolvement Test)	Regulated Value (Content Test)	Regulated Value (Dissolvement Test)		
Alkylic-Hg	ND	ND	ND	ND	JEA Notice No. 64	0.0005
Hg	<0.005mg/ℓ	<0.005 mg/ℓ	<2 mg/ℓ	<0.005mg/ℓ	ditto	0.0005
Cd	<0.3 mg/ℓ	<0.1 mg/ℓ	<5 mg/ℓ	<0.1 mg/ℓ	JIS K-0102	0.05
Pb	<3 mg/ℓ	<1 mg/ℓ	<50 mg/ℓ	<1 mg/ℓ	JIS K-0102	1
Organic-P	<1 mg/ℓ	<1 mg/ℓ	5 mg/ℓ	<1 mg/ℓ	JIS K-0102	--
Cr⁶⁺	<1.5 mg/ℓ	<0.5 mg/ℓ	<25 mg/ℓ	<0.5 mg/ℓ	JIS K-0102	0.04
As	<1.5 mg/ℓ	<0.5 mg/ℓ	<25 mg/ℓ	<0.5 mg/ℓ	JIS K-0102	0.4
CN	<1 mg/ℓ	<1 mg/ℓ	<5 mg/ℓ	<1 mg/ℓ	JIS K-0102	0.01
PCB	<0.003 mg/ℓ	<0.003 mg/ℓ	<0.15 mg/ℓ	<0.003 mg/ℓ	JEA Notice No. 59	--
Organic-Cl		<40 mg/ℓ²⁾ ³⁾	<40 mg/ℓ²⁾ ³⁾		JEA Notice No. 13	--

the outlet. These values are evaluated to be on the way of environmental improvement in the long term aspect."

Proposed Plan for Water Clarification of the Lake

Depending   he target of water clarification at the lake which was set on List "B" reg   g COD value at 5 mg/l, the dredged thickness of the lake-bed ranging 80 h   de was proposed as shown in Table 4, which was based on the distribution of the contents of more than five environmental substances by the vertical sampling of bottom sediment at many points in the lake. After all, the total volume of the bottom sediment to be removed at the lake was assumed to be 1.6×10^6 m^3.

Effect of Water Clarification by Dredging

The accumulated volume of dredged soil at the lake from 1977 to 1990 has amounted to 350×10^3 m^3 out of 1.6×10^6 m^3 planned for dredging. COD values, as index of water clarification, have been measured every year in Figure 6 since 1976 when dredging work started. Water clarification has been attained about 35 percent of the time on the basis of recent COD values.

Meanwhile, according to "Theory of Peak Value in Summer Season" the dissolved substances out of bottom sediment are most activated in summer. Consequently, the number of plankton extraordinarily increases, and the

TABLE 3.   LEGALLY REGULATED VALUE OF TOXIC SUBSTANCES

Mark	Place Thickness	m	Origin	Heavy Metal content (mg/kg-dry wt.)									COD (mg-/ℓ)⁻
				T-Hg	R-Hg	Cd	Pb	O-P	Cr⁶⁺	As	CN	PCB	
R-1	River	1~2	Urban waste	1.9	ND	38	530	ND	ND	48	ND	15	100
R-2	"	0.5~1	Leather factory	0.18	ND	0.6	58	ND	1.4	74	1.1	0.01	222
R-3	"	2~3	Chemical factory	100~500	ND	ND	72	ND	ND	30	ND	ND	44
L-1	Lake	1	Household waste	--	--	--	--	--	--	--	ND	ND	100
L-2	"	0.7~1	Household waste	--	--	2.4	19	--	--	--	ND	ND	41
L-3	"	0.3~1.1	Household waste	0.3	ND	1.3	50	ND	ND	10	ND	ND	50
S-1	Harbor	0.3~4	Chemical factory	100~500	--	1.6	250	ND	0.06	86	ND	ND	40
S-2	"	1.5	Paper mill factory	0.3	ND	1	20	ND	ND	6	ND	ND	225
S-3	"	3	Paper mill factory	0.1	--	0.3	--	--	--	--	--	5~63	150

TABLE 4.   THICKNESS OF BOTTOM SEDIMENT TO BE REMOVED

	Environmental Substance	Specified Value to be Removed	Thickness to be Removed
Lake-bed Sediment & Soil (Less than 15% of Organic Content)	Ignition Loss	16. 5%	69 cm
	C O D	100 mg/g	80 cm
	T - C	70 mg/g	61 cm
	Sulfate Content	1 mg/g	63 cm
Specification for Water Clarification	Dissolving Rate of Phosphorus	2 mg/m^2/day	75 cm
Thickness of Dredged Lake-bed (Final Decision)			70 cm

background value of total phosphorus (T-P) duly increases.   Therefore, minimizing the increase of COD background value increases water clarification.   In this regard, monthly changes of T-P values in 1980-1981 and 1989 are comparatively shown in Figure 7.
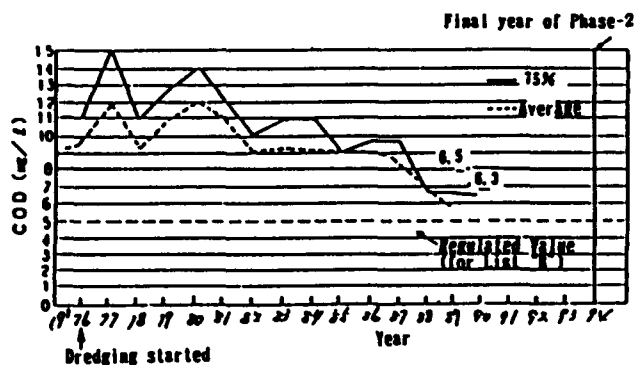
Figure 6. Yearly changes of COD of of the lake water
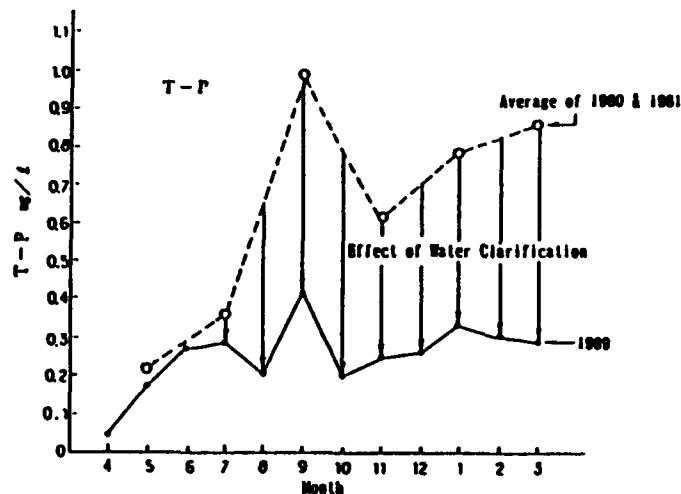
Figure 7. Monthly changes of T-P of the lake water

As mentioned in this chapter, dredging of bottom sediments has greatly removed COD, T-P, total nitrogen (T-N), etc., which are the main factors against water clarification. Furthermore, keeping the waterdepth (or sea-depth) helps to improve biological environment.

SEDIMENT SOLIDIFICATION METHOD

Dredging bottom sediments is generally effective on water clarification as reported in the previous chapter. However, in Japan disposal areas for dredged sediments have become smaller in number and narrower in each area. The sediment solidification method in this chapter is one of the stabilizations which were researched and studied at Japan Sediments Management Association in order to solve limitation of disposal areas.

Typical Properties of Solidification Sediments

a. **Change from soft muddy state to rigid.** The mechanism of chemical reaction on sediment solidification is generally explained in Figure 8. Table 5 shows a test result of sediment solidification.
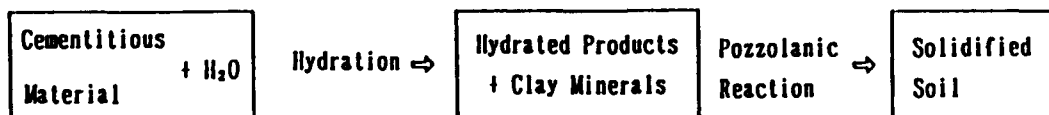
Figure 8. Principle of solidification method

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TABLE 5. PROPERTIES OF SOLIDIFIED SEDIMENT

Properties of Raw Bottom Sediment

Test Item		Bottom Surface		Mid-layer	
1 Water Content (%)		474.8	505.7	493.9	492.4
		513.5		474.3	
		528.7		508.9	
2 Wet Density (kg/l)		2.329	2.346	2.242	2.238
3 Specific Gravity		2.359		2.207	
		2.350		2.264	
4 Grain Distribution	Fine sand	3%		2%	
	Silt	74%		63%	
	Clay	23%		35%	
	Colloid	8%		23%	
	<74 μm	97%		98%	
	Max. size	0.25 mm		0.25 mm	
	60% size	0.023 mm		0.024 mm	
	30% size	0.0059 mm		0.0033 mm	
5 Chemical Test	Ig. Loss	24.6		25.7	
	pH(H_2O)	7.4(17.9° C)		7.7(18.0° C)	
	pH(KCl)	7.1(18.1° C)		7.4(17.9° C)	
	Sulfate Content (%)	0.67		0.35	

Compressive Strength of Solidification Test

14 days strength

Material		Mixed Ratio kg/m³	at Laboratory (kgf/m³)	at Field (kgf/m³)	—/—
N P C		300	1.20	0.33	0.28
G	a	250	1.48	0.47	0.32
	b	250	1.48	0.53	0.36
S	A	200	1.24	0.54	0.44
	B	200	1.24	0.55	0.44
	C	200	1.24	0.50	0.40

28 days strength

Material		Mixed Ratio kg/m³	at Laboratory (kgf/m³)	at Field (kgf/m³)	—/—
N P C		300	1.60	0.34	0.21
G	a	250	1.52	0.51	0.36
	b	250	1.52	0.59	0.35
S	A	200	1.42	0.59	0.42
	B	200	1.42	0.57	0.40
	C	200	1.42	0.55	0.39

NPC : Normal Portland Cement
G : General Cementitious Material
S : Special Cementitious Material

b. **Addition of more cement to organic sediment for solidification.**
Organic matters in bottom sediment is the greatest obstacle for
hydration and pozzolanic reaction. Figure 9 shows an example of a
solidification test which shows organic matter as a substantial
obstacle. At this test, normal portland cement was used. Curves in
Figure 9 clearly decrease while ignition loss as an index of organic
matter increases.
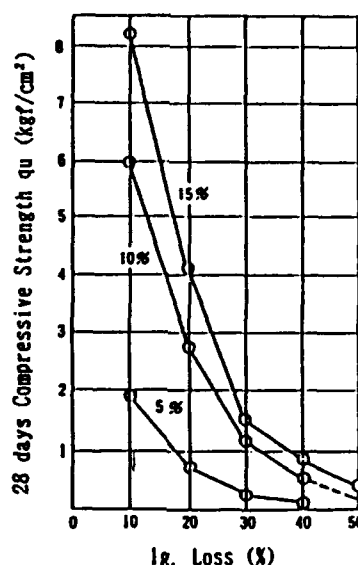
Figure 9. Relationship between ignition loss and compressive strength

c. **Effectiveness on bad odor.** On the process of solidification by
cement, calcium in cement and hydrogen sulfate (H_2S) gas in bottom
sediment are combined easily under alkalic condition (pH=12), and
then H_2S gas, which is the main origin of bad odor, disappears for
the new production of calcium sulfate. The following is an example
of bottom sediment solidification at Tago-no-ura where H_2S gas was
remarkably generated.

(1) Leaving 15 min after mixing 100 g of quick lime (CaO) with
10 kg of bottom sediment at Tago-no-ura for 5 min by using
rotary mixer (50 rpm), the odor of H_2S gas has completely dis-
appeared, and the typical dark brown color of raw sediment also
disappeared with separation of clear water from the sediment.
Assuming 1,000 ppm of H_2S gas is generated from 1 m^3 of sedi-
ment, the required mixing ratio of CaO is calculated to be
1.96 g/m^3 by using the formula:

$$Wc = Vg \cdot rg \cdot R$$

where

Wc = required mixing ratio of CaO (g/m^3)
Vg = mole number of H_2S gas generated from 1 m^3 of sediment
rg = mole weight of H_2S gas
R = (CaO/H_2S) = 1.64

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(2) If pH value of sediment indicates alkali, ammonium salt contained in the sediment is dissolved into stimulus ammonia (NH_3) gas. In this case, the deodorization of NH_3 gas can be temporarily attained by spreading some acid on the sediment for neutralization.

d. **Effectiveness on fixation of toxic substances.** When a solution becomes alkali, metal (M') ion in the solution and excess (OH) ion chemically react (M + OH — MOH) and produce a deposit of oxygenhydrate (MOH). This MOH is so hard to dissolve into the solution that the density of (M) ion enormously decreases. The fixation effect of toxic substances by solidification is based on the above mechanism. Figure 10 shows a test result of lime-mixing stabilization by Bechtel Company for the purpose of removing the heavy metals.
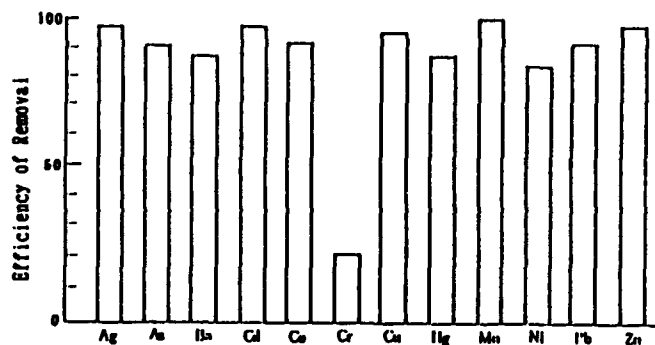
Figure 10. Effect of removing heavy metal ion

Sediment Solidification Methods

Sediment solidification methods are basically classified into two methods: (a) In Situ Solidification, and (b) Solidification at Temporary Disposal Area.

In Situ Solidification Method

In Situ solidification method is to solidify directly bottom sediment at the original seabed (riverbed or lakebed) or to solidify dredged sediment at permanent reclaimed land. Currently, methods illustrated in Table 6 are applied to many projects. Objectives of in situ solidification are:

a. Trafficability of construction machines by surface solidification, and land creation by sand capping on the solidified rigid layer.

b. Utilization for construction materials by full solidification.

c. Stabilization of foundation for the structures by solidification.

Solidification at Temporary Disposal Area

This type of solidification is to solidify dredged sediment at temporary disposal area and then to transport to a permanent disposal area. Table 7 shows three methods currently applied. Objectives of this type are:

TABLE 6.   IN SITU SOLIDIFICATION METHOD (SURFACE SOLIDIFICATION METHOD)
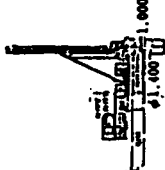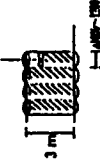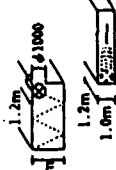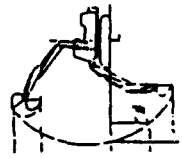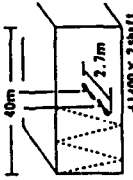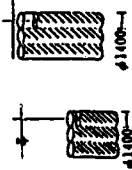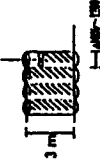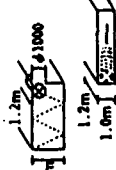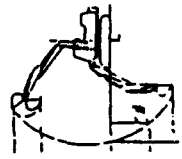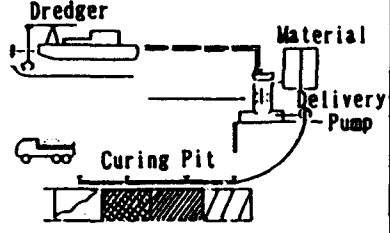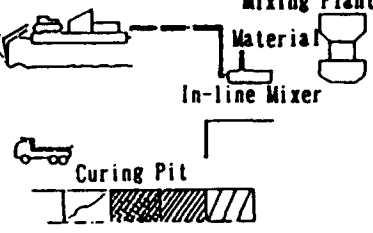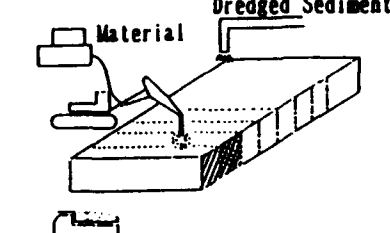
	Continuous Lateral Operating Type	Column-Shaped Lateral Operating Type	Single Operating Type	Rotary Operating Type	Stabilizer Type	Back Hoe Type
Sketch of Machine						
Operation						
Main Specification	Thickness — Max 3.0 m Width — 4.0 m Capacity 5.0~5.5 m³/h	Depth — Max 8.0 m Capacity 2.5~3.5 m³/h	Depth — Max 3.0 m Capacity 2.5~3.0 m³/h	Depth — Max 3.0 m Capacity 2.0~3.0 m³/h	Depth — Max 1.5 m Capacity 2.5~3.5 m³/h	
Solidifying Material	Slurry	Slurry	Slurry	Slurry or Powder	Mostly Powder	Powder

TABLE 7. SOLIDIFICATION METHOD AT TEMPORARY DISPOSAL AREA

	Mixing Plant Type (ex. MUDIX Method)	In-line Mixing Type (ex. KH Mixing Method)	Field Mixing Type (ex. Rotary Operation Type)
Execution	Dredger — Material — Delivery Pump — Curing Pit	Mixing Plant — Material — In-line Mixer — Curing Pit	Material — Dredged Sediment
Work Specification	Capacity : 25m³/h, 50m³/h, 100m³/h Material : Powder Depth of Pit : Max. 30m	Capacity : 30m³/h, 150m³/h Material : Powder Depth of Pit : Max. 30m	Capacity : 20~30m³/h Material : Slurry or Powder Depth of Pit : Max. 20m

a. To make easy handling for transportation to a final disposal area and/or for earth works there.

b. To make effective use with required properties by solidification.

Required function for Effective Use

At the planning stage of effective use of solidification sediments, there are dully different kinds of required functions which may be classified into mechanical function and environmental function.

Mechanical Required Function

a. Example-1. To transport dredged bottom sediment to the permanent disposal area without spilling out of vehicles.

Unconfined compressive strength of solidified soil can be generally evaluated for transportation.

$qu > 0.3$ kgf/cm² : easy for transportation
$qu = 0.05 - 0.3$ kgf/cm² : depending on the properties and condition of transportation
$qu < 0.05$ kgf/c² : very difficult for transportation

The required value of unconfined compressive strength of solidified sediment is $qu = 0.5 - 1.0$ kgf/cm² in many cases because of the variety of raw properties.

b. Example-2. To have trafficability on disposal area for construction machine.

Table 8 shows required cone index of the ground for the trafficability of construction machines in general. Therefore, required

TABLE 8.   NECESSARY CONE INDEX FOR TRAFFICABILITY

Machine for Earth Work	Required Cone Index qc (kgf/cm^2)
Bulldozer (Very soft ground type)	> 2
Bulldozer (Soft ground type)	> 3
Standard Bulldozer (Middle size)	> 5
Standard Bulldozer (Larger type)	> 7
Scrape-dozer	> 6
Scrape (Pulled type)	> 7
Motor-scraper	> 10
Dump-truck	> 12

compressive strength of solidification sediment shall be enough to be qu – 0.5 - 1.0 kgf/cm^2.

c.   Example-3.   To reuse for construction materials.

As strength of solidified soil increases with the time, the plastic behavior at an early stage changes to the rigid behavior, as shown conceptually in Figure 11. This figure shows that the solidified soil "C" has a clear peak in its strength at a comparatively low strain condition.
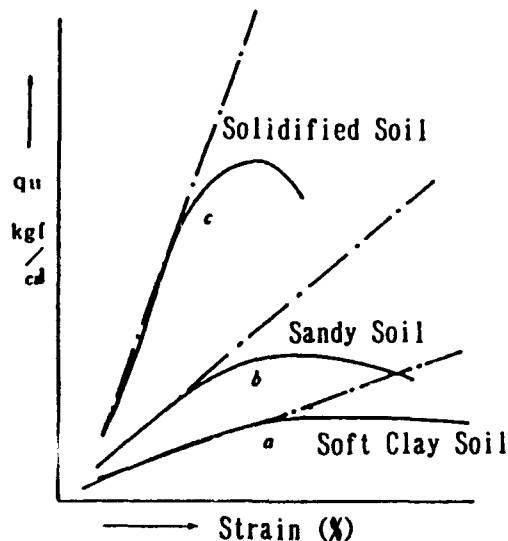
Figure 11.   Behavior of soil

The mechanical behavior is considered to be identified with the modulus of deformation E_{50}. Table 9 gives standard values of the modulus of deformation E_{50} for several kinds of construction materials. This table may be applied to the case on effective use of solidified soil or sediment.

