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EVALUATION AND CALIBRATION OF THE TETRA TECH DREDGED MATERIAL D--ETC(U)
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Dredged Material Research Program

TECHNICAL REPORT D-78-47

EVALUATION AND CALIBRATION OF THE TETRA TECH DREDGED MATERIAL DISPOSAL MODELS BASED ON FIELD DATA

by

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Final Report

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under DMRP Work Unit Nos. 1B06 and 1B07

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WATERWAYS EXPERIMENT STATION, CORPS OF ENGINEERS
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IN REPLY REFER TO: WESEV 30 September 1978

SUBJECT: Transmittal of Technical Report D-78-47

TO: All Report Recipients

1. The technical report transmitted herewith represents the results of an evaluation and calibration of the Tetra Tech dredged material disposal models based on field data. This study was one of the major efforts to be accomplished under Task 1B (Movements of Dredged Material) of the Corps of Engineers' Dredged Material Research Program (DMRP). Task 1B was part of the Environmental Impacts and Criteria Development Project of the DMRP, which was a broad, multi-faceted investigation that included the environmental impacts and other aspects of open-water disposal of dredged material.

2. Two mathematical models were developed by Tetra Tech, Inc., for predicting the short-term physical fate of material disposed in an estuarine environment by an instantaneous disposal operation or a continuous discharge disposal. Since the latter part of 1976, the Hydraulics Laboratory of the U. S. Army Engineer Waterways Experiment Station (WES) has been involved in an evaluation and calibration of these models. Model evaluation has centered around an analysis of the conceptualization of the physical processes and the corresponding theoretical description of those processes. In this phase, computer programming errors have been corrected and several modifications have been made to the models in order to represent the disposal processes more realistically. Model calibration has centered around determining the more realistic way to apply the models to a particular disposal operation and a subsequent variation of model coefficients to match computed results with data collected during DMRP-sponsored field studies by Yale University (DMRP Work Unit 1B09 reported by Bokuniewicz et al. in Technical Report D-78-7).

3. Although these models still have not undergone sufficient calibration and subsequent verification to warrant confidence in a quantitative sense, the limited calibration discussed herein and the in-depth evaluation the models have received justify confidence in a qualitative sense, especially if the material is properly characterized and the models are judiciously applied to adequately represent a real disposal operation.

4. From the evaluation and testing program including the data collected from the field studies, the following conclusions can be made concerning the short-term models at this time:

a. The models can realistically simulate what happens in the water column during the release. The limiting factor determining which model or models to apply is the relationship between the time required for the leading edge of the descending cloud to impact the bottom and the time required to empty the hopper dredge or barge.

b. These models cannot accurately describe the detailed structure of the impact and subsequent bottom surge as observed and discussed in Bokuniewicz et al. However, with proper selection of coefficients, the lateral spread and the rate of change in the total volume of the radially expanding surge can be estimated.

c. A reasonable description of the concentrations within the surge and long-term phase is dependent on an adequate characterization of the sediment properties of the dredged material.

5. These models will provide useful predictive information on the behavior of dredged material during aquatic disposal. Such information is important to those concerned with the environmental consequences of Corps activities, as it will aid in predicting the area of possible impact of the material.

JOHN L. CANNON
Colonel, Corps of Engineers
Commander and Director

Unclassified

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Prediction of the short-term physical fate of dredged material discharged into an aquatic environment based on general or specific site data and observations is extremely difficult because of the variability in the factors that influence the fate of the material. As a result, mathematical models were developed by Tetra Tech, Inc., for predicting the short-term physical fate of material disposed in an estuarine environment. Two models

(Continued)

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20. ABSTRACT (Continued).

were developed, one for an instantaneous disposal operation and one for a continuous discharge disposal.