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TABLE 9. MODULUS OF DEFORMATION FOR CONSTRUCTION MATERIALS

	Material	Modulus of Deformation E_{50} (kgf/cm^2)	Test Method
1	Soil	~100~	by CVT Test
	Sand	100~500	
	Mixture of Gravel Sand & Clay	500~2,000	
	Crushed Stone	500~2,000	
	Soil Cement	10,000	
2	Pit Sand	500	by Plate Loading Test at Test Pavement
	Crusher-run	1,000	
	Grain Controlled Crushed Stone	1,000	
	Soil Cement	15,000	
	Lean Concrete	40,000	
	Macadam	2,500	
	Slag	1,000	
3	Grain Controlled Crushed Stone	3,000	by Plate Loading Test at Actual Road
	Crusher-run	1,100	
	Sand	350	
4	Soft Clay	5~40	for Foundation Design of Pile
	Normal Clay	40~80	
	Loose Sand	80~150	
	Stiff Sand	100~200	
	Dense Sand	500~800	
	Dense Gravel & Sand	1,100~2,000	

Environmental Required Function

As the effect of preventing the dissolvement of heavy metals and the effect of the deodorization are explained in the section, Typical Properties of Solidified Sediment, the research and study, which were carried out by Japan Sediments Management Association, are reported here.

Test results of the bottom sediment sampled at the lake are shown in Tables 10 and 11. The purpose was to study the environmental impact on underground water when the bottom sediment was solidified and then reclaimed at the disposal area.

a. **Specification of solidification.** At first, volumetric ratio of dredged sediment and pit sand were 20 and 40 percent and then 125 kg/m^3 of cementitious material was added. Finally test pieces were made for 28-day compressive strength after mixing the above three. The pit sand has the following properties:

Grain Distribution : Sand 92 percent, Silt & Clay 8 percent
Specific Gravity   : 2.708, Water Content 6.1 percent
pH : 6.4, Ignition Loss 1.5 percent

TABLE 10.   TEST RESULT OF BOTTOMS SEDIMENT AND
SUBSOIL AT THE LAKE

Test Item	Sample	Sediment (A)	Sediment (B)	Sediment (C)
Grain Distribution	Gravel(2000μm~)%	0	0	0
	Sand(74 ~2000μ-m)%	5	2	1
	Silt (5~75 μm) %	62	63	60
	Clay (~ 5 μm) %	33	35	39
	Max. Grain Size mm	0.42	0.42	0.25
Consistency	Liquid Limit w_L %	126.0	129.0	350.6
	Plastic Limit w_p %	57.8	62.8	81.5
	Plastic Index I_p	68.2	66.2	75.6
JIS Classification		(MH)	(MH)	(MH)
Specific Gravity G_3		2.426	2.510	2.454
Natural Condition	Water Content w %	226.3	238.3	350.6
	Wet Density ρ^t g/cm^3	1.217	1.214	1.150
pH		5.8	5.8	5.9
lg. Loss %		12.6	11.8	13.5

TABLE 11. CHEMICAL PROPERTIES

Test Item		A	B	C
pH		5.8	5.8	5.9
Ig. Loss	%	12.6	11.8	13.5
COD	mg/g	43.0	41.4	69.5
Sulfate Content	mg/g	0.85	0.72	1.17
T-N	mg/g	3.29	3.03	4.44
T-P	mg/g	4.55	4.38	4.80
T-Fe	%	9.1	9.4	8.1
T-Mn	mg/kg	1200	1100	1100
ORP		-80	-90	-50
Conductivity	(μs/cm)	320	307	384
Cd	mg/kg	1.1	0.98	0.94
Cu	mg/kg	86	81	77
Zn	mg/kg	510	490	480
As	mg/kg	19.7	16.3	12.8

b. **Method of dissolvement test.** The 20-day dissolvement test was carried out by using the apparatus shown in Figure 12. Following dissolvements were measured at the test.

(1) Dissolved quantity out of raw sediments "A" and "B".
(2) Dissolved quantity out of solidified sediment mixed with pit sand by 20 and 40 percent volumetric ratios.

c. **Result of dissolvement test.** Result of dissolvement test on raw sediments ("A" & "B") and solidified sediments (20 and 40 percent mixing ratios) are shown in Table 12 with the legally regulated values in Japan.

d. **Consideration on the result.**

(1) Whether the sediment was solidified or not, there is some possibility the regulated values of organic substances might be exceeded. However, the sediment has no problem unless the water at the lake is greatly discharged into the river which may be intaken for drinking water.

(2) The environmental impact on underground water can be neglected since dissolved quantities of heavy metal cleared the regulated values by solidification.

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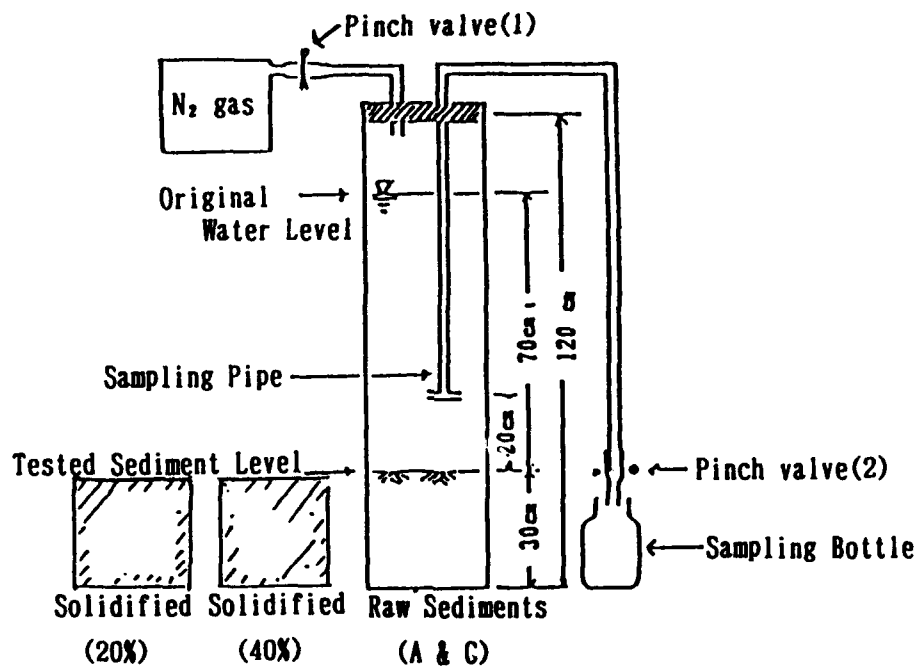
Figure 12. Dissolvement test apparatus

APPLICATION OF SOLIDIFICATION METHOD

Application of two types of solidification methods are introduced here.

In Situ Solidification Method

The large scale in situ solidification test were conducted at the disposal area shown in Figure 13.

Owner : Public Cooperative of Tokyo Port Wharf
Project Name : The Shallow Solidification Work for the Extension of Off-Haneda Disposal Area

Three areas, 4-2B, 3-2B, and 3-1B, were already reclaimed with dredged soil and should be entirely covered with excavated soil for the use as a part of Haneda Airport. However, the dredged soil had such a high water content and a high organic content that filling work for whole areas was quite impossible. Therefore, the shallow solidification method was applied to create a rigid surface layer where the filling work could then be carried out. Figure 14 shows the overall work flow of new land creation on the reclamation area of dredged soil.

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Check Item	Raw Sediment A	Raw Sediment C	Solidified Sediment 20%	Solidified Sediment 40%	for Water Supply	for Toxic Waste	for Toxic Sea-bed	for Health	for Underground Water	for Fishery River	for Fishery Lake	for Agriculture
Date												
Time												
Weather												
Air Temperature (°C)												
Water Temperature (°C)												
pH	3.5～5.4	3.5～5.1	5.9～12.0	5.3～12.0	5.8～8.6							6.7～7.5
Turbidity (deg.)	55～1	39～1	2～1	4～1	<2							
SS (mg/l)	66～<1	67～<1	2～<1	6～<1	—					<25	<3.0	<100
COD (mg/l)	5.4～3.5	5.3～2.8	4.2～40.3	3.3～35.0	<10					-	<4.0	<6.0
T-N (mg/l)	5.16～6.04	5.04～5.42	3.14～18.5	2.62～10.8	—							
NH4-N (mg/l)	0.30～5.51	0.13～3.61	0.79～12.4	0.76～10.1	—	(<10*)				<0.1	<0.1	<1.0
T-P (mg/l)	0.614～0.005	0.438～0.009	0.009～0.030	0.007～0.023	—							
PO4-P (mg/l)	0.480～<0.002	0.350～<0.002	0.014～<0.002	0.033～<0.002	—							
S-F.	4.15～0.03	3.85～0.02	<0.01～0.05	<0.01～0.02	<0.3							
S-Mn	0.03～0.43	0.04～0.68	<0.01～0.01	<0.01～0.01	—							
S-Ca	16.3～14.7	16.1～14.1	17.9～113	17.6～106	—							
SO4	168～114	168～110	163～76	165～68	—							
Cd	<0.001～<0.001	same as A	same as A	same as A	<0.01	<0.3	<0.1	<0.01	<0.01			
As	<0.002～<0.002	same as A	same as A	same as A	<0.05	<1.5	<0.5	<0.05	<0.05			
Cu	<0.01～<0.01	same as A	<0.01～0.04	<0.01～0.06	<1.0							
Zn	0.07～0.14	0.06～0.11	0.02～<0.01	0.01～<0.01	<1.0							
F	<0.05～<0.05	same as A	<0.2～2.2	<0.5～0.9	—							
Conductivity	437～315	416～306	297～1870	308～1950	—							
DO	7.9～8.9	8.4～8.2	8.8～7.6	8.7～8.4	—							
CN (mg/l)					ND	<1	<1	ND	ND			
Pb (mg/l)					<0.1	<3	<1	<0.1	<0.1			
T-Hg (mg/l)					ND	<0.005	<0.005	<0.0005	<0.1			
Tri-Chloro-Ethilene (mg/l)					<0.03							
Tetra-Chloro-Ethilene (mg/l)					<0.01							

Figure 13. Location of dredged soil reclaimed disposal areas

Reclaimed with Dredged Soil → Solidification Work for Rigid Layer → Filling Work with Excavated Soil
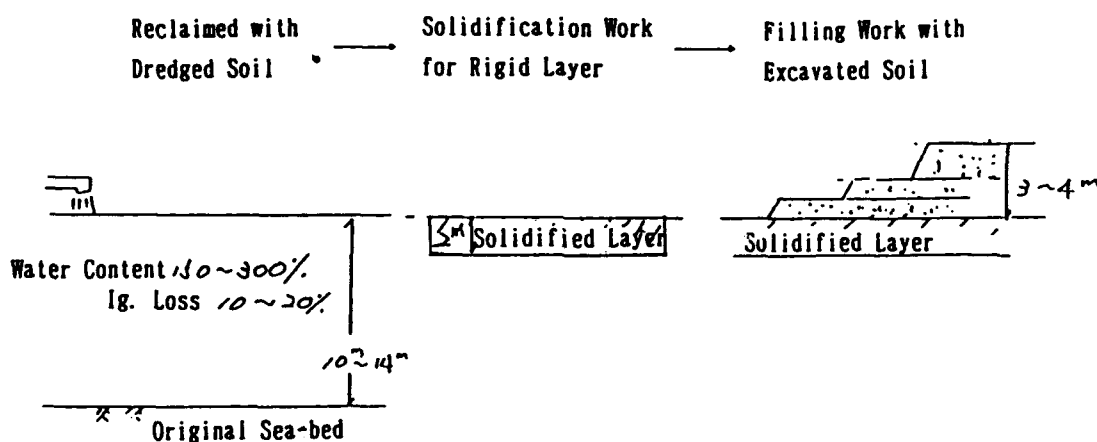
Figure 14. Overall work flow

For the solidification work, the lateral-operation type shown in Table 6 was mostly employed. Eighteen sets of machines have been employed so far. As of August 1991, the filling work at Section 3-1B had already been completed, and that at Section 3-2B is currently being promoted.

The specification of the solidified layer follows:

    Unconfined compressive strength at 28 days : $qu > 2$ kgf/cm^2
    Thickness of solidified layer   : 2 m
    Mixing Ratio of cementitious material   : 120 kg/m^3
    (Mixing ratio was decided on the test result of job mix.)

The measurement after solidification consists of the Dutch cone test (double-tube type) and the unconfined compressive strength test as shown in Figure 15.
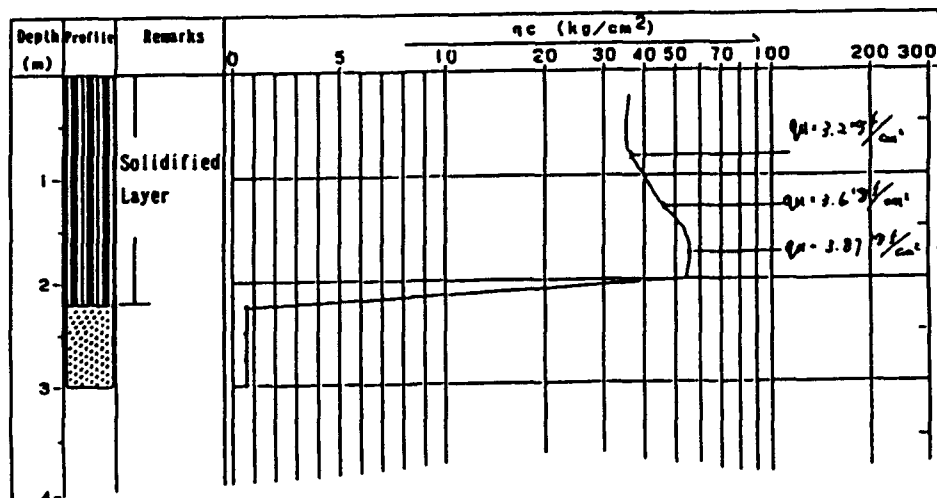
Figure 15. Test results of Dutch cone and unconfined compressive strength

Solidification Method at Temporary Disposal Area

An example of this method of solidifying at a plant for the use of refilling material is introduced here.

Owner : Koto Flood Control Office of Tokyo Metropolitan
Government
Project Name: Double Sheet-pile Quaywall work at Sumida River
Super-Dike

Effective use of solidified dredged soil has been carried out on this project for the purpose of refilling material onto the space between the double sheet-pile quaywall. The outline of this work is shown in Figure 16.
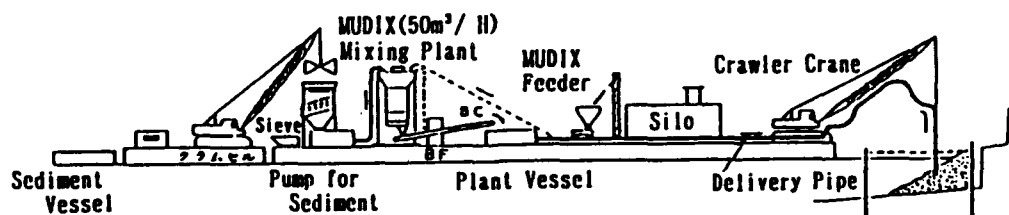
Figure 16. Outline of double sheet-pile quaywall work

A plant type mixing method (MUDIX Method) shown in Table 7 is employed for this work. According to the report of this work, the test result of the solidified sediments which were cured for 28 days in the wet-air condition and in the water condition are comparatively shown in Figure 17. The result says that the coefficient of variety in the water condition is generally smaller than that in the wet-air condition. Such difference considered that the water condition is rather uniform in temperature, especially in case of massive effect. The depth of sampling and the strength of the sample are shown in Figure 18.

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Properties of Dredged Sediment

Water Content (%)	92.8~146.2	
Wet Density	1.303~1.447	
Content of Fine Particle (%)	57.1~86.3	
Shearing Strength (by Vane Test)	$(0.73~2.11 \times 10^2)$	Designed Strength 1 kgf/cm²
Ignition loss (%)	9.7~25.0	
PII	7.09~7.87	
JIS Flow Value (mm)	120~154	

Mixing (120 kg/m³)

Curing in Wet Air (28 days)

Air Temp 0~6°C

$n = 80$
$\bar{x} = 2.29$ (kgf/cm²)
$s = 1.48$ (kgf/cm²)
$V = 64.6$ (%)

q_u (kgf/cm²)

Curing in Water (28 days)

Water Temp 7~8°C

$n = 63$
$\bar{x} = 3.28$ (kgf/cm²)
$s = 1.60$ (kgf/cm²)
$V = 48.8$ (%)

q_u (kgf/cm²)
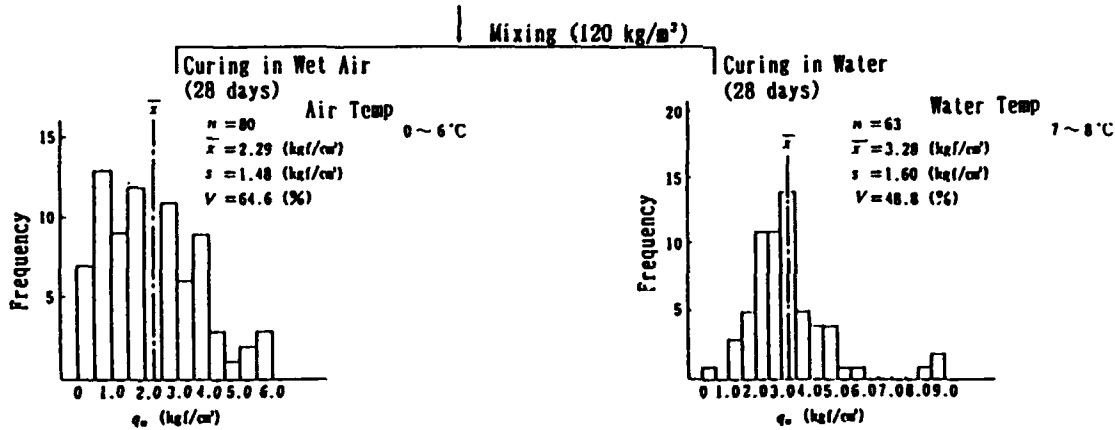
Figure 17. Comparison of strength in different curing condition at site
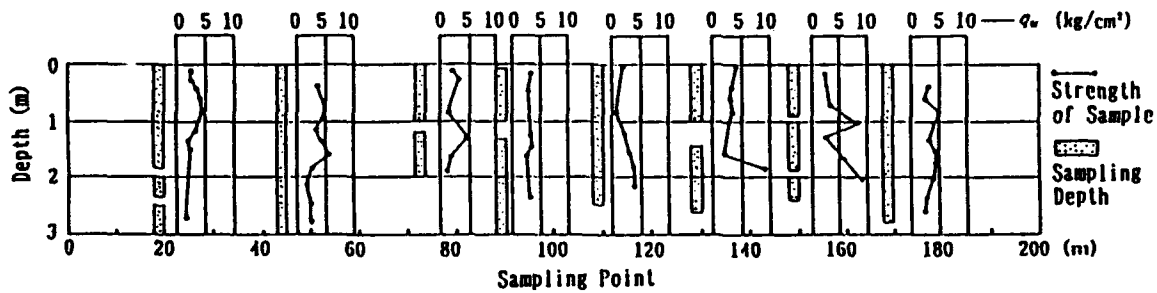
Figure 18. Depth of sampling and strength of sample

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CONCLUSION

Properties of bottom sediments are remarkably scattered in many situations. Therefore, the required functions on dredged sediments for the purpose of effective use have been duly multiclassified. In this regard, the solidification method and its technique shall be considered to be the most appropriate one for the effective use of dredged sediments in a short time. On the other hand, the solidification method includes the matter of Ph to be solved by some countermeasure. However, in Japan research for the effective use of bottom sediments has been promoted by engineers from many faculties since providing the disposal area has been becoming harder. The new technology for this purpose shall be researched and developed with high credibility, environmental safety, and reasonable cost.

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SOLIDIFICATION/STABILIZATION TECHNOLOGY FOR REDUCING THE MOBILITY OF HEAVY METALS IN POLLUTED SEDIMENTS

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ABSTRACT

Polluted sediments from four harbors in the United States were solidified/stabilized with portland cement in bench-scale treatability studies. The effects of solidification/stabilization (s/s) processing on the mobility of metals was investigated using laboratory leach tests conducted on untreated and treated sediments. Laboratory testing showed that s/s processing reduced the leachability of some but not all metals in contaminated sediments. In some cases, s/s increased the leachability of metals. The data suggest that there is potential for mobilization as well as immobilization of metals in contaminated bottom sediments by s/s processing. The data also suggest that the effectiveness of metal immobilization by s/s processing is highly sediment and metal specific.

INTRODUCTION

Contaminated bottom sediments can adversely affect surface water quality through resuspension of contaminated solids, diffusion of contaminants from sediment pore water, bioturbation assisted release of dissolved and particulate bound contaminants, and convective flow of sediment pore water due to groundwater gradients. Alternatives for reducing or eliminating the adverse effects of polluted bottom sediments on surface water quality include capping with clean sediment, removing contaminated material by dredging, and in situ s/s.

S/S is a promising treatment technology for immobilizing contaminants in situ bottom sediments and dredged material in confined disposal facilities. S/S processing eliminates free water by hydration with a setting agent and reduces contaminant mobility by altering the chemical form of contaminants and/or microencapsulating contaminants in a cemented matrix. Setting agents include cements, pozzolans, lime, kiln dust, and blast furnace slag. Other additives, such as bentonite and soluble silicates, are sometimes used to improve the physical/chemical properties of solidified/stabilized products.

We report here the metals data from laboratory leach tests conducted on solidified/stabilized sediments prepared in bench-scale treatability studies using portland cement. The comparison to data for leaching of metals from untreated sediment is also discussed.

MATERIALS AND METHODS

Sediments

Sediments used in this study were form Indiana Harbor, Indiana; Everett Harbor, Washington; New Bedford Harbor, Massachusetts; and Buffalo River, New York. Figure 1 shows the site locations for these sediments. Sediment chemical characterization is presented in Table 1.

Indiana Harbor is a small, highly industrialized harbor on Lake Michigan in northwestern Indiana, approximately 10 miles southeast of Chicago, Illinois. Indiana Harbor and the Grand Calumet River which empties into Lake Michigan through Indiana Harbor have a long history of sediment and water quality problems. Indiana Harbor has been designated an area of concern by the International Joint Commission (United States and Canada). The Buffalo River which discharges into Lake Erie has also been designated an area of concern by the International Joint Commission because of sediment and water quality problems related to industrial and municipal discharges.

New Bedford Harbor is a highly contaminated site that has been closed to fishing and lobstering because of bioaccumulation of contaminants from sediments in the harbor. This harbor has been selected by the U.S. Environmental Protection Agency for cleanup under the Federal Superfund cleanup program because of hazardous posed to human health and the environment.
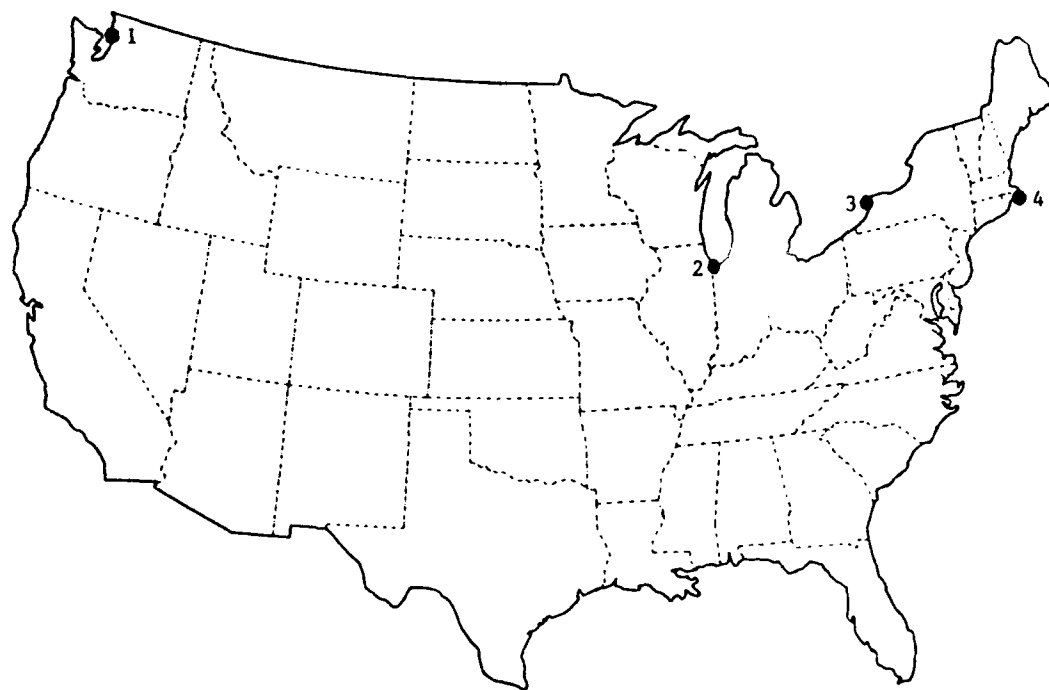
1   Everett Harbor, Washington
2. Indiana Harbor, Indiana
3. Buffalo River, New York
4. New Bedford Harbor, Massachusettes

Figure 1.   Location of sites used in laboratory studies

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TABLE 1. CONCENTRATION OF METALS IN SEDIMENTS (MG/KG DRY WEIGHT)

	Sediment			
Metal	IH*	EH*	NBH*	BR*
Arsenic	29.5	5.7	**	**
Cadmium	20.0	3.3	35.4	**
Chromium	650	39.7	754	56.6
Copper	**	73.4	1730	59.0
Lead	879	48.1	2013	81.0
Nickel	**	21.4	122	34.0
Zinc	4125	148	3017	151

 * IH = Indiana Harbor, Indiana; EH = Everett Harbor, Washington; NBH = New
    Bedford Harbor, Massachusetts; BR = Buffalo River, New York.
 ** Not analyzed.

     Everett Harbor is located in Everett, Washington, approximately 20 miles
north of Seattle, Washington. Studies indicate that upland disposal of
dredged material from Everett Harbor could result in mobilization of metals
and adverse water quality impacts (Palermo et al. 1989).

Solidification/Stabilization Processing

     Sediments were blended with portland cement in a laboratory mixer. The
ratios of portland cement to wet sediment are presented in Table 2. Intersti-
tial water in the sediments was used to hydrate the portland cement. After
mixing for approximately 5 min, freshly prepared solidified/stabilized sedi-
ment was cured at 23 °C and 98 percent relative humidity in a curing chamber
for 28 days. After curing, solidified/stabilized specimens were crushed and
then leached as described in the next section.

Batch Leach Tests

     Solidified/stabilized sediment from New Bedford Harbor, Massachusetts,
and Buffalo River, New york, was leached for metals using the sequential batch
leach test described by Myers and Zappi (1991). This procedure uses
distilled-deionized water, a four-to-one ratio of water-to-dry solids by
weight, and 24 hr of shaking time, followed by centrifugation of $0.45-\mu$ mem-
brane filtration. The leachate is collected and preserved for chemical analy-
sis, and the solids are then resuspended with fresh distilled-deionized water.
The shaking and separation steps are repeated for a selected number of cycles.

TABLE 2.   CEMENT/SEDIMENT RATIOS AND SEDIMENT PHYSICAL CHARACTERISTICS

Sediment	CSR*	Water Content**	Grain Size Classification		
			Sand†	Silt††	Clay‡
Indiana Harbor	0.3	0.88	35	60	5
Buffalo River	0.2	0.73	‡‡	‡‡	‡‡
Everett Harbor	0.3	1.57	40	45	15
New Bedford Harbor	0.3	1.78	33	67	0

* - Weight of cement to weight of wet sediment.
** - Weight of water to weight of dry sediment solids.
† - Percent greater than 70 μm.
†† - Percent less than 70 μm and greater than 2 μm.
‡ - Percent less than 2 μm.
‡‡ - No data.

Solidified/stabilized sediment from Indiana Harbor, Indiana, and Everett Harbor, Washington, were leached using a serial, graded leaching procedure (Environmental Laboratory 1987). In this procedure, separate samples of solidified/stabilized sediment are challenged with distilled-deionized water over a range of liquid-to-solids ratios. This test is somewhat easier to conduct than the sequential leach test because the solids being leached have to be handled and measured only once. The serial, graded leaching procedure, however, requires analysis of desorption isotherms in order to estimate immobilization effectiveness by S/S processing (Environmental Laboratory 1987).

Untreated sediments were leached using the sequential batch leach test described in another paper presented at this meeting (Brannon and Myers 1991). This procedure is essentially the same as the procedure used to leach solidified/stabilized sediments from New Bedford Harbor and the Buffalo River except that there is no need to crush the sediment and the test is conducted under nitrogen to preserve the anaerobic conditions typical of bottom sediments.

RESULTS

The mass leached from solidified/stabilized sediments was normalized with respect to the amount of sediment that was treated by S/S processing in order to account for dilution by addition of portland cement. In the following sections, the normalized mass leached from solidified/stabilized sediments is compared to the mass leached from untreated sediments for various metals.

Normalized masses leached from solidified/stabilized Indiana Harbor sediment are shown in Figure 2. As shown in Figure 2, S/S processing using portland cement reduced the mobil ty of arsenic, cadmium, chromium, and zinc
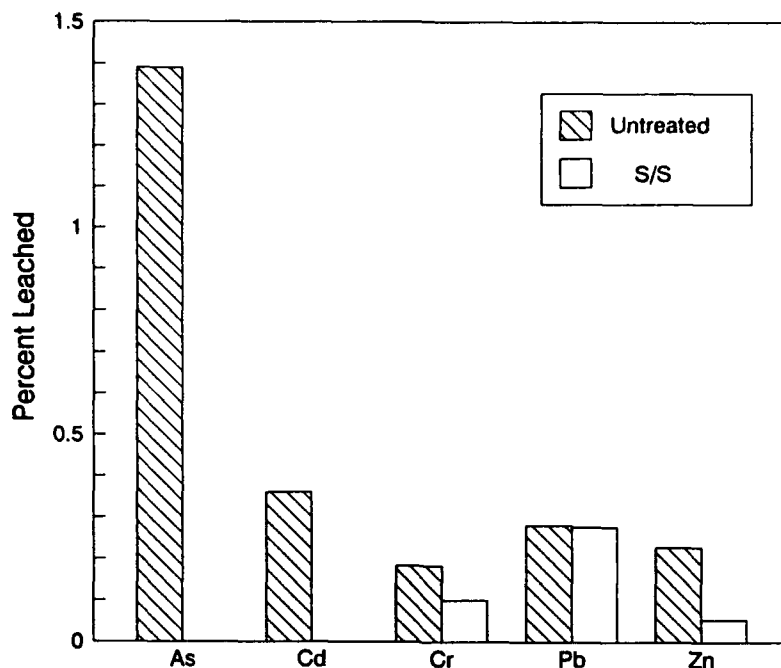
Figure 2. Normalized contaminant mass leached from Indiana Harbor sediment

in Indiana Harbor sediment. Leaching of arsenic and cadmium was virtually eliminated. The mass releases of chromium and zinc, although not completely eliminated, were substantially less than the releases from untreated sediment. The leachability of lead was about the same from solidified/stabilized and untreated sediment.

Normalized masses leached from solidified/stabilized Buffalo River sediment are shown in Figure 3. S/S processing using portland cement was generally ineffective in reducing the mobility of metals in Buffalo River sediment, as indicated in Figure 3. Although the mass releases of zinc and lead for solidified/stabilized sediment were sightly reduced relative to untreated sediment, the mass releases for chromium, copper, and nickel for solidified/stabilized sediment were substantially higher than the releases for untreated sediment.

Normalized masses leached from solidified/stabilized New Bedford Harbor sediment are shown in Figure 4. Leaching of cadmium and lead were completely eliminated, and the mobility of cadmium, chromium, and zinc were significantly reduced in New Bedford Harbor sediment by S/S processing using portland cement (Figure 4). The amounts of copper and nickel released during batch leaching, however, were significantly higher for solidified/stabilized sediment than for untreated sediment.

Normalized masses leached from solidified/stabilized Everett Harbor sediment are shown in Figure 5. S/S processing using portland cement completely eliminated the release of arsenic, cadmium, copper, nickel, and zinc in Everett Harbor sediment and indicated in Figure 5. The mass releases of
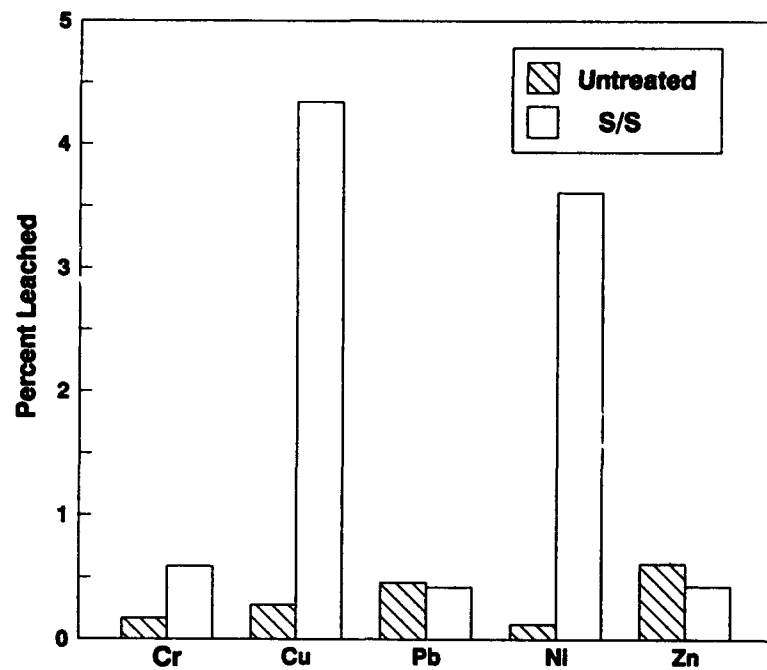
Figure 3. Normalized contaminant mass leached from
Buffalo River sediment
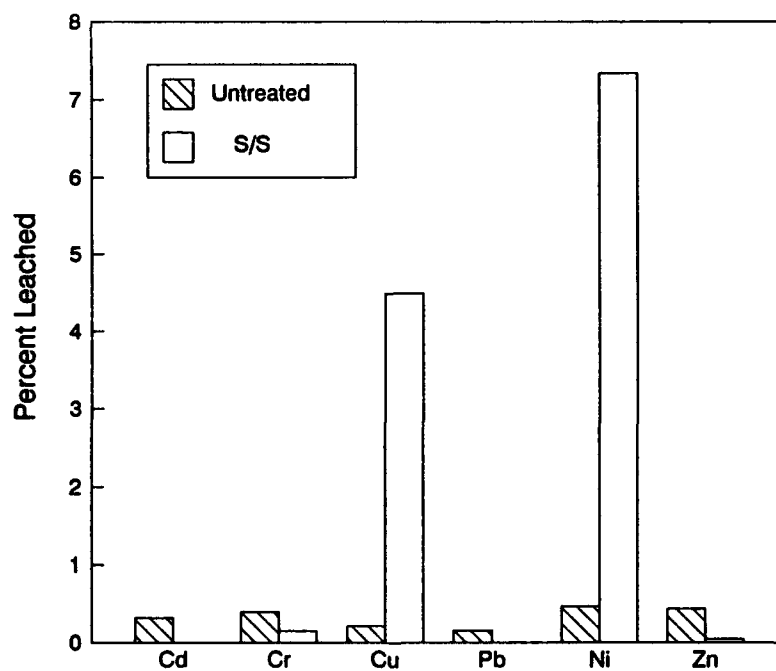
Figure 4. Normalized contaminant mass leached from
New Bedford Harbor sediment
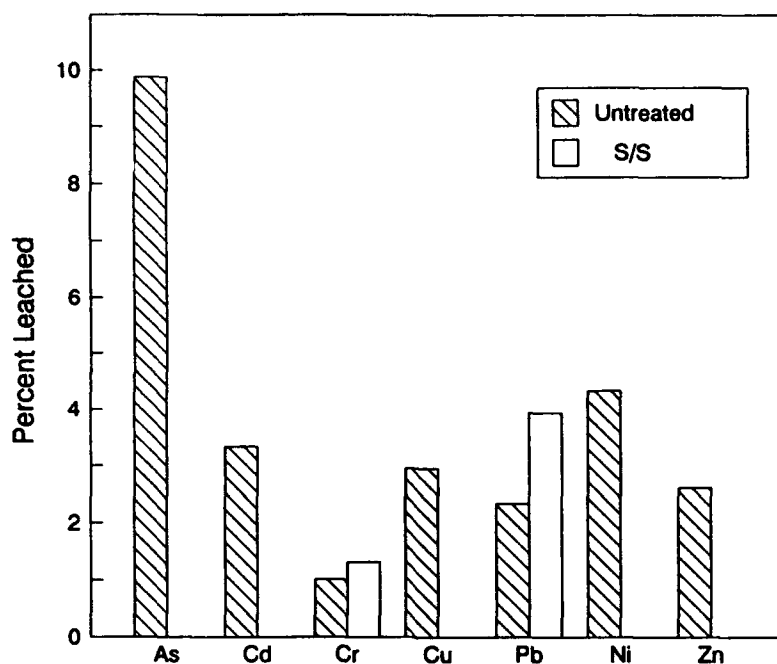
Figure 5. Normalized contaminant mass leached from
Everett Harbor sediment

lead and chromium, however, were greater for solidified/stabilized sediment
than for untreated sediment.

DISCUSSION

S/S is a technology for reducing the pollutant potential of contaminated
materials through alteration of physical and chemical properties. The batch
leach tests and methods of data analysis reported in this paper were designed
to provide a basis for evaluating chemical alteration of metals in sediments
by S/S processing. The leachability of some metals, such as arsenic and cad-
mium, was completely eliminated, and of some other metals was significantly
reduced. However, complete chemical stabilization of all metals was not
achieved for any of the four sediments tested, and in some cases, metal
mobility was enhanced.

Although portland cement was the only S/S process discussed in this
paper, the results are representative of a wide range of S/S processes. Batch
leach tests on untreated and solidified/stabilized sediments prepared using
propriety S/S processes, portland cement, and other nonproprietary processes
have shown that the chemical stabilization properties of the various processes
are very similar (Environmental Laboratory 1987; Myers and Zappi 1988; Palermo
et al. 1989; Fleming et al. 1991). The similarities include mobilization of
copper and nickel in New Bedford Harbor and Buffalo River sediments.

One important aspect of field application of S/S technology was not
addressed in the laboratory tests discussed in this paper. In the field, S/S
processing provides physical stabilization (conversion of a semisolid from a
plastic state to a solid) that reduces the accessibility of water to

contaminated solids. Together, physical stabilization and chemical stabilization provide two lines of defense against contaminant migration. When chemical stabilization of contaminants by S/S processing is not 100 percent effective, physical stabilization to reduce accessibility of water to contaminated solids can be the governing factor for water quality protection.

CONCLUSIONS

The leachability of some metals in polluted bottom sediments can be reduced by S/S processing. However, chemical stabilization of metals in bottom sediments is rarely 100 percent effective, and in some cases, metal mobility can be increased. The data suggest that immobilization mechanisms for S/S processing are highly sediment and metals specific.

Reactions of S/S reagents with contaminants in bottom sediments is not well understood, and it is, therefore, difficult to predict which sediments and which metals are good candidates for S/S technology. Because of the potential for misapplication, laboratory leach tests are required to evaluate the applicability of S/S technology to sediment and dredged material.

ACKNOWLEDGEMENT

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REFORMING TEST ON DREDGED SEDIMENT WITH POLYMER SOLIDIFYING AGENT AND A STUDY OF ITS EFFECTIVENESS

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ABSTRACT

The recent grave concern in sediment dredging is the difficulty in finding places nearby to dispose of or utilize the dredges. Most of such places are far and limited in space so that the dredge has to be carried away for disposal via an intermediate disposal area. It is therefore desirable to compound solidifier, particularly, a high polymer type one, with the dredge. The present study describes the results of experiment which applied a high polymer solidifier to several types of dredges from the lakes and swamps. For evaluation of a cement type solidifier employing high polymer substance, both the "spread test" and the usual test for the cement type solidifier should be done for comparison. The advantages of the dredge obtained with a high polymer type solidifier are as follows. 1) The treated soil is neutral and can be reduced to the earth without polluting it. 2) The volume compounded was several kgs/m3 of the dredge, hardly increasing transportation cost. 3) The soil has been improved to allow easy loaded consolidation/ dehydration. 4) By feeding it into a surface compression type dehydrator, the soil will reach below the liquid limit, allowing its use for civil engineering works.

SYNOPSIS

The recent largest problem of dredged sediment treatment is difficulty in securing an area for final disposal or for reclamation of dredged sediment in the vicinity of dredging site. Even if available, such an area is normally limited in size and far from dredging site, leaving no other choice but to process dredged sediment at an intermediate treatment site and carry it out by dump truck, instead of direct transport from dredging site to dumping area. However, another difficulty in providing wide space for intermediate treatment leads to mixing the solidifying agent in dredged sediment. From the viewpoint of soil formation with dredged sediment, demand for admixture of a polymer solidifying agent is on the increase. This report discusses the results of experimental application of polymer solidifying agents to the sediment samples taken from several lakes and marshes.

The evaluation method of soil reforming by the cement solidifying agent is not applicable for assessing the performance of the polymer solidifying agent admixed in dredged sediment. Polymer solidifying agent needs an expansion test, in addition to the test for the cement solidifying agent. Results of both tests should be compared with each other to clarify the soil reforming effect and applicability of polymer solidifying agent.

The dredged sediment treated with polymer solidifying agent has the advantages listed below, which will satisfy the requirements for dredged sediment treatment.

a. The dredged sediment treated with polymer solidifying agent is chemically neutral, reducible to ground soil without proliferation of environmental pollution.

b. Admixture volume of polymer solidifying agent is several kilograms per cubic meter of dredged sediment, hardly increasing transportation cost.

c. Admixture of polymer solidifying agent reforms dredged sediment, facilitating load consolidating dehydration of the sediment.

d. Mechanical dehydrator of the compressing type (face-pressing type) dehydrates the dredged sediment treated with a polymer solidifying agent to below liquid limit, making it possible to utilize the sediment as material for civil work.

TEST SAMPLES

As shown in Figure 1 on sludge sediment, content of water pollutants is higher in the upper layer and decreases in the lower layer where water environment used to be well balanced. On the assumption that the pumping dredger would perform dredging work, we prepared test samples from dredged sediment by injecting an appropriate coagulant into muddy water of 10 percent sludge content (volume) and agitating the water before settling consolidation (Figure 2). Table 1 shows the water content of four deposit and dredged sediment samples, FG, FR, NN, and MK, which were taken from the lakes and marshes.