Since the latter part of 1976, the Hydraulics Laboratory of the U. S. Army Engineer Waterways Experiment Station (WES) has been involved in an evaluation and calibration of these models. Model evaluation has centered around an analysis of the conceptualization of the physical processes and the corresponding theoretical description of those processes. In this phase, computer programming errors have been corrected and several modifications have been made to the models in order to more realistically represent the disposal processes. Model calibration has centered around determining the most realistic way to apply the models to a particular disposal operation and a subsequent variation of model coefficients to match computed results with data collected during Dredged Material Research Program (DMRP) sponsored field studies by Yale University (DMRP Work Unit No. 1B09).

Conclusions of the evaluation and calibration study can be summarized as follows:

a. The limiting factor determining which model or models to apply is the relationship between the time required for the leading edge of the descending cloud to impact the bottom and the time required to empty the hopper dredge or barge.

b. No quantitative significance should be attached to predictive computations from either model until knowledge of the required coefficients is improved.

c. The most sensitive coefficients in the models are drag and entrainment coefficients in the descent and collapse phases and the bottom friction coefficient.

d. The models cannot accurately describe the detailed structure of the impact and subsequent bottom surge as observed during the field studies by Yale University. However, as shown in the calibration efforts, with proper selection of the more sensitive coefficients, the lateral spread and total volume of the radially expanding surge can be estimated.

e. A reasonable description of the suspended sediment concentrations is dependent on an adequate characterization of the sediment properties of the dredged material.

The inputs for instantaneous dump and continuous discharge models are listed in Appendices A and B, respectively. Appendix C presents a program listing to generate the velocity tape at the Duwamish disposal site. Appendix D presents an example problem combining results from both dredged material models.

PREFACE

The study reported herein was conducted by the Hydraulics Laboratory (HL) and Environmental Laboratory (EL) of the U. S. Army Engineer Waterways Experiment Station (WES) during the period July 1976-April 1978. The work was conducted under Dredged Material Research Program (DMRP) Work Unit No. 1B06, "Evaluation of Koh-Chang Model (Phase I) and Sensitivity Analyses," and 1B07, "Participation in Field Verification of Koh-Chang Model and Further Sensitivity Analysis." The DMRP is sponsored by the Office, Chief of Engineers, U. S. Army, and is monitored by EL.

Dr. B. H. Johnson, Mathematical Hydraulics Division (MHD), HL, and Mr. B. W. Holliday, Environmental Impacts and Criteria Development Project (EICDP), EL, conducted the study and prepared this report under the general supervision of Messrs. H. B. Simmons, Chief, HL, and M. B. Boyd, Chief, MHD. Dr. R. M. Engler, Manager, EICDP, managed the project for the DMRP under the general supervision of Dr. John Harrison, Chief, EL.

Director of WES during the conduct of this study and the preparation and publication of this report was COL J. L. Cannon, CE. Technical Director was Mr. F. R. Brown.

CONTENTS

CONVERSION FACTORS, U. S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

U. S. customary units of measurement used in this report can be converted to metric (SI) units as follows:

Multiply	By	To Obtain
cubic feet	0.02831685	cubic metres
cubic feet per second	0.02831685	cubic metres per second
cubic yards	0.7645549	cubic metres
degrees (angle)	0.01745329	radians
Fahrenheit degrees	5/9	Celsius degrees or Kelvins*
feet	0.3048	metres
feet per second	0.3048	metres per second

* To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use the following formula: $C = (5/9)(F - 32)$. To obtain Kelvin (K) readings, use: $K = (5/9)(F - 32) + 273.15$.