The test samples were prepared as follows:

a. FG: Test samples were taken from No. 51 sampling point (0 to 60 cm deep) by backhoe. Waste refuse and other foreign matters contained in the samples were removed by a sieve of 4.72-mm mesh. The samples are composed of the following two kinds:

   (1) Sediment of natural water content.

   (2) Sediment whose water content was adjusted by diluting above sediment 10 times with water (10 percent sludge content), leaving it for 24 hr to encourage sludge sedimentation, and removing supernatant water.

b. FR: Test samples, which were filtrated by a sieve of 4.72-mm mesh to remove waste refuse and other foreign matters, are composed of the following two kinds:

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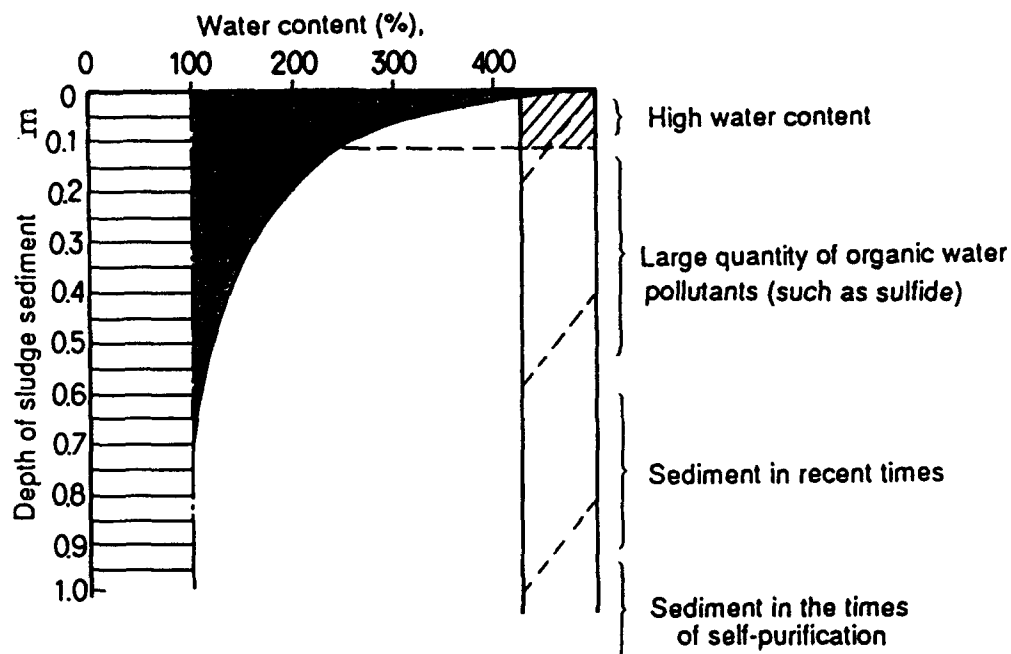
Figure 1. Formation of sludge sediment

(1) Ratio of sediment to lake water
= 10% to 90% (volumetric ratio)
= 10 cm to 90 cm

(2) Settling cylinder
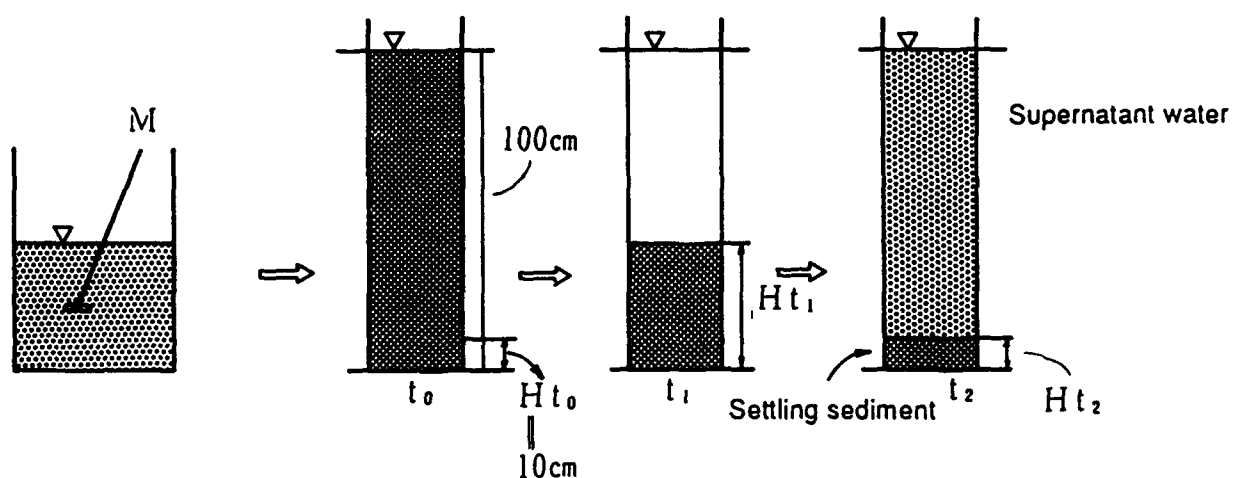
Figure 2. Sample preparation by settling muddy water

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TABLE 1.   RESULTS OF BASIC PROPERTIES TEST ON SEDIMENTS

Sampling Point No.		Unit	FG	FR	NN	MK	Remarks
Analytical Item							
pH			6.4	7.6	6.4	(7.4)	
Water Content		%	139.0	430.4	221.2	150.0	
Ignition loss		%	12.3	12.9	9.0	9.8	
Volumetric weight		g/cc	1.337	1.134	1.274	1.350	
Specific gravity			2.499	2.656	2.587	2.624	
Grading composition							
	Sand	%	8.4	7.0	1.6 / 0.7	2.1	
	Silt	%	39.4	47.0	66.4 / 72.3	39.0	
	Clay	%	52.2	46.0	31.9 / 27.1	58.9	
Chemical Oxygen demand (COD)		mg/g	53.9	57.5	33.1	55.1	
Total nitrogen (T-N)		mg/g	3.59	8.30	2.17	2.78	
Total phosphorus (T-P)		mg/g	6.00	1.09	1.12	1.00	
Sulfide		mg/g	0.3	27.8	0.07	0.07	
Oxidation-reduction potential (ORP)		mV	-240	-410	-170	-20	
Liquid limit		%	109.6	214.0	167.2 / 145.8	99.0	
Areolar limit		%					

(1) Sediment of natural water content.

(2) Sediment whose water content was reduced by aerating and drying above sediment in a room.

c. MK: Test samples, which were filtered by a sieve of 4.72-mm mesh to remove waste refuse and other foreign matters, are composed of the following two kinds:

(1) Sediment of natural water content.

(2) Sediment whose water content was adjusted by diluting above sediment 10 times with water (10 percent sludge content), leaving it for 24 hr to encourage sludge sedimentation, and removing supernatant water.

d. NN: (To be provided.)

Table 2 presents the results of tests conducted on the samples.

REACTION CHARACTERISTICS OF POLYMER SOLIDIFYING AGENT TO SOIL PARTICLES

Polymer solidifying agent is roughly classified into a natural agent and a synthetic agent. Both natural and synthetic polymer solidifying agents coagulate the solids contained in dredged sediment and dehydrate the sediment, eliminating its fluidity. As shown below the admixture of polymer solidifying agent transforms dredged sediment and makes it possible to load treated sediment on a dump truck for transport.
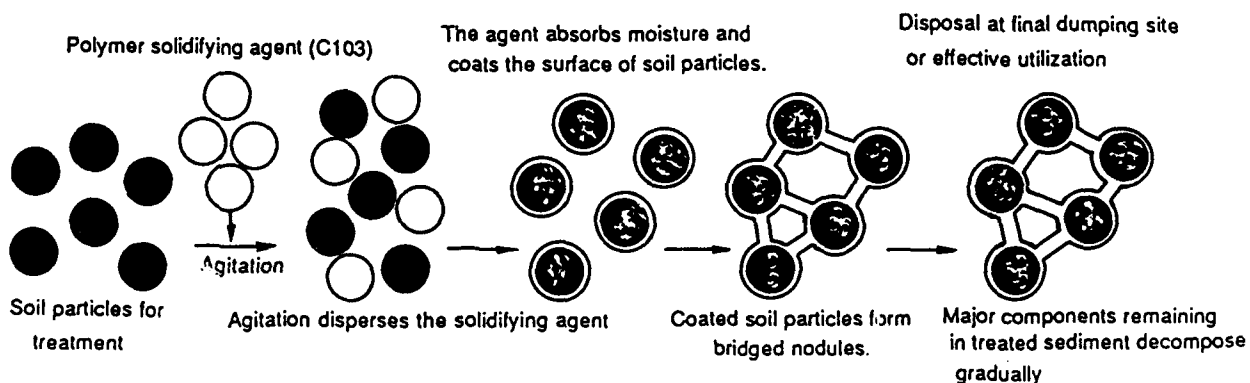
Table 3 shows the reaction characteristics of natural and synthetic polymer solidifying agents, respectively, against the slurry which will be generated by the mud treatment method. The table indicates that more than 30 sec will be enough for the reaction.

TABLE 2. TEST ON SAMPLES

Solidifying Agent		Test Samples					Remarks
		FG	FR	NN	MK		
Ordinary portland cement		0	0	0	0		
Special solidifying agent	CS10	0	0 (A)	0	0		
	CS23	0	0 (B)	0	0		
Polymer solidifying agent	Natural C101	0	0	0	0		
	Synthetic C103	0	0	0	0		

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TABLE 3. REACTION CHARACTERISTICS OF POLYMER SOLIDIFYING AGENTS
TO SLURRY BY MUD TREATMENT METHOD

Natural Polymer Solidifying Agent	Synthetic Polymer Solidifying Agent
(1) The agent is effective at mois-ture absorption, requiring only 30 or 60 seconds for agitation and mixture. (2) The sediment treated with the agent has an appearance of ordi-nary crumbly soil, which is easy for handling. Vibration causes neither water leakage nor defor-mation of the sediment. (3) The sediment treated with the agent is chemically neutral without toxicity. The agent is soluble and decomposes slowly, so that the sediment becomes harmless and safe. (4) Combined application of cement with the agent can adjust the sediment at any strength. (5) The sediment treated with the agent loses stickiness and adhe-sion, so that it hardly *adheres* to hopper.	(1) The agent reacts to sediment in a short time, requiring 1 or 3 minutes for agitation and mixture. (2) Admixture volume of the agent is smaller compared to line and cement solidifying agents. (3) Combined application of calcium chloride, such as slaked lime, with the agent reforms sediment for easy handling.

TEST METHOD

Test Method of Polymer Solidifying Agent

Hydraulic solidifying agents, such as cement and lime, stabilize the strength of sediment gradually in the course of time. On the other hand, such function cannot be expected of polymer solidifying agent, but it combines soil particles and forms bridged nodules, thereby reforming and stabilizing sedi-ment. For former agents, there is already an established test method avail-able. However, test method of the latter agent is still incomplete and under study for development.

To evaluate the reformed condition of the sediment treated with polymer solidifying agent, the sediment is exposed to physical vibration and its extent of deformation (called "deformation ratio" hereinafter) is measured in the test on the agent.

Test Procedure

Vibration test uses a table-type vibrator, whose specifications are listed in the table below, and follows the procedure from a to d.

   a. Admixture of solidifying agent. Take a sediment sample of 500-mℓ volume into a mortar mixer of 2-ℓ capacity, and agitate the sample

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for five minutes after injecting a specified quantity of polymer solidifying agent.

b. <u>Charging of agitated sample.</u> Set a flow cone at the center of the table-type vibrator, and charge the agitated sample (reformed sediment) into the flow cone to form two layers. Tamp each layer 15 times over the surface so that the tip of a tamping rod enters

Specification of Table-Type Vibrator (JIS 1132)

Specification		Additional Tools
Model	Motorized vibrator	Flow cone, tamping rod, and calipers (for the flow test specified in JIS R5201)
Motor	Single phase, 100 VAC	
Amplitude	1.5 mm	
Frequency	3000 - 3500 rpm	
Table dimension	450 mm × 600 mm	
Weight	250 kg	

into approximately one-half depth of the layer. After tamping both layers, fill the head space of the flow cone with additional sample and level the top surface.

c. <u>Measurement before test.</u> Take out the flow cone straightly upward. Measure the assumed maximum diameter of the formed sample and the dimension at the right angle to the diameter by calipers. Specify the average of the measurements as the flow value before vibration (f_o).

d. <u>Vibration test.</u> Switch on the table-type vibrator, and measure the expansion of the sample at specified vibration time. Specify the measurement as the flow value at each vibration time (f_t). Calculate the deformation ratio (xi_1) at each vibration time from the formula below:

$$xi_1 = f_t \, / \, f_1$$

f_1: Inner diameter of flow cone (100 mm)

Admixing Condition of
Polymer Solidifying Agent

Polymer solidifying agent is classified by material into a natural agent and a synthetic agent. Both solidifying agents have been used for the treatment of the surplus soil discharged from construction work. The following discusses the effectiveness of the agents in the treatment of surplus soil. It is necessary to take note, however, that water content is in the order of 100 percent below for surplus soil, while it reaches several hundred percent for dredged sediment.

a. Polymer solidifying agent absorbs free and interstitial water of soil particles, and the absorption increases along with the lapse of time. The surplus soil treated with the agent is chemically neutral

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without proliferation of toxicity, and therefore favorable for vegetation.

b. Use of machinery for civil and building work, such as backhoe and biaxial kneading mixer, activates the reaction of polymer solidifying agent and reforms surplus soil within several tens of seconds or several minutes of mixing.

c. Though no established judgement criterion is available for transport, test results by vibrator indicate that expansion of the surplus soil treated with polymer solidifying agent is limited over a period of time.

d. Combination of cement or lime solidifying agent with polymer agent demonstrates synergetic effect.

Application of polymer solidifying agent to dredged sediment requires careful study of the agent's admixing conditions.

Physical properties of the dredged sediment treated with polymer solidifying agent, such as acceptable strength for transport on dump truck, are yet to be clarified. However, maintenance of deformation ratio (expansion) at 100 percent expansion for a long time and absence of adhering sludge on the surface of container can be used as a guideline. To make sure of the properties, actual test at treatment site is still required.

In the reforming test on dredged sediment by polymer solidifying agent, we conducted an unconfined compression test, which is a judgement criterion for cement solidifying agent, to compare unconfined compression strength (qu), in addition to the vibration test on the sediment treated with polymer agent to clarify the properties of reformed sediment, though the results are not discussed in this report.

Determination of Appro-
priate Agent and Agitation Time

To find out optimum admixing conditions, we conducted a comparison test using a table vibrator on both natural and synthetic solidifying agents, whose effectiveness has been proved on the treatment of surplus soil. Tables 4 to 9 show the test results.

Admixture volume of polymer solidifying agent is normally 3 or 4 kg/m³ of dredged sediment. With an admixture volume of 4 kg/m³, effectiveness of the agent can be summarized as below:

a. Agitation time should be more than 120 to 300 sec to stabilize sediment's deformation ratio at 100 percent.

b. In our observation on the adhesion of treated sediment to the surface of container and others, the synthetic polymer solidifying agent demonstrated better performance than the natural agent.

Based on the above study results, we concluded that synthetic polymer was the optimum solidifying agent and that agitation time should be five minutes. Though "Test Method of Stabilized Treated Soil" specifies the agitation

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TABLE 4. NATURAL POLYMER SOLIDIFYING AGENT (C101) WITH MK SAMPLE

	Agitation Time (Second)	Flow Value (mm)	Deformation Ratio (%)	External Appearance
1	30	100 × 100 → 120 × 120	120	Sticky and considerable adhesion to container.
2	60	100 × 100 → 107 × 107	107	(ditto)
3	120	100 × 100 → 100 × 100	100	Sticky but no adhesion to container.
4	150	100 × 100 → 100 × 100	100	(ditto)
5	180	100 × 100 → 100 × 100	100	(ditto)

TABLE 5. SYNTHETIC POLYMER SOLIDIFYING AGENT (C103) WITH MK SAMPLE

	Agitation Time (Second)	Flow Value (mm)	Deformation Ratio (%)	External Appearance
1	30	100 × 100 → 132 × 132	120	Sticky and considerable adhesion to container.
2	60	100 × 100 → 120 × 120	107	(ditto)
3	120	100 × 100 → 109 × 107	100	(ditto)
4	150	100 × 100 → 100 × 100	100	Sticky but no adhesion to container.
5	180	100 × 100 → 100 × 100	100	(ditto)

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TABLE 6. NATURAL POLYMER SOLIDIFYING AGENT (C101) WITH FG SAMPLE

	Agitation Time (Second)	Flow Value (mm)	Deformation Ratio (%)	External Appearance
1	30	100 × 100 → 120 × 120	120	Sticky and considerable adhesion to container.
2	60	100 × 100 → 107 × 107	107	(ditto)
3	120	100 × 100 → 109 × 107	100	Sticky but no adhesion to container.
4	150	100 × 100 → 100 × 100	100	(ditto)
5	180	100 × 100 → 100 × 100	100	(ditto)

TABLE 7. SYNTHETIC POLYMER SOLIDIFYING AGENT (c103) WITH FG SAMPLE

	Agitation Time (Second)	Flow Value (mm)	Deformation Ratio (%)	External Appearance
1	120	107 × 107 → 132 × 132	120	Sticky and considerable adhesion to container.
2	180	100 × 100 → 120 × 120	112	(ditto)
3	240	100 × 100 → 109 × 107	108	(ditto)
4	300	100 × 100 → 100 × 100	100	Sticky but no adhesion to container.
5	180	100 × 100 → 100 × 100	100	(ditto)

Notes:

(1) Agitation time was more than 120 to 300 sec to stabilize sediment's deformation ratio at 100 percent.

(2) In our observation on the adhesion of treated sediment to the surface of container and others, synthetic polymer solidifying agent demonstrated better performance than natural agent.

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TABLE 8. COMPARISON OF NATURAL AND SYNTHETIC POLYMER AGENTS WITH FR SAMPLE

Admixture volume (Kg/m³)	Natural Polymer Solidifying Agent (C101)		Synthetic Polymer Solidifying Agent (C103)	
	Flow Value	Deformation Ratio	Flow Value	Deformation Ratio
0	172 × 172 → 255 × 255	148	172 × 172 → 255 × 255	148
2	165 × 165 → 215 × 215	130	162 × 162 → 223 × 223	138
4	130 × 130 → 152 × 152	117	112 × 112 → 140 × 140	125
6	110 × 110 → 125 × 125	113	100 × 100 → 118 × 118	118
8	105 × 105 → 117 × 117	114	100 × 100 → 116 × 116	116

TABLE 9. COMPARISON OF NATURAL AND SYNTHETIC POLYMER AGENTS WITH FR SAMPLE

Admixture volume (Kg/m³)	Natural Polymer Solidifying Agent (C101)		Synthetic Polymer Solidifying Agent (C103)	
	Flow Value	Deformation Ratio	Flow Value	Deformation Ratio
0	120 × 120 → 180 × 180	150	120 × 120 → 180 × 180	150
1	112 × 112 → 145 × 145	129	112 × 112 → 132 × 132	119
2	108 × 108 → 125 × 125	116	100 × 100 → 112 × 112	112
3	108 × 108 → 116 × 116	108	100 × 100 → 102 × 102	102
4	108 × 108 → 110 × 110	102	100 × 100 → 100 × 100	100

time to be three minutes, our test clarified that polymer solidifying agent
needed agitation for more than three minutes. We conducted reforming test on
dredged sediment after setting those conditions mentioned above.

Test Method of Cement Solidifying Agents

Cement solidifying agents are roughly classified into ordinary portland
cement and the special solidifying agent which aims at forming the soil free
from elution of harmful substances such as organic substance and metal.
Admixture volume of the agent and curing time of the mixture determine the
possibility to transport treated sediment on dump truck. The unconfined com-
pression strength of the mixture is normally 0.5 kgf/m^2 as a guideline.

We prepared samples to test cement solidifying agents in accordance with
the standard of Japan Soil Engineering Society (JSF T821 1990) specified in
"Commentary on the Procedure of Soil Tests" (Section 6- "Sample Preparation of
Stabilized Treated Soil without Compaction," Chapter 5- "Stabilization Test")
published by the Society, and measured the unconfined compression strength of
the samples in accordance with their standard (JSF T511 1990) specified in the
same (Section 1-"Uniaxial Compression Test on Soil," Chapter 7-"Shearing
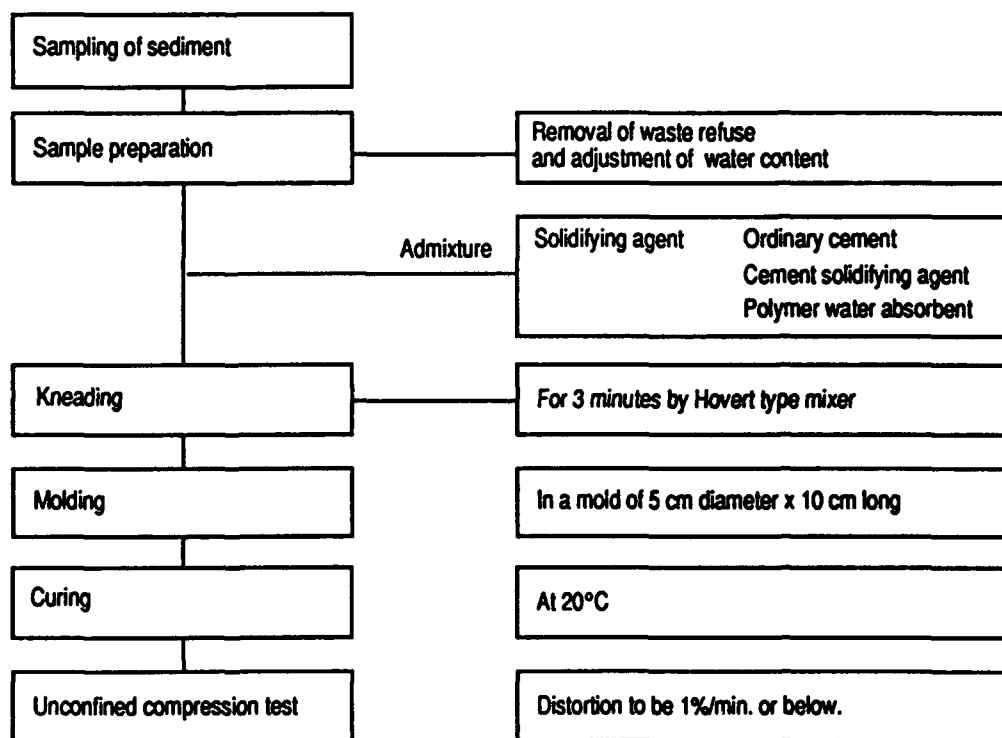Test"). Figure 3 shows the test procedure.

Figure 3. Test procedure of cement solidifying agent

a. **Sample.** Solidified samples were crushed with knife.

b. **Preparation of sample solution.** Take 30 g of crushed sample (wet
sample) and put approximately 50 ml of distilled water into a clean
100-ml beaker. Loosen the crushed sample thoroughly with a clean

policeman to prepare a soil suspension. Leave the suspension for more than 30 min but less than 3 hr, and use it as a sample solution for pH measurement.

c. pH measurement. We used a pH meter with glass electrode for pH measurement. For the measurement of electric conductivity, we used the solution prepared for pH measurement. Our pH measurement conformed to "pH Measuring Method of Soil," the standard of Japan Soil Engineering Society (T7T-1968(79)).

TEST RESULTS

Results of Reforming Test

Relation between admixture volume of solidifying agent (kg/m^3) and deformation ratio of sample after vibration is shown for each sample in Figure 7 (a) to (d) and Table 10 and 11 for polymer solidifying agent (C103), and Figure 8 (a) to (d) and Table 12 (a) to (d) for cement solidifying agent. Figure 4 below shows the comparison of four sediment samples on the admixture volume and liquid limit which no longer cause deformation, silt and clay (%), ignition loss, chemical oxygen demand (COD), total nitrogen (T-N) and total phosphorus (T-P) of sulfide. The following summarizes major characteristics of each sample.

a. FG: This sludge sediment has a high total phosphorus (T-P) and a low true specific gravity.

b. FR: This sludge sediment contains an abnormally large quantity of sulfide and shows a high total nitrogen (T-N). Its oxidation-reduction potential (ORP) is as low as -400 mV, indicating that it is an anaerobic sediment.

c. NN: This sludge sediment shows the least COD among the samples. For other analytical items, this sample is not much different from the others.

d. MK: This sludge sediment shows an oxidation-reduction potential (ORP) of -40 mV, indicating that it is a sediment in the water of aerobic state. For other analytical items, this sample is not much different from the others.

Figure 5 shows the relation between admixture volume of solidifying agent and water content of sediment, obtained from the tests on the samples with different water content. Polymer solidifying agent shows extremely limited ratio between the water content fluctuation and the admixture volume, in comparison with cement solidifying agent, indicating its high adaptability to fluctuation.

Figure 6 shows the relation between the ratio of water content of sample to liquid limit at initial solidification and the admixture volume of solidifying agent, which stabilizes deformation ratio at 100 percent for polymer agent and secures 0.5 kgf/cm^2 third-day unconfined compression strength, allowing for transport in dump truck for cement (special) agent. The following is a summary of analytical results.

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(Figure not provided)

Figure 4.
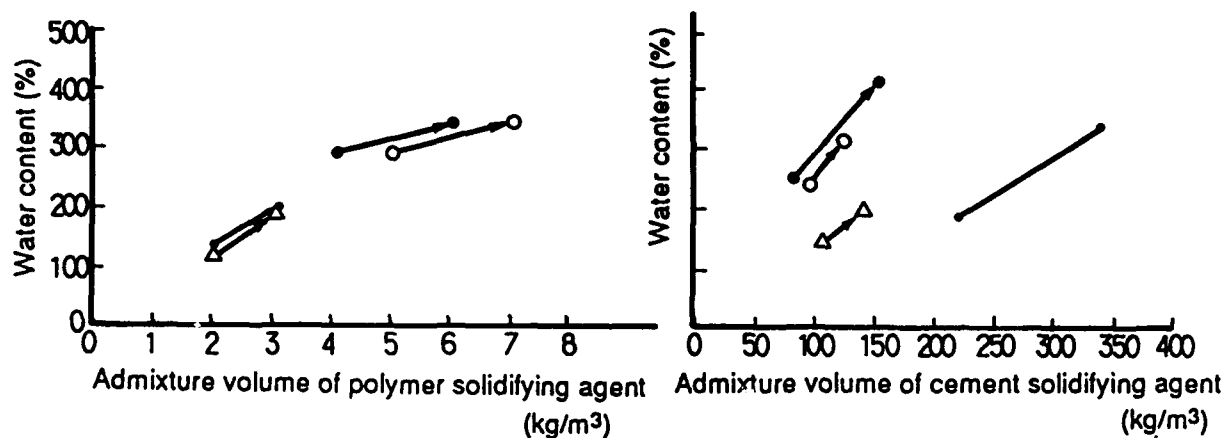
Figure 5. Admixture volume of solidifying agent and water
content of sample (100 percent deformation ratio
for polymer solidifying agent and 0.5 kgf/cm^2
third-day strength for cement solidifying agent)
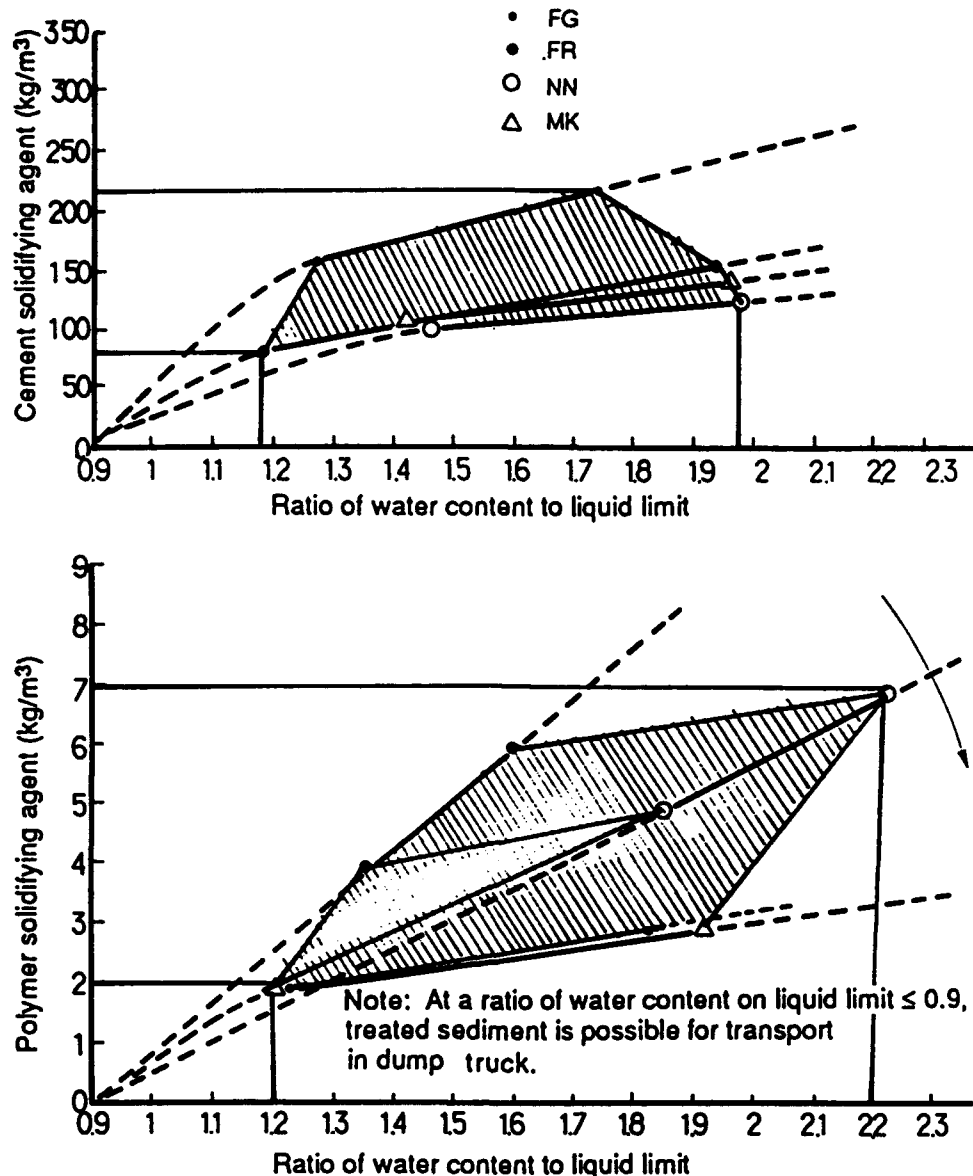
Figure 6. Ratio of water content to liquid limit
and admixture volume of solidifying agent

a. Sediment treatment becomes easier in the arrow direction. (FR)
sample is the most difficult sediment for treatment. It is because,
as discussed before, the sediment contains as large quantity of
sulfide and total nitrogen (T-N), in addition to its extremely
anaerobic property, requiring a large quantity of polymer solidi-
fying agent.

b. (NN) sample was taken from a lake which takes a ling time for water
replacement because of absence of flow velocity. The sample is a
sediment which accumulated in the water of extremely limited concen-
tration of fine suspended solid and salt, requiring a large admix-
ture volume of polymer solidifying agent.

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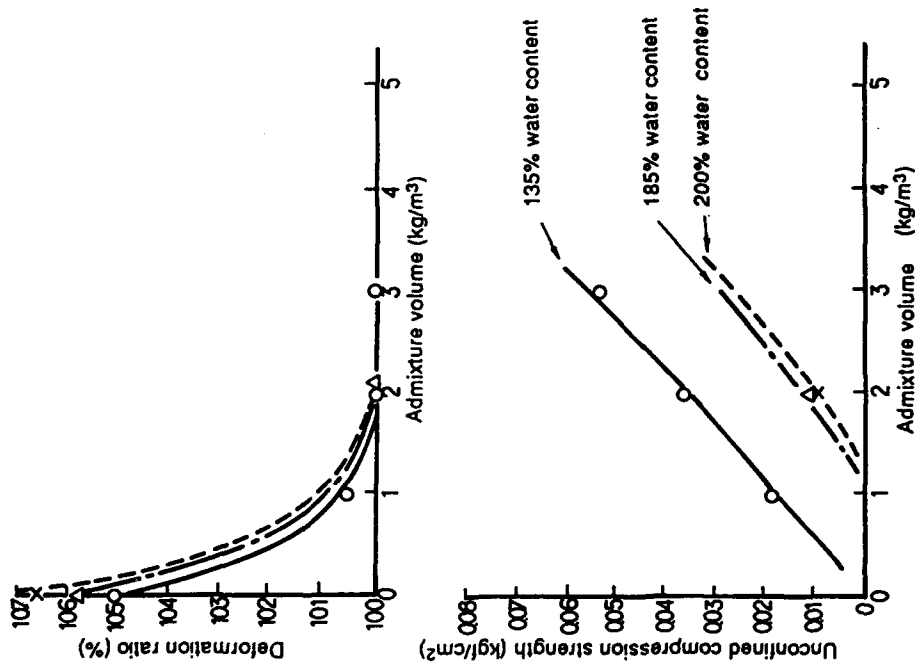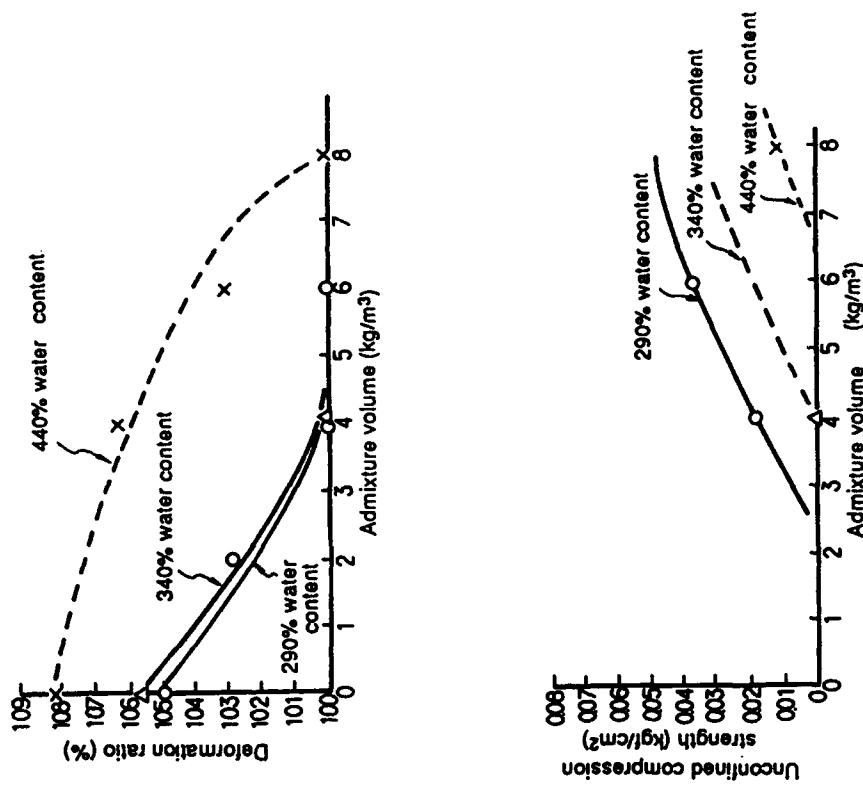
Figure 7. Test results of polymer solidifying agent (Continued)

(a) Test on FG Sample

(b) Test on FK Sample
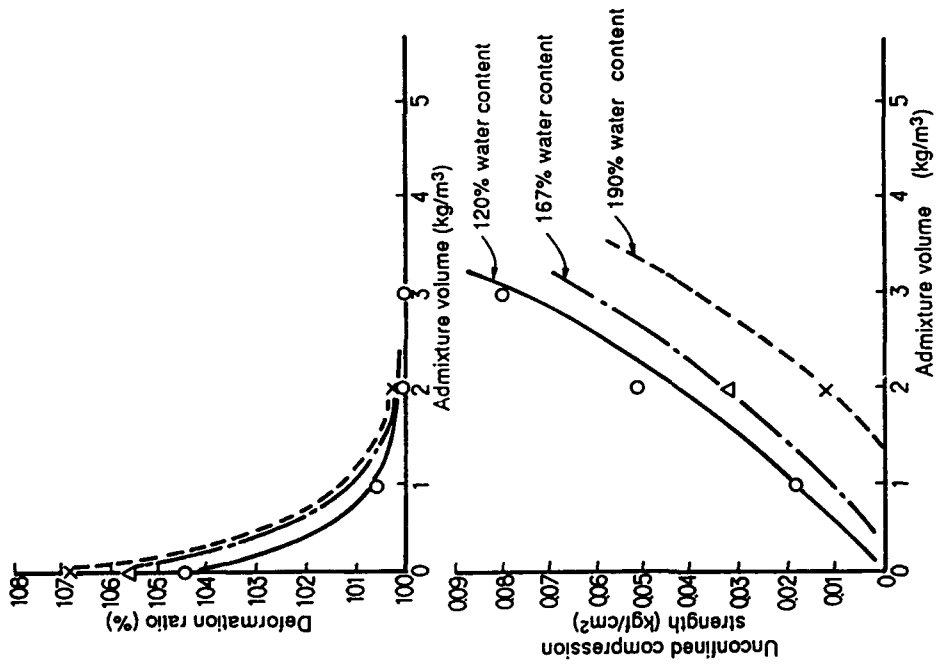
(c) Test on MK Sample
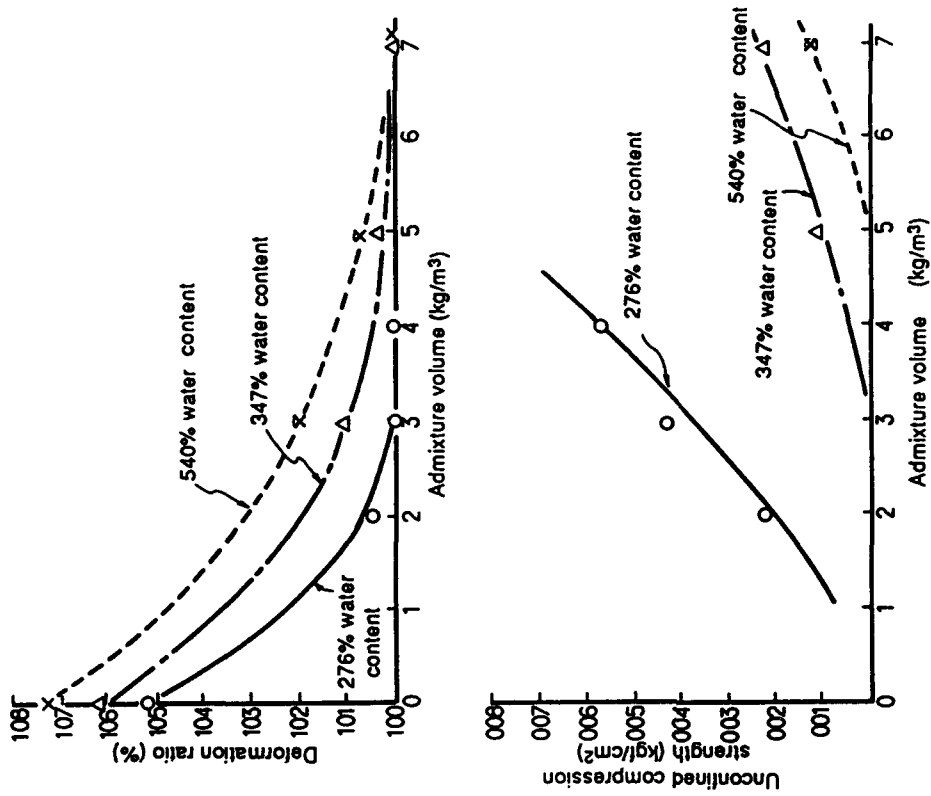
(d) Test on NN Sample

Figure 7. (Concluded)

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TABLE 10. GENERAL TEST RESULTS OF FG SAMPLE

Item		Water Content (%)									
		290%				340%	440%				
Admixture volume (kg/m³)	0	2	4	6	4	0	2	4	6	8
Flow value (mm)	130×130 / 194×194	107×107 / 137×137	100×100 / 100×100	100×100 / 100×100	100×100 / 100×100	172×172 / 255×255	162×162 / 223×223	112×112 / 140×140	100×100 / 118×118	100×100 / 116×116
Deformation ratio	149	128	100	100	101	148	138	125	118	116
Unconfined compression strength	First day	>0.01	>0.01	0.018	0.037	>0.01	--	--	>0.01	>0.01	0.012
	Seventh day	>0.01	>0.01	0.034	0.037	0.035	--	--	>0.01	>0.01	0.012
	Twenty-eighth day	>0.01	>0.01	0.040	0.048	0.035	--	--	>0.01	>0.01	0.015
pH	7.7	8.0	7.0	7.0	7.3	--	--	7.2	7.2	7.3
Water content (%)	290	290	290	290	339	--	--	420	421	420
Cone index	>0.1	>0.1	0.5	1.6	0.3	--	--	>0.1	>0.1	>0.1

Solidifying agent: Polymer solidifying agent (C103)
Unconfined compression strength: 2 kgf/cm²

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TABLE 11. TREATMENT EFFECT OF POLYMER SOLIDIFYING AGENT ON NM SAMPLE

Solidifying agent	Blank	Synthetic Agent			Blank	Synthetic Agent			Blank	Synthetic Agent			Natural
Admixture volume (kg/m³)	0	3	5	7	0	3	5	7	0	2	3	4	6
pH	6.8	6.8	6.8	6.7	6.8	6.8	6.9	6.8	7.1	6.9	6.8	6.7	6.7
Water content (%)	540	541	540	540	347	347	347	347	276	248	244	249	284
Flow value													
Before vibration (mm)	152 x 152	120 x 120	110 x 110	105 x 105	142 x 142	117 x 117	105 x 105	100 x 100	135 x 135	100 x 100	100 x 100	100 x 100	100 x 100
After vibration (mm)	258 x 258	151 x 150	118 x 118	107 x 107	227 x 227	129 x 129	109 x 109	100 x 100	205 x 205	104 x 104	100 x 100	100 x 100	108 x 108
Deformation ratio (%)	172	120	107	102	162	110	103	100	152	104	100	100	100
Strength Test — First day													
U.C. strength (kg/cm²)	•	•	•	0.016	•	•	0.011	0.021	•	0.022	0.043	0.050	0.015
Water content (%)	540	540	532	520	347	347	342	337	276	248	244	249	284
Volumetric weight (g/cc)	1.119	1.107	1.107	1.105	1.120	1.120	1.116	1.120	1.125	1.171	1.138	1.182	1.146
Eighth day													
U.C. strength (kg/cm²)	•	•	•	0.018	•	•	0.011	0.022	•	0.032	0.043	0.056	0.056
Water content (%)	540	541	540	530	347	347	342	337	276	242	244	244	284
Volumetric weight (g/cc)	1.119	1.107	1.107	1.106	1.125	1.120	1.116	1.118	1.135	1.162	1.119	1.116	1.116
Twenty-eighth day													
U.C. strength (kg/cm²)	•	•	•	0.018	•	•	0.012	0.022	•	0.032	0.057	0.091	0.091
Water content (%)	540	537	537	537	347	347	340	340	276	242	242	244	284
Volumetric weight (g/cc)	1.119	1.107	1.107	1.106	1.125	1.120	1.116	1.116	1.135	1.166	1.172	1.168	1.166

(a) Test on FG Sample

(b) Test on FK Sample

Figure 8. Test results of polymer solidifying agent
(relation between admixture volume and
compression strength) (Continued)

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(c) Test on MK Sample

(d) Test on NN Sample

Figure 8. (Concluded)

TABLE 12. TEST RESULTS OF CEMENT SOLIDIFYING AGENT
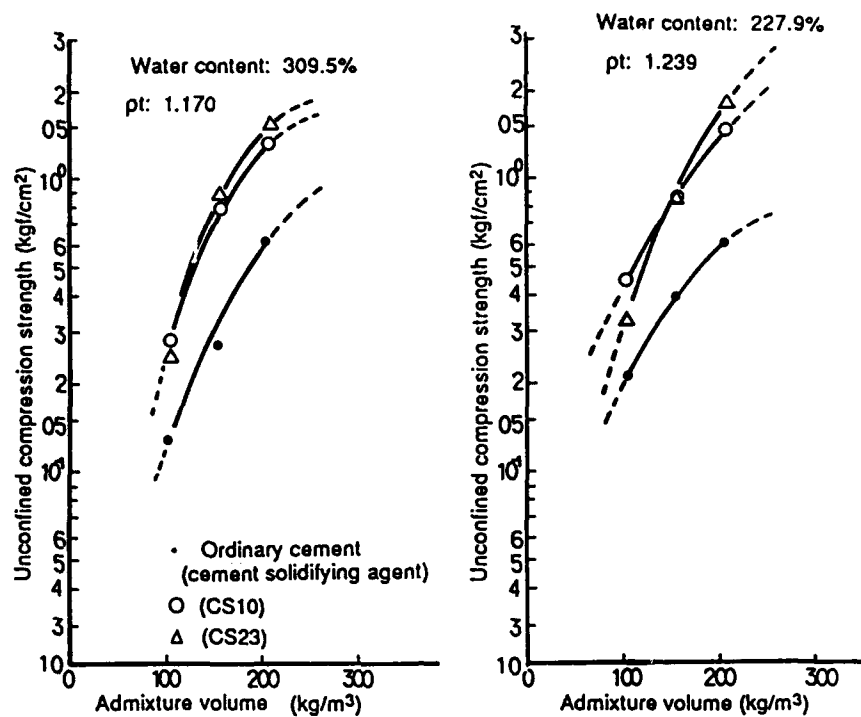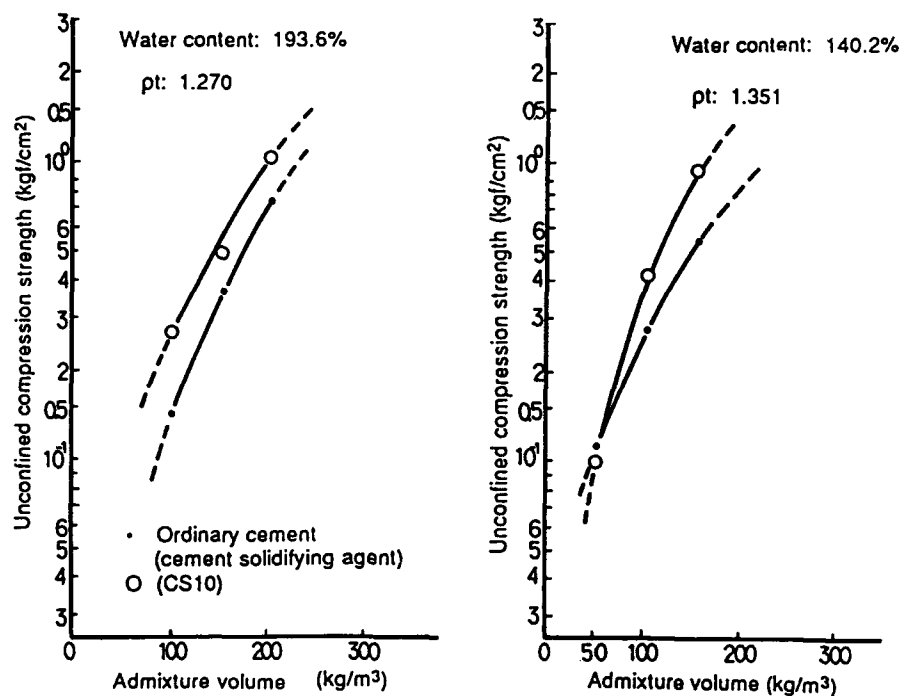
(a) Test on FG Sample

Water Content	Solidifying Agent	Admixture Volume (kg/m³)	U.C. Strength (qu) (kgf/cm²)		
			3rd day	7th day	28th day
190.3% pt = 1.129	Ordinary cement	100	0.05(*)	0.08(*)	0.20(*)
		150	0.07(*)	0.15(*)	0.30(*)
		200	0.16(*)	0.32(*)	0.68
	Cement agent (CS10)	100	0.14(*)	0.34(*)	0.54
		150	0.19(*)	0.80	1.01
		200	0.43(*)	1.36	1.68
	Cement agent (CS23)	100	0.22(*)	0.34(*)	0.62
		150	0.37(*)	0.70	1.27
		200	0.64	1.66	2.76
138.6% pt = 1.312	Ordinary cement	100	0.14(*)	0.21(*)	0.25(*)
		150	0.18(*)	0.39(*)	0.51
		200	0.26(*)	0.72	1.34
	Cement agent (CS10)	100	0.30(*)	0.51	0.64
		150	0.41(*)	1.06	1.22
		200	0.67	2.54	3.86
	Cement agent (CS23)	100	0.28(*)	0.45(*)	0.64
		150	0.50	0.98	1.36
		200	0.93	2.87	4.23

U.C. Strength: Unconfined compression strength
(*) Not acceptable.

(Continued)

TABLE 12. (Continued)

(b) Test on FK Sample

Water Content	Solidifying Agent	Admixture Volume (kg/m^3)	U.C. Strength (qu) (kgf/cm^2)				
			1st day	3rd day	7th day	28th day
414.1% pt = 1.141	Ordinary cement	100	0.09(*)	0.21(*)	0.45	0.99
		150	0.11(*)	0.32(*)	0.60	1.51
		200	0.15(*)	0.58	1.26	2.72
	Cement agent (CS10)	100	0.07(*)	0.34(*)	0.76	1.54
		150	0.10(*)	0.46	1.16	2.14
		200	0.12(*)	0.70	1.82	3.67
252.2% pt = 1.208	Ordinary cement	100	0.12(*)	0.59	1.17	1.88
		150	0.34(*)	1.05	2.08	3.22
		200	0.42	1.38	2.81	4.96
	Cement agent (CS10)	100	0.32(*)	0.74	1.62	2.54
		150	0.56	1.65	2.90	3.92
		200	0.75	2.31	4.00	5.72

U.C. Strength: Unconfined compression strength
(*) Not acceptable.

(Continued)

TABLE 12.   (Continued)

(c) Test on NN Sample

Water Content	Solidifying Agent	Admixture Volume (kg/m³)	U.C. Strength (qu) (kgf/cm²)		
			3rd day	7th day	28th day
309.5% pt = 1.170	Ordinary cement	100	0.13(*)	0.22(*)	0.38(*)
		150	0.28(*)	0.58	0.88
		200	0.62	1.42	1.66
	Cement agent (CS10)	100	0.28(*)	0.52	0.68
		150	0.80	1.42	1.67
		200	1.35	2.45	2.86
	Cement agent (CS23)	100	0.25(*)	0.18(*)	1.02
		150	0.90	1.70	2.70
		200	1.54	2.37	3.82
227.9% pt = 1.239	Ordinary cement	100	0.23(*)	0.44(*)	0.62
		150	0.42(*)	0.88	1.15
		200	0.66	1.54	1.82
	Cement agent (CS10)	100	0.48(*)	0.79	0.92
		150	0.91	1.61	1.81
		200	1.54	3.24	3.58
	Cement agent (CS23)	100	0.35(*)	0.94	1.44
		150	0.92	2.24	3.18
		200	1.92	4.28	5.64

U.C. Strength: Unconfined compression strength
(*) Not acceptable

(Continued)

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TABLE 12. (Continued)

(d) Test on MK Sample

Water Content	Solidifying Agent	Admixture Volume (kg/m³)	U.C. Strength (qu) (kgf/cm²)		
			3rd day	7th day	28th day
193.6% (pt - 1.270)	Ordinary cement	100	0.14(*)	0.30(*)	0.49
		150	0.37(*)	0.78	1.04
		200	0.74	1.33	1.85
	Cement agent (CS10)	100	0.27(*)	0.62	0.93
		150	0.49	1.26	1.78
		200	1.04	2.30	2.96
140.2% (pt - 1.351)	Ordinary cement	100	0.10(*)	0.13(*)	0.15(*)
		150	0.28(*)	0.50	0.68
		200	0.57	0.94	1.33
	Cement agent (CS10)	100	0.17(*)	0.15(*)	0.18(*)
		150	0.43(*)	1.83	1.07
		200	0.98	1.49	2.00

U.C. Strength: Unconfined compression strength
(*) Not acceptable.

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c. Ratio of water content to liquid limit (moisture volume) and required admixture volume: Ratio of water content to liquid limit is 1.2 to 2.2 for polymer solidifying agent and 1.18 to 1.95 for cement solidifying agent, while admixture volume is 2 to 7 kg/m^3 for the former agent and 80 to 210 kg/m for the latter.

d. The cement solidifying agent used for the tests was a special cement developed for the treatment of the sediment containing organic substances. As shown in Figure 6, (FG) sample demanded a large admixture volume of the cement. It is because, as discussed before, this sediment sample is featured by a high total phosphorus and a low true specific gravity, indicating that the sediment contains a large quantity of corrosive organic substances.

Safety of Reforming Treatment

Land-based treatment of dredged sediment is subject to exhaust standard of heavy metals. As shown in Table 13, the sediment samples treated with both polymer and cement solidifying agents were within the permissible limit of heavy metals. Table 14 and 15 (a) and (b) show the analytical results against exhaust standard of heavy metals when the dredged sediment treated with solidifying agent is returned to the farmland. Table 16 are the irrigation water standards. According to Table 14, zinc (Zn) exceeded its permissible limit, which is not unusual. Although zinc affects the growth of agricultural products, dredged sludge containing a large quantity of nutrient salt, such as total nitrogen and total phosphorus, contributes to production (Table 17). Thus, excessive zinc content is hardly problematic.

CONCLUSION

The present study aims at developing a test method of dredged sediment treated with polymer solidifying agent to meet different requirements for sediment treatment and disposal, and also effective utilization of sediment as a nutrient salt source to be reduced to farmland and for other purposes. The study clarified that polymer solidifying agent was one of effective means to reform dredged sediment and that the sediment treated with the agent could satisfy those requirements.

Removal of eutrophic sludge sediment improves water quality of lakes and marshes. Application technology of polymer solidifying agent will certainly contribute to and accelerate the improvement to a great extent.

The task to be taken up in the future is a comprehensive demonstration test, including application development of a practical solidifying agent which promises high safety and workability at treatment site.

TABLE 13. RESULTS OF ELUTION TEST ON SOLIDIFIED SEDIMENT

Sediment Sample	Admixture Volume of Solidifying Agent (kg/m²)	Elution Test based on No. 13 Lead-Based Treatment Standard (land filling)* (unit: mg/liter)							
		3rd day	7th day						28th day
		As	As	T-Hg	Cd	Pb	Cu	Zn	As
Polymer Solidifying Agent									
FK Water content: 414.1% pt = 1.141	2	<0.01	<0.01	--	--	--	--	--	<0.01
	3	<0.01	<0.01	<0.0005	<0.01	<0.1	<0.02	<0.03	<0.01
	5	<0.01	<0.01	--	--	--	--	--	<0.01
FG Water content: 138.6% pt = 1.312	5	--	<0.02	<0.0005	<0.005	<0.02	<0.05	<0.01	--
NN Water content: 227.1% pt = 1.239	3	--	<0.01	<0.0005	<0.01	<0.1	<0.02	<0.03	--
Cement Solidifying Agent									
FG Water content: 138.6% pt = 1.312	150A	--	<0.02	<0.0005	<0.005	<0.02	<0.05	<0.01	--
FK Water content: 414.1% pt = 1.141	100A	<0.01	<0.01	--	--	--	--	--	<0.01
	150A	<0.01	<0.01	<0.0005	<0.01	<0.1	<0.02	<0.05	<0.01
	200A	<0.01	<0.01	--	--	--	--	--	<0.01
	150B	<0.01	<0.01	<0.0005	<0.01	<0.1	<0.02	<0.07	<0.01
NN Water content: 227.1% pt = 1.239	150A	--	<0.01	<0.0005	<0.01	<0.1	<0.02	<0.05	--
	150B	--	<0.01	<0.0005	<0.01	0.1	<0.02	<0.07	--
	150C	--	<0.01	<0.0005	<0.01	<0.1	<0.02	<0.05	--
*Reference value		<1.5	<1.5	<0.005	<0.3	<3.0	(<3.0)	(<5.0)	<1.5

Preparation of Eluate

Eluate was prepared in accordance with Notification No. 13 of Environment Agency, Sample (B) and Test Solution (B).

Measuring Method

As: JIS K 0102 (1986) 62.2, Atomic absorption spectrophotometry
T-Hg: Notification No. 59 of Environment Agency, Appendix 3, Reduction-gasification atomic absorption spectrophotometry
Cd: JIS K 0102 (1986) 55.2, Atomic absorption spectrophotometry
Pb: JIS K 0102 (1986) 54.2, Atomic absorption spectrophotometry
Cu: JIS K 0102 (1986) 52.2, Atomic absorption spectrophotometry
Zn: JIS K 0102 (1986) 53.2, Atomic absorption spectrophotometry

TABLE 14. TEST RESULTS OF NIKATA SAMPLE FOR REDUCTION TO FARMLAND

	Analytical Item	Reference value (mg/mg)	Result	Remarks
Content	T-Hg	2	0.27	Fertilizer restriction
	Cd	5	0.56	Fertilizer restriction
	As	50	5.70	Fertilizer restriction
	Cu	(80)	48.30	Reduction to farmland
	Zn	120	145.00	Reduction to farmland
Acid solubility	As	15	0.55	Reduction to farmland
	Cu	125	14.50	Reduction to farmland
Others	Electric conductivity (*1)	--	570 µs/cm	Influence over agricultural products
	ORP (*2)	--	-292 mV	Influence over agricultural products

Note: (1) Content test should be conducted to compare its results with the test results of previous year and also the results of acid solubility test.
(2) Reference value of electric conductivity of agricultural irrigation water (for paddy) is 300 µs/cm.

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TABLE 15. ANALYSIS OF INFLUENCE OVER VEGETATION (CONTINUED)

(a) Test on FG Sample

Solidifying Agent	Water Content	Admixture Volume (kg/m³)		pH			Electric Conductivity (ms/cm)		
				1st day	7th day	28th day	1st day	7th day	28th day
Polymer agent	290%	0		7.7	7.5	7.5	2.12	2.12	2.12
		2		8.0	7.5	7.5	2.20	2.20	2.21
		4		7.0	7.3	7.3	2.21	2.20	2.21
		6		7.0	7.3	7.3	2.23	2.22	2.21
	340%	0		--	--	--	--	--	--
		2		--	--	--	--	--	--
		4		7.3	7.3	7.3	2.30	2.31	2.30
	440%	0		7.3	7.2	7.2	2.33	2.32	2.32
		4		7.2	7.2	7.2	2.32	2.32	2.32
		6		7.2	7.2	7.2	2.33	2.33	2.33
		8		7.3	7.2	7.2	2.34	2.34	2.35
Cement agent	416.1% pt = 1.161	Ordinary cement	100	12.4	12.3	11.5	4.41	3.11	2.39
			150	12.3	12.4	11.6	5.28	3.88	3.01
			200	12.4	12.6	11.6	6.28	5.41	2.10
		Cement agent (CS10)	100	12.4	12.2	11.2	4.28	3.15	2.27
			150	12.4	12.3	11.4	5.05	3.74	2.13
			200	12.4	12.6	11.5	5.88	4.84	2.01

(CONTINUED)

TABLE 15. (CONCLUDED)

(b) Test on FK Sample

Water Content	Admixture Volume of Solidifying Agent (kg/m³)	pH			Electric Conductivity (ms/cm)		
		1st day	7th day	28th day	1st day	7th day	28th day
276%	2	7.1	7.1	7.1	0.22	0.22	0.22
	3	6.9	6.9	7.0	0.23	0.24	0.23
	4	6.8	6.8	6.8	0.24	0.23	0.24
	6	6.7	6.7	6.7	0.24	0.24	0.25
347%	3	6.8	6.9	6.9	0.21	0.21	0.21
	5	6.7	6.7	6.7	0.24	0.23	0.24
	7	6.8	6.8	6.7	0.24	0.23	0.24
540%	3	6.8	6.8	6.8	0.22	0.23	0.23
	5	6.7	6.8	6.7	0.23	0.23	0.23
	7	6.8	6.7	6.7	0.24	0.23	0.23

TABLE 16. STANDARD OF AGRICULTURAL IRRIGATION WATER (FOR PADDY)

Analytical Item	Permissible Limit	Analytical Item	Permissible Limit
pH	6.0-7.5	Electric conductivity	300 μm/cm(0.3 ms/cm) or below
Chemical Oxygen Demand (COD)	6 mg/liter or below	Heavy metal	
Suspended Solid (SS)	100 mg/liter or below	As	0.05 mg/liter or below
Dissolved Oxygen (DO)	5 mg/liter or below	Zn	0.5 mg/liter or below
Total Nitrogen (T-N)	1 mg/liter or below	Cu	0.02 mg/liter or below

TABLE 17.   INFLUENCE OF SALT CONCENTRATION IN EXTRACT OF WATER SATURATED SOIL ON VEGETATION
(In accordance with USDA Handbook No. 60)

(Electric conductivity: ms/cm = 1000 µs/cm = mmho cm⁻¹)

Electric conductivity (mmho cm⁻¹)	0	2	4	8	16
Influence on agricultural products	Negligible influence	Affects salt-sensitive products	Affects the yield of most agricultural products	Satisfactory yield only from salt-resistant agricultural products	Satisfactory yield from a few strongly salt-resistant agricultural products alone
Salt concentration in extract (N)	0.0	0.02	0.04	0.08	0.16
Osmotic pressure(bar)	0	1	2	4	8
Proposed classification	Non-salt sediment	Weak salt sediment	Medium salt sediment	Strong salt sediment	Extremely strong salt sediment

Mikata sample falls in this range.

Above table indicates that the border between non-salt sediment and salt sediment is found at E Co = 4 mmho cm⁻¹. The value when converted to osmotic pressure of the water in a holding pond, is approximately 5 bar.

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BENCH-SCALE TESTS OF INNOVATIVE TREATMENT TECHNOLOGIES ON SEDIMENTS FROM GREAT LAKES, RIVERS, AND HARBORS

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ABSTRACT

The Great Lakes National Program Office has established the Assessment and Remediation of Contaminated Sediments (ARCS) Program in response to the 1987 Amendments to the Clean Water Act. The ARCS Program is charged with assessing and demonstrating remedial options for contaminated sediment problems in the Great Lakes. As part of the program, the application to sediments of innovative treatment technologies from the hazardous waste and mineral processing fields is being considered. A set of technologies was identified, through a literature survey, for laboratory testing with sediment samples collected from five Great Lakes Areas of Concern (Ashtabula River, Ohio; Buffalo River, New York; Grand Calumet River, Indiana; Saginaw River and Bay, Michigan; and Sheboygan River, Wisconsin). Tests were conducted utilizing the following processes: Zimpro/Passavant's Wet Air Oxidation process, Resource Conservation Company's Basic Extraction Sludge Treatment, Remediation Technology's Low Temperature Thermal Desorption process, and Soil-Tech's Taciuk process. Analyses were performed on feed materials and all process residues to determine process efficiency and effectiveness.

INTRODUCTION

The work I am going to discuss was performed as part of the U.S. Environmental Protection Agency's Assessment and Remediation of Contaminated Sediment Program, which we refer to as the ARCS Program. The ARCS Program was created to address concerns raised in the 1987 amendments to the U.S. Clean Water Act. Specifically, through the ARCS Program we will develop methods for assessing the state of contamination in sediments in the Great Lakes, and we will test technologies for the remediation of contaminated sediments.

The ARCS Program was directed by the U.S. Congress to focus our efforts on five areas of concern in the Great Lakes: the Sheboygan River in Wisconsin, on Lake Michigan; Saginaw River and Bay in Michigan, on Lake Huron; the Ashtabula River in Ohio, on Lake Erie; and the Buffalo River in New York, also on Lake Erie.

The sediments in our five study areas are contaminated with a wide variety substances, including heavy metals, nutrients, conventional pollutants, and organic compounds. These contaminants are generally broken down into two main groups--inorganic and organic. The inorganics include heavy metals such as cadmium, chromium, lead, mercury, and zinc. The organic contaminant problems are usually associated with polychlorinated biphenyls (PCBs) and the polynuclear aromatic hydrocarbons (PAHs). Additionally, the Great Lakes have been subjected to high loads of nutrients such as phosphorus and nitrogen, as well as biological oxygen demand from wastewaters.

DISCUSSION

This paper will describe first how we selected the technologies to be tested; second, the general philosophy of our technology tests; third, the technologies; and finally, the results of these tests.

In order to identify which technologies should be tested by the ARCS Program, a literature survey was performed by Mr. Daniel Averett of the U.S. Army Corps of Engineers. Through this report, Mr. Averett identified a set of six major technology types that were worthy of further study by the ARCS Program. Those technology types were: particle classification, bioremediation, immobilization, chemical destruction, extraction, and thermal destruction/extraction. At this time, the bench scale-tests will be discussed that were conducted in a laboratory setting and performed with three of these technology types: chemical destruction, extraction, and thermal extraction.

Before the specific tests are discussed, a description of the basic philosophy employed during these technology evaluations is necessary. Many of the technologies Mr. Averett identified had not been tested on contaminate sediments. The technologies had been developed in the hazardous waste treatment field or the mineral processing industry. In order to better understand how these technologies perform when treating sediments, we chose to evaluate them in the laboratory, using bench top equipment that simulated the actual treatment units.

For these bench-scale tests, small volumes of material (from less than 1 ℓ to a maximum of 200 ℓ) were processed through these laboratory units. Chemical Characterization tests were conducted on the raw sediment material prior to treatment and on all of the output streams produced by the treatment process. For some of the technologies, there were only two outputs--a water and a solid product. For other technologies, there were as many as four products--water, solids, oil, and organic extracts. These end products were analyzed for the following parameters: PCBs, PAHs, heavy metals, nutrients, TOC, oil and grease, etc. The results of these tests will be presented later.

This description is of the glassware simulation used for Resource Conservation Company's solvent extraction technology known as the Basic Extraction Sludge Treatment (B.E.S.T.) process. The B.E.S.T. process, as it is commonly referred to, uses the aliphatic solvent triethylamine to separate organic contaminants from soil and sediment. The end products of this process are a dry solid, a water fraction, and an oil fraction that contains the organic contaminants. This technology does not destroy contaminants, but it does separate and concentrate them in a greatly reduced volume for further treatment. This extreme example occurs where the laboratory equipment used bears very little resemblance to the full-scale process.

Remediation Technology's low-temperature thermal desorption unit was also tested. This technology heats the sediments to temperatures just below incineration (around 530 °C). The organic contaminants are volatilized from the sediments and collected in a condenser system. This technology also does not destroy any contaminants, but it does concentrate the organics in a greatly reduced volume. Remediation Technology's pilot-scale, truck-mounted unit was used to process one of out samples from the Ashtabula River. This example represents the opposite extreme where the laboratory treatment process very closely resembles the full-scale unit.

The Taciuk process, another low-temperature thermal desorption unit, was also tested under the ARCS Program. This technology was originally developed to recover oil from oil shales and tar sands and is now being marketed as a hazardous waste treatment process.

Finally, Zimpro/Passavant's Wet Air Oxidation unit was evaluated by ARCS. The Wet Air Oxidation process was developed over 30 years ago for the treatment of municipal wastewater treatment plant sludges. This process has been very effective in destroying PAHs and somewhat less effective in breaking down PCBs. Both of these laboratory units are not quite replicates of their full-scale counterparts, but they are more advanced that the glassware-type operation described earlier.

RESULTS

The preliminary results of the test conducted on sediments from the Grand Calumet and Buffalo Rivers indicate that PAHs are a major concern. The Taciuk process successfully removed over 99 percent of the PAHs from both samples, and the solid residue from the process successfully passed the USEPA's hazardous waste test, the Toxicity Characteristic Leaching Procedure, or TCLP test.

The Wet Air Oxidation process was applied to a sediment sample from the Grand Calumet River. The initial concentration of PAHs was measures at 24 ppm. After treatment, the PAHs were reduces to 1 ppm, and average destruction efficiency of 96 percent. The destructive capacity of the process varied with the individual PAH, ranging from a low rate of 82 percent for chrysene to a high rate of 99.9 percent of benzo(b) fluoranthene.

The data for the tests conducted with the Remediation Technology process and the B.E.S.T. process are not yet completed. The ReTeC process was tested on a sediment sample from the Ashtabula River, and the B.E.S.T. Process was tested on samples from the Buffalo, Grand Calumet, and Saginav Rivers. Final reports on all of the bench-scale tests are expected in July 1992.

In conclusion, the early results from out bench-scale tests have demonstrated that the organic contaminants present in Great Lakes sediment can be removed or destroyed with high efficiencies in a laboratory setting. The next step in the ARCS program, performing treatment technology demonstrations in the field, is happening now. By the end of 1992, it will be possible to say with some authority whether these technologies work not only in the laboratory but also in field applications.

ORIGIN AND TRANSPORTATION OF AIRBORNE MICROPOLLUTANTS INTO BOTTOM SEDIMENTS IN AN URBAN RIVER

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ABSTRACT

The origin, transport, and fate of hydrocarbons in the Nogawa River basin, a typical urban river running through residential areas in suburban Tokyo, was studied both in normal and high water conditions. Aliphatic hydrocarbons (nSHCs) and PAHs found in the river water in normal water condition originated mainly from gray water. nSHCs and PAHs found in high water originated mainly from runoff water. The also originated from roadside dust and were washed off into runoff water. nSHCs accumulated in the bottom sediments during high water, but they released back to water during normal water condition to decrease concentration in the sediments. On the contrary, PAHs always accumulated in the bottom sediments by their high absorbability onto sediments, and the highest concentration of PAHs was noted in the bottom sediments. Atmospheric nSHCs and PAHs seemed to be the origin of roadside dust. They were transported onto the surface of road during rain. Although the emission of automobiles seemed to be the origin of nSHCs, it is most probable that PAH originated from other distant sources than automobiles emission nearby.

INTRODUCTION

Numerous chemicals that originated from human activities are known to be discharged into environment in various forms such as suspended particulate, dust, and mist. These substances are directly discharged into water bodies or transported through atmosphere, and a part of them is deposited on land or directly on water surface. In rainy days, those airborne chemicals deposited on land in previous dry weather period will be washed off by stormwater.

Although most of stormwater runoff is introduced into the sewer system in the area with a combined sewer system, stormwater overflow is still discharged directly into public water bodies without any treatment. Chemicals are also discharged directly into public waters in the areas with separate sewer system and, of course, with no publicly owned sewer system. Some of

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these chemicals are known to be degraded biologically, whereas others remain in the bottom sediments of the water. They may have significant impact on aquatic ecosystem. Jensen (1983) estimated the input and output of petroleum hydrocarbons in a coastal marine area of Denmark and reported that 21 percent of the total weight of C_{12}-C_{36} fraction has deposited on the sediment.

A number of investigations have been reported on the importance of stormwater runoff as a major pathway of chemicals from land origin into an aquatic environment (Browne 1980, Field et al. 1980, Duda et al. 1982). However, there have been reported few studies on the behavior of hydrophobic petroleum hydrocarbons.

Sources of hydrocarbons to urban stormwaters include accidental spills, deliberate dumping of waste oil and fuels, emission from engines, crankcase drippings, fallout from atmospheric particulates, spillage of the products during refining and transportation, natural seepage, and natural biogenic sources (Fam et al. 1987). Brown et al. (1985) has shown that the most probable source of crankcase oil-like petrochemical hydrocarbons found in the sediments of the Hillsbrough River was the stormwater runoff. Walkeham (1977) has reported that the petroleum hydrocarbon in the sediment in Lake Washington bordered by Seattle on the west was almost from urban stormwater runoff, and the contribution from naturally occurring hydrocarbons appeared to be minor. Hamilton et al. (1984) pointed out that the plant wax hydrocarbons found in the suspended matter in the upper Green-Duwamish river, Washington, originated from algae and that a secondary sewage treatment plant was a major point source of hydrocarbons to the river. Sternstorm et al. (1984) and Fam et al. (1987) investigated the hydrocarbons found in 15 watersheds in the San Francisco Bay area and reported that the hydrocarbons in undeveloped areas were of biogenic origins and that the major anthropogenic sources of hydrocarbons in the stormwater runoff from urban areas originated from motor oil and diesel fuel.

Those reports estimated that hydrocarbons found in aquatic environments such as rivers, lakes, and estuary were transported by stormwater runoff from urban area where hydrocarbons exist in the form of smoke and soot of the factory and emission of the incomplete combustion of automobiles during cruising, deceleration, and idling. The objective of this study is to know the origin, the transport, and the fate of the petroleum hydrocarbons, i.e. aliphatic and polycyclic aromatic hydrocarbons, in bottom sediments of urban river with special emphasis on the contribution of stormwater runoff and the role of bottom sediments.

MATERIALS AND METHODS

The Nogawa River is a tributary of the Tama River in Tokyo. The river originates from a spring in the City of Kokubunji and runs thorough residential areas of suburban Tokyo with several inflows of spring water and numerous discharges of urban runoff and gray water. The area of the Nogawa River basin is 46.3 km^2 with population of 410,000. Eighty-seven percent of the basin was served with public-owned separate sewer system. In the remaining 13 percent with no sewer system, gray water is allowed to be discharged directly into the river without any treatment. Average rate of flow is 20 x 10^3 m^3 day^{-1}, and 82 percent originates from gray water. The river finally flows into the Tama River at Setagaya-ku in Tokyo.

River water and bottom sediment were collected at a sampling station in the mid-stream of the river. Street dust, runoff water, graywater, dry precipitation, and rain water were sampled in the upperbasin of the sampling station. Water samples were collected in a glass bottle and transported to laboratory after NaCl was added to 3 percent and pH was adjusted to 2.0 with 1 N HCl in situ. Petroleum hydrocarbons were extracted from the sample by fractionation into dichloromethane (sample: dichloromethane = 10:3 in volume). The extract was dried over sodium sulfate and excess dichloromethane was evaporated by Kuderna-Danish (KD) evaporative concentration to have the final volume of 1 ml. The concentrate was charged into a glass column packed with silica gel (10 mm by 300 mm). Aliphatic hydrocarbons (nSHCs) were eluted with 30 ml of n-hexane. Polycyclic aromatic hydrocarbons (PAHs) were eluted with 30 ml of n-hexane/benzen solution (1:1 v/v). Each fraction was concentrated and dried by a rotary evaporator.

nSHCs were dissolved into 1 ml of hexane and separated and identified by a gas chromatography (Shimazu, GC-14A) with a hydrogen flame ionization detector. A capillary glass column (0.25 mm by 25 m) packed with ULBON HR-101 (Chromatopacking Center Co.) was used. Temperature of the injector was 320° C, and that in the column increased from 60 to 240° C with the rate of 4° C per minute.

PAHs were dissolved into 2 ml of methanol and determined by a high performance liquid chromatography (Tosoh, model CCPE) with a column packed with TSK gel (ODS-80TM, 4.6 x 250 mm) at room temperature. The elute used was methanol/water solution (95:5, v/v) with a flow rate of 1.0 ml/min. A fluorescence detector (Shimazu, RF 535) at a wave length of 295 nm for excitation and 490 nm for emission was used.

Solid samples were sieved to remove large particles such as stones and litters and were preserved in amber bottles at -20° C. Bottom sediments were centrifuged at 3,000 rpm for 10 min to remove excess water. Prior to hydrocarbon analysis, a part of each sample was ovendried at 105° C for two hours to determine dry weight.

Petroleum hydrocarbons in the solid samples were extracted by dichloromethane with mortars. The extract was passed through a glass fibre filter (Whatman GF/F). The filtrate was washed successively with 10 percent sodium carbonate, 1N sodium hydroxide and 1 N HCl, and finally, was neutralized by water. The sample was dried over sodium sulfate and concentrated and dried by a rotary evaporator.

The concentrate was charged to the column of silica gel, and nSHCs and PAHs fractions were separated. The concentration of each component was determined by the same procedure as water sample.

RESULTS AND DISCUSSION

nSHCs and PAHs in the River

Concentrations of nSHCs with carbon number from 11 to 30 in the bottom sediments and river waters both in normal and high water conditions are shown in Figure 1. The higher concentrations of nSHCs were noted in samples during high water than that during normal water condition. It is clear that, in the
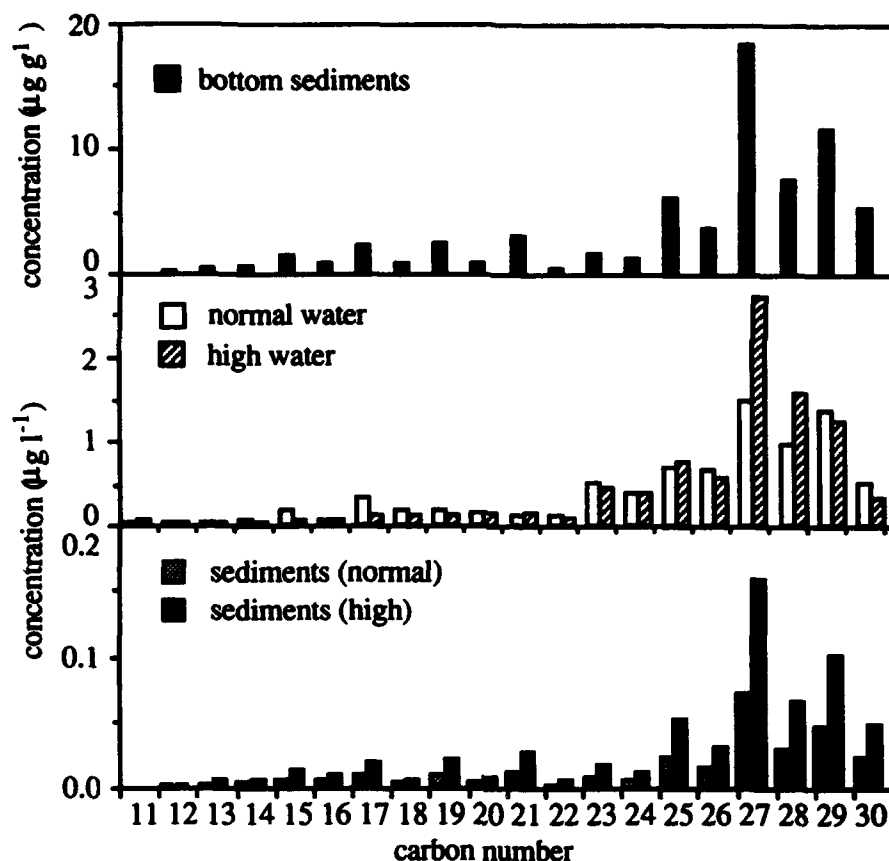
Figure 1.   Concentrations of nSHCs with carbon number from
11 to 30 in the bottom sediments and river
waters both in normal and high water conditions.

basis of volume, there are far larger concentrations of nSHCs in the bottom
sediments (surface sediments).

The bottom section of Figure 1 shows calculated concentrations of nSHCs
assuming bottom sediments were resuspended with the same concentration as the
suspended solids (SS) concentrations in the water both in normal and high
water conditions, 3.85 mg l^{-1} and 8.64 mg l^{-1}, respectively. The amount of
nSHCs attached to particles in the bottom sediments were far smaller than
those in water. More than 50 percent of nSHCs in the river water with carbon
number more than 23 were attached to the SS. The percent attached increased
with the increase in the number of carbon, and more than 90 percent of nSHCs
with carbon number of 29 and 30 were associated with SS. Both attached and
dissolved concentrations of nSHCs in the water, therefore, were higher than
the concentrations estimated from the attached concentrations of nHSCs in the
bottom sediments. Thus, nSHCs in the water seemed not to have accumulated in
the bottom sediments.

Concentrations of PAHs, i.e., benzo(a)anthracene (B(a)A), benzo(k)fluor-
anthene (B(K)F), benzo(a)pyrene (B(a)P) and benzo(ghi)perylene (B(ghi)P), in
the sediments and water samples are shown in Figure 2. Similar to nSHCs,
volumetric concentrations of PAHs in the bottom sediments were far higher than
those in the water samples. Concentrations in the high water condition were

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also higher than those in normal water. Contrary to nSHCs, PAHs in the bottom sediments were higher than those in water if they were resuspended into water with the same SS concentration as the water. Therefore, PAHs seemed to have accumulated in the bottom sediments in higher concentrations than in the water.
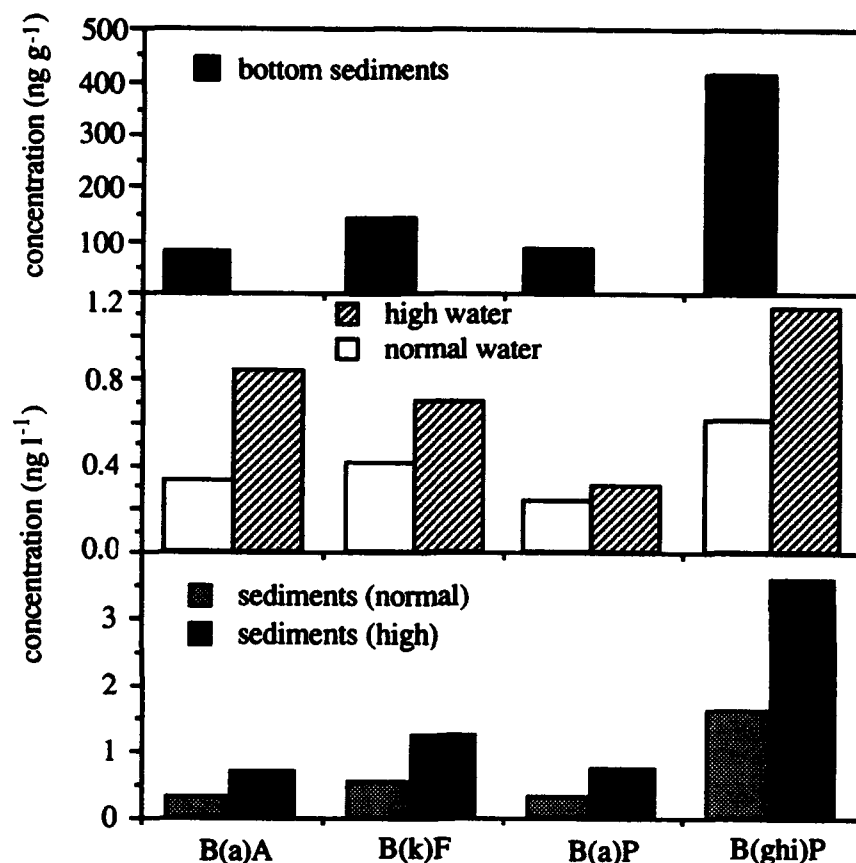
Figure 2. Concentrations of PAHs in the sediments and water samples

Loadings of nSHCs from the Basin

To estimate origin and fate of petroleum hydrocarbons in the bottom sediments, loadings from various sources in the upper basin of the sampling point were estimated based on the monitoring data. Figure 3 shows three possible sources of nSHCs in normal water condition. The largest source of nSHCs discharge was gray water, and contributions of other sources were almost negligible.

Figure 4 shows total amount of discharge into the upper basin, i.e. input loading, and output loading at the point of sampling, which is the daily amount of nSHCs passed at the point of sampling with the flow of water. The amount of output was larger than that of input.

There should be some contribution of so-called self-purification with the flow of river. The input of SS by gray water, for example, was estimated to be 162 kg day^{-1}. Total output was only 39.7 kg day^{-1}. Thus, significant self-purification, at least more than 75.5 percent, can be expected through
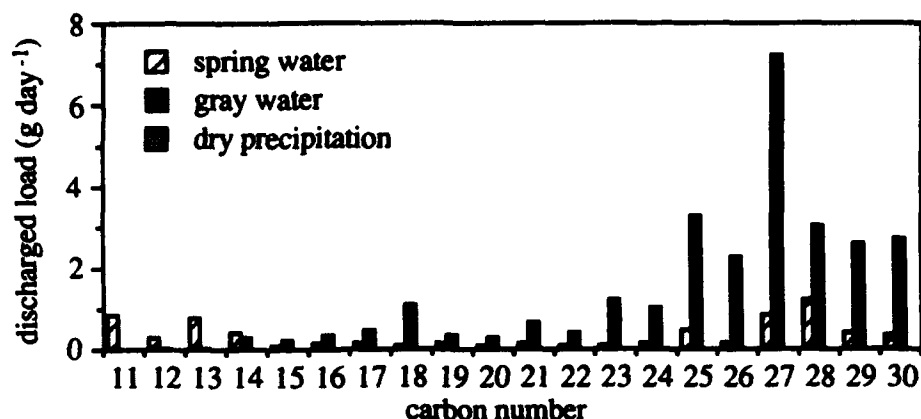
Figure 3.　Sources of nSHCs in normal water condition
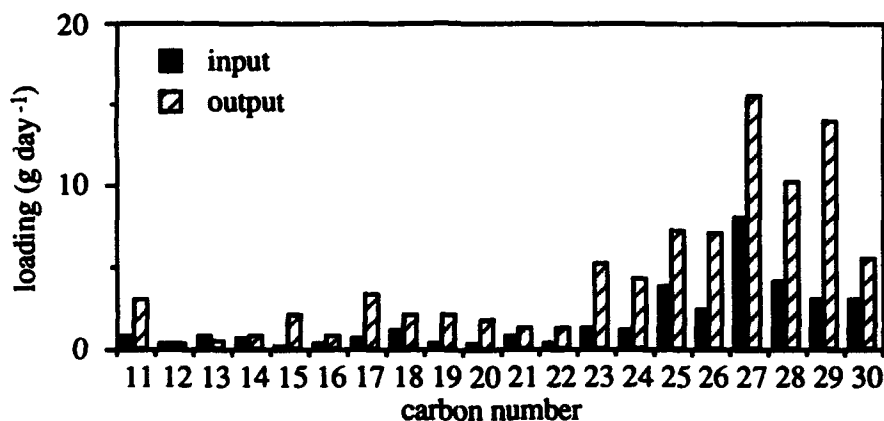
Figure 4.　Input and output loadings

sedimentation.　Therefore, nSHCs attached to SS might be removed with the sedimentation of SS.　The fact that the output of nSHCs was larger than the input, on the contrary, indicates that there should be other sources of nSHCs discharge.

Figure 5 shows two additional sources of nSHCs that may contribute only in high water condition.　The largest source of nSHCs discharge was urban runoff.　The contribution of rain water itself was negligible.　It must be noted that the contribution of urban runoff was approximately 10 times as large as that of gray water.　Figure 6 shows input and output of nSHCs.　Contrary to the normal water condition, the amount of input was larger than that of output, indicating normal self-purification.
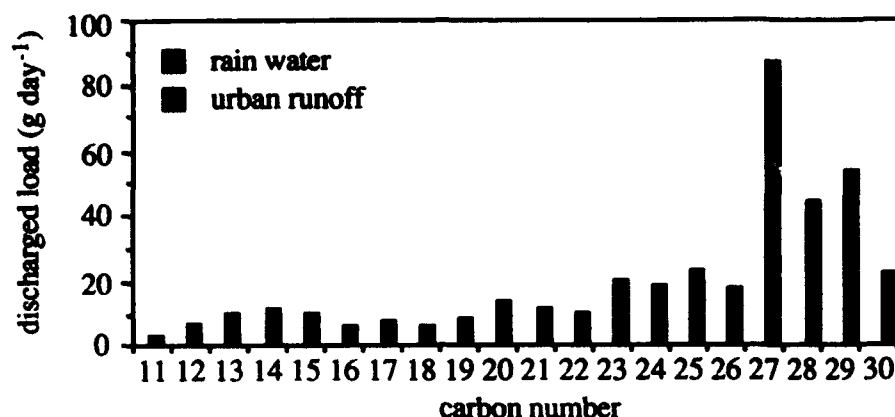
Figure 5. Sources of nSHCs in high water condition
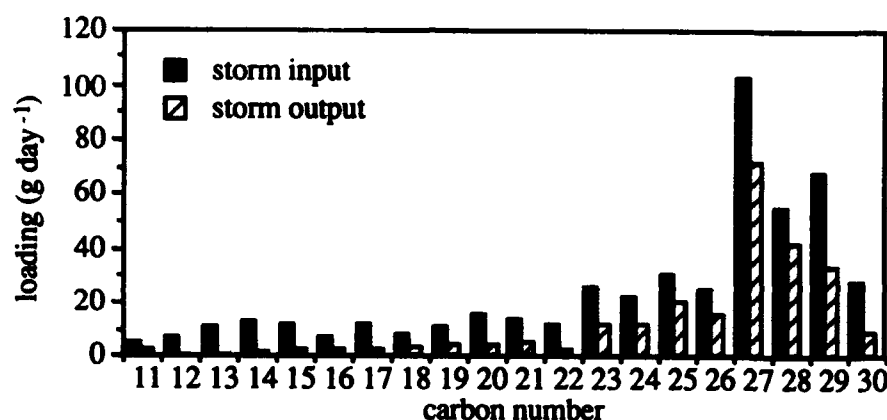
Figure 6. Input and output loadings of nSHCs in high water condition

Thus, nSHCs were discharged into river mainly by urban runoff. Most of nSCHs in urban runoff (more than 90 percent, not shown here) were associated with suspended sediments. Hoffman et al. (1984) reported that petroleum hydrocarbons were transported with runoff water and, especially, that most of the hydrocarbons were associated with suspended particles during high water in the estuarine water of Rhode Island. Latimer et al. (1986) reported that most of petroleum hydrocarbons in runoff water were adsorbed on SS.

Generally, urban runoff water contains various particles of terrestrial origin such as fine particles from asphalt and concrete pavements, and soil particles. It is most likely, therefore, the hydrocarbons discharged into the Nogawa River with runoff water may be adsorbed onto SS and deposited on the bottom of the river. The accumulated nSHCs in the bottom sediments seemed to be another source of nSHCs discharge in dry weather condition.

Loadings of PAHs from the Basin

Figure 7 shows three possible sources of PAHs in normal water condition. Similar to nSCHs, the largest source of PAHs discharge was gray water, and contributions of other sources were negligible. Input and output loadings are also shown in Figure 7. Contrary to nSHCs, output was smaller than input

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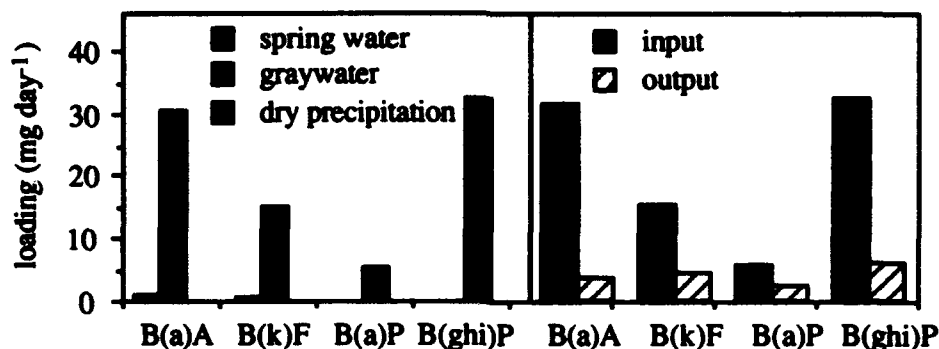
Figure 7. Sources and input and output loadings of PAHs in
          normal water condition

indicating accumulation of PAHs in the bottom sediments even in normal water
condition.

Figure 8 shows two additional sources of PAHs associated with rain. The
largest source of PAHs discharge was also urban runoff. The contribution of
rain water was negligible. It is remarkable that the contribution of urban
runoff was more than 100 times as large as that of gray water. Input and
output of PAHs in high water condition are shown in Figure 8. The output was
negligible in spite of large amount of PAHs input by urban runoff.
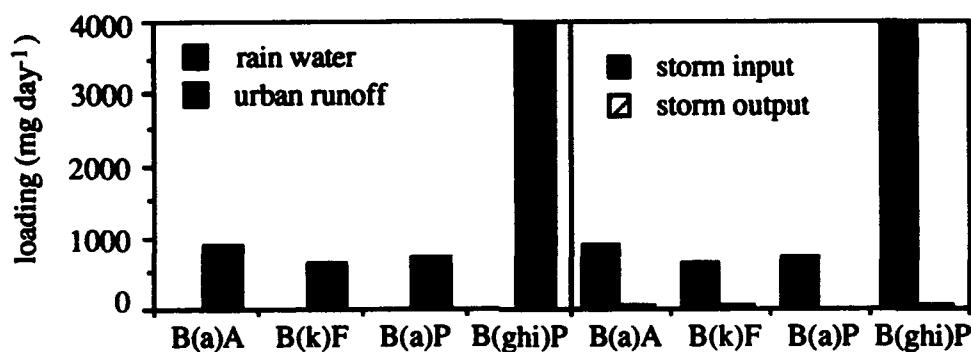
Figure 8. Sources and input and output loadings of PAHs
          in high water condition

Most PAHs discharged into the river originated from urban runoff. Simi-
lar to nSHCs, most of them (more than 95 percent, not shown here) were associ-
ated with suspended sediments. It is well known that large amount of PAHs are
adsorbed onto suspended sediments (Latimer et al. 1986, Hoffman et al. 1982,
1984, 1985, Herrmann 1981). It is most likely, therefore, PAHs discharged
into the river with runoff water may also be adsorbed onto SS and deposited on
the bottom of the river. The higher absorbability of PAHs than nSHCs may
enhance the adsorption onto both suspended and bottom sediments with little

remaining PAHs in water and little release back into water. Thus, most of PAHs discharged into the basin accumulated in the bottom sediments.

Transportation of Airborne Hydrocarbons to Runoff Water

It is known that petroleum hydrocarbons are discharged into atmosphere in the form of smoke and soot from factories and by emission of incomplete combustion from automobiles. They are washed out by rain down to land surface and transported with stormwater runoff from urban area (Herrmann 1981).

Yamane et al. (1991) reported concentrations of nSHCs and PAHs in the surface soil of the Nogawa Park, with was loc_ted near the sampling site in the Nogawa River, in dust of roadside nearby, and on route 20 with heavy traffic in contrast with the residential district of the Nogawa basin.

Only nSHCs with carbon number of 27 and 29 were detected in the surface soil of the Nogawa park and were below 1 μg g^{-1}. Therefore, it is not likely that nSHCs in the surface of the soil were transported to runoff water. The distribution of hydrocarbons in the street dust corresponded with that of runoff water, thus indicating to be a major source of nSHCs to runoff water. The concentration of nSHCs in the dust of route 20 was far higher than that in residential area. It is well known that major hydrocarbons used in motor oil are those with carbon number around 23; particle hydrocarbons in emission from diesel engine are mainly those with around 20; and those in gasoline and light oil are mainly those with around 14 (Simoneit et al. 1981, Brown 1985, Fam et al. 1987). The origin of street dust seemed to be emission of automobiles nearby.

PAH contents in park soil were ca. 5 ng g^{-1} dry weight and in street dust and in roadside dust of route 20 ranged from 20 to 40 ng g^{-1}. The nSHCs in roadside dust of route 20 was 10-30 times as high as that in street dust of residential area, whereas concentrations of PAHs were almost the same. Therefore, it is most probable that PAHs did not originate from emission of automobiles.

Lygren et al. (1984) reported that hydrocarbons are deposited within 100 m from highway as small particles of dustfall in Norway. In the Nogawa River basin, hydrocarbons contents in rainwater was negligible. Most hydrocarbons in emission of automobiles, therefore, seemed not to suspend in atmosphere, but adsorbed on fine particles of dust, greater than 10 μm, and deposited on road surface or surrounding area. Hagenmaier et al. (1986) determined PAH concentrations in surface sediments of the River Neckar, primary sludge of wastewater and organic fraction of municipal refuse. Furthermore, PAH originated party from traffic and mostly from incompletely combustion of woods at home.

The concentration of nSHCs and PAHs in the dust of roadside did not show significant increase during consecutive fine days (not shown here). However, they increased after rainfall. There are no sources except rainfall to increase hydrocarbon contents in the roadside dust. Thus, it seemed that raindrops adsorbed hydrocarbons in the atmospheric dust and precipitated on the road to increase their concentration in spite of large amount of output with urban runoff.

CONCLUSIONS

The origin, transport, and fate of hydrocarbons in the Nogawa River basin, a typical urban river running through residential areas in suburban Tokyo, was studied both in normal and high water conditions. The specific conclusions derived from this study are as follows:

a. nSHCs and PAHs found in the river water in normal water condition originated mainly from gray water.

b. nSHCs and PAHs found in high water originated mainly from runoff water. They also originated from roadside dust and were washed off into runoff water.

c. nSHCs accumulated in the bottom sediments during high water, but they were released back to water during normal water condition to decrease concentration in the sediments. On the contrary, PAHs always accumulated in the bottom sediments by their high absorb-ability onto sediments, and the highest concentration of PAHs were noted in the bottom sediments.

d. Atmospheric nSHCs and PAHs seemed to be origin of roadside dust. They were transported onto the surface of the road during rain. Although the emission of automobiles seemed to be the origin of nSHCs, it is most probable that PAH originated from other distant sources than automobiles emission nearby.

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QUESTIONS AND ANSWERS

15th Meeting, US/Japan Experts on Management
of Bottom Sediments Containing Toxic Substances

Mr. Taizo Nakano

Q: Describe contaminants in sediments at Osaka.

A: Bottom sediments, organic substances, heavy metals, disposed in other areas and do not pass standards.

Q: What kind of dredges were used - hopper or cutter suction?

A: Most cases resort to hopper types.

Q: What size were the areas?

A: Approximately 300 hectares. Volume was 30 MCM of dredged substances.

Mr. Norman Francingues

Q: From these biological examples of treatment, can you give us some results?

A: Results are not available on these examples but we have results from other sites that show reductions after only a few weeks.

Q: Techniques have been demonstrated and considered; do you have plans for major demonstration project? *If so, when, where and who would bear costs?*

A: We have an ongoing project in Waukegan and can get you some information through EPA.

Dr. James Brannon

Q: After sample did you change water on the upper level every day?

A: We are combining the water with the mud.

Q: Did they contain organic substances? If so, how much?

A: Yes, about 12 ppm PCB.

Comment: We found centrifugal force took out sediment.

Q: Is time lapse important in a time like this?

A: Time is important. Samples change over time. Test samples as soon as possible to maintain aerobic condition. Do it under nitrogen atmosphere.

Q: Have you put sands through wet and dry cycles to see how it affects release rates?

A: No, due to finding we just had a wet cycle; however, we did recent samples and saw slight increase.

Q: Do you have estimate of PCB rate loss in that 1,200-ppm sample?

A: On the order of 29 $mg/m^2/hr$ in that sample.

Q: 1,200 ppm was large amount - why so big?

A: At New Bedford, material from transforms fell into the water.

Q: What is condition where sample taken?

A: The water was shallow and the sedimentation was thin.

Mr. Takeo Maekawa

Q: We have done research on removing solids from effluents at confined sites. Use of chemicals and polymers are effective for solid removal but we get toxicity to organisms. Do you get similar results?

A: Coagulates have been used in landfills but have had no such problems.

Q: You referenced use of a pump. What kind? How did the solids react?

A: Oozer pump dredge reported in past meetings. Vacuum pump characterized as high concentration or density dredge.

Dr. Thomas Fredette

Q: In order to separate pollutants, capping is becoming popular in Japan. When selecting thickness or siting of capping, might it provide environment for organisms.

A: Yes. We are concerned about organisms burrowing into contaminated material so we must get proper thickness. We believe these sites are beneficial to fisherman. Their topographic shape is similar to ocean floor and attracts flounder and other fish.

Q: Any conflict with fisherman?

A: Some sites were closed because fishermen became so plentiful. However, in nine sites this has been no problem.

Q: What is capping material and source? Do you have to compete?

A: Usually another dredged material without contaminants. No conflict with construction industry--not construction-grade sand.

Q: (1) Basic philosophy is to directly cap pollutant. Why transport before?
   (2) Water depth of 90M--do you have problem with turbidity?
   (3) What is thickness?

A: (1) Need to increase water depth like channel, so to construct cap in place, must transport.
   (2) We consider water column impacts and have a number of management options to consider in order to reduce impact.
   (3) We try for range of 50 to 100 cm thick.

Q: (1) How do you prevent mix of contaminated and cap material?
   (2) Can you cap with a hydraulic dredge?

A: (1) Mix was a concern, but our cores show a sharp line. The contained material seems to have strength and integrity.
   (2) Behavior of hydraulic dredge capping is similar to mechanical. Lower density and more spread would be with hydraulic.

Comment: If you submerge the pipe in hydraulic dredge, it might give better concentration.

Q: What sort of time constraints are put on you by EPA to cap after placing contaminated material?

A: We like to have capping start within 2 weeks of placing contaminated material. Time to complete is less critical, usually takes a month or so.

Mr. Akira Teramoto

Q: Where in relation to dredge did you take measurements?

A: We took several measurements--tip and rear of dredge to center, left, and right.

Mr. Hiroyuki Sakamoto

Q: What solidifers did you use?

A: A cement-like compound as solidifying agent.

Q: (1) What soil parameters did you use to see if soil has workability?
   (2) How do you adjust its workability?

A: We use flow test. Fluidity is critical, neither too hard or too soft. We use flow test standard for Japan. Soil may sometimes have large foreign objects. We use screen to remove. May add water for fluidity. We would look at diffusion through test.

Mr. Makoto Natori

Q: Have you tried to identify biological organisms used?

A: Very difficult to do; we did not in this case.

Q: You are returning water to marsh, but may it not contain a lot of phosphate?

A: Depends on care, but here the water at bottom has higher level of phosphate and supernatant has lesser level.

Mr. Hideo Hamabata and Mr. Yusuke Suda

Q: The cost for dredging seemed high. What was cost/CM?

A: That was careless mistake. I will revise now - dredge $19M, capping $13M, porous oxidation $300K, conveyance $500K, and converse river water $11M. As for unit cost, I have data but cannot pull it out now.

Q: Are there concerns with heavy metal or petroleum by-products?

A: In Japan, we have been able to dispose of heavy metals below standards in most areas.

Q: You mentioned micro-organisms. In the future can we improve the situation with bio-engineering?

A: Yes, some are using it, but it is beyond scope of Sea Blue.

Q: Do you backwash or forewash?

A: The system is the crucial point. We backwash and use a dual system.

Q: Organisms present would depend on time of year. Some workable in Tokyo may not be so here in LA. Is it not so?

A: It is extremely crucial how we process the organisms. They may not react as we humans might wish. What works in Tokyo may well not work in LA. Technology process is important.

Mr. Wada

Q: How much cementitions material does he mix to get the results?

A: It depends on water content, from 120 to 170 kilo per cubic meter.

Q: What is the approximated cost per kilo of material?

A: 20,000 yen/ton approximately.

Mr. Thomas Myers

Q: Do you know what are the reasons why in Harbor of Buffalo results were so different?

A: No, I do not.

Q: Data are significantly different for what I have. Unthinkable these heavy metals.

A: Geochemistry of metals and sediments is complex. Colloidal system, organic carbon can be mobilized by solidification process. We began with the ideal that we could mobilize metals. We are concerned about misapplication of this technology.

Comment: Adding cement to mobilize metals is well established in the mining industry of the United States.

Q: Could you get these leaching speeds if you repeat the process many times?

A: Test done to remove the metals sequentially. Then tested untreated material for comparison. We tried to leach as much as we could so in the final analysis speed was not critical.

Comment: From the presentations here it is apparent the Japanese are ahead of the US in this field. It would be helpful in future if you could share chemical sedimentation techniques with us.

Q: What kind of solidifying agent did you use--and the unconfined compressive strengths. It would seem the amount of compound would impact the leaching.

A: We have run different tests with different agents and can supply results to you. In general, we have found little difference in results due to use of different agents. The agent used definitely impacts on the strength of the resulting material. These data are available. We have also done durability testing.

Mr. Kiyoihi Nikaido

Q: What kind of polymer did you use?

A: Mainly polyachrin acid and other natural polymers.

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Mr. Steve Garbaciak

Q: Will you come up with ballpark estimates on cost per cy?

A: Yes, we will have the Feb results (report) that will give estimate of upscaling to full operation.

Q: I compliment you on an interesting report. Have you conducted tests in 1 to 1.5M? Have you tested for leaching?

A: Material represents top 1 meter of area--removed with clam shell. Bulk of contamination in Great Lakes increases the deeper you go. Leaching tests are being subjected on heavy organic rather than heavy nutrient samples.

Q: Did you run tests before treatment?

A: TCLP test on only one rather than all.

Q: Can we get literature for Great Lakes program?

A: Sure. Leave me your name.

Dr. Mitsumasa Okada

Q: Explain how you collected roadside dust samples--collect dust or system?

A: Broom and dust collectors.

Q: Is consideration being given to trapping pollutants before getting into water course and becoming sediment?

A: Not during this research, but we know that in cases of separated sewer systems, storm water goes into supply systems, particularly in new development. Rain water goes into public supply system. Japanese government is developing ponds to capture rainfall for the PAH. It will be easy to remove--easily attaches to suspended sediments. This also applies to P&N.

Q: Have you looked at metals through atmospheric sediments?

A: No, have no interest, vowed to never study heavy metals.

Comment: U.S. interested in using wetlands to help in both urban and rural areas to clean runoff.

Response: The climate and land are different in Japan. Don't know whether the process would apply there. Hope this conference continues forever.