EVALUATION AND CALIBRATION OF THE TETRA TECH DREDGED MATERIAL DISPOSAL MODELS BASED ON FIELD DATA

PART I: INTRODUCTION

1. The Dredged Material Research Program (DMRP) of the U. S. Army Corps of Engineers has as one of its objectives to provide more definitive information on the environmental aspects of dredging and dredged material disposal operations. This large interdisciplinary program is concerned with all aspects of the problem of disposing of dredged material, an integral part of which is the determination of where the material goes when discharged into the aquatic environment. Prediction of the short-term physical fate of dredged material discharged into an aquatic environment based on data and observations from other specific study sites is extremely difficult because of the variability in the factors that influence the fate of the material. As a result, a mathematical model of the physical processes affecting the fate of dredged material is considered extremely desirable. The model needs to be flexible enough to permit consideration of local environmental conditions, sediment characteristics, and initial discharge conditions imposed by the different methods of disposal. As a first step toward this objective, the DMRP initiated an effort (Work Unit No. 1B01) to assess the existing mathematical models applicable to the disposal of dredged material in terms of assumptions, limitations for practical usage, and degree of verification. The literature review prepared by Johnson[1] revealed very little development of mathematical modeling of the physical fate of dredged material released in an aquatic environment. It was determined that a model developed by Koh and Chang[2] was the most promising for prediction of the short-term dispersion and settling of dredged material. However, the model was developed for application in an ocean environment and would not handle disposal operations in a dynamic environment such as an estuary. As a part of the DMRP, Tetra Tech, Inc., was assigned the task of making major modifications to the Koh-Chang

model to expand its applicability. Two models, one for a continuous discharge and one for an instantaneous dump, resulted from this study.[3] These models were not designed for use over time frames within which erosion and resuspension play dominant roles, and no attempt was made to incorporate these phenomena into the Tetra Tech models.

2. In computer experimentation with these models, various problems have been encountered that have resulted in modifications to the original models. In addition, modifications have been made to increase the versatility of the models. A brief description of both the bottom dump and the continuous discharge models is given in Part II (with special emphasis on the input data required for model operation and the output provided) before detailed discussions of the computation cycles and modifications to each model are presented in Parts III and IV. Part V presents the results from a limited but systematic variation of the many coefficients contained in the models, i.e., a sensitivity analysis.

3. The Tetra Tech models are at the forefront of the state of the art in numerical simulation of sedimentological processes involving dredged material but have been subjected to very limited testing and evaluation. Although the models are considered to be conceptually sound, field verification is needed to establish their predictive capabilities and to provide rational guidance for their use. Initial work toward this objective has been conducted by the Hydraulics Laboratory at the U. S. Army Engineer Waterways Experiment Station (WES), and results are summarized in Part VI of this report.

PART II: THEORETICAL DEVELOPMENTS

4. In both models the behavior of the material is assumed to be separated into three phases: convective descent, during which the dump cloud or discharge jet falls under the influence of gravity; dynamic collapse, occurring when the descending cloud or jet either impacts the bottom or arrives at the level of neutral buoyancy at which descent is retarded and horizontal spreading dominates; and long-term passive dispersion, commencing when the material transport and spreading are determined more by ambient currents and turbulence than by the dynamics of the disposal operation. Figures 1 and 2 illustrate these phases for the instantaneous dump and jet models, respectively.

Convective Descent

5. In the bottom dump model, a single cloud that maintains a hemispherical shape during convective descent is assumed to be released. Since the solids concentration in discharged dredged material is usually low, the cloud is expected to behave as a dense liquid; thus a basic assumption is that a buoyant thermal analysis is appropriate. The equations governing the motion are those for conservation of mass, momentum, buoyancy, solid particles, and vorticity. These equations are straightforward statements of conservation principles and will not be presented here. It should be noted that the entrainment coefficient associated with the entrainment of ambient fluid into the descending hemispherical cloud is assumed to vary smoothly between its value for a vortex ring and the value for turbulent thermals. As shown in Part V, model output is quite sensitive to the entrainment coefficient, which in turn is dependent upon the material being dumped (the higher the moisture content, the larger the value of the entrainment coefficient). Developmental research by JBF Scientific Corporation is under way to better represent the entrainment of the ambient fluid.

6. A number of dredging vessels discharge material through openings at the bottom of the vessel while moving. Hopper dredges typically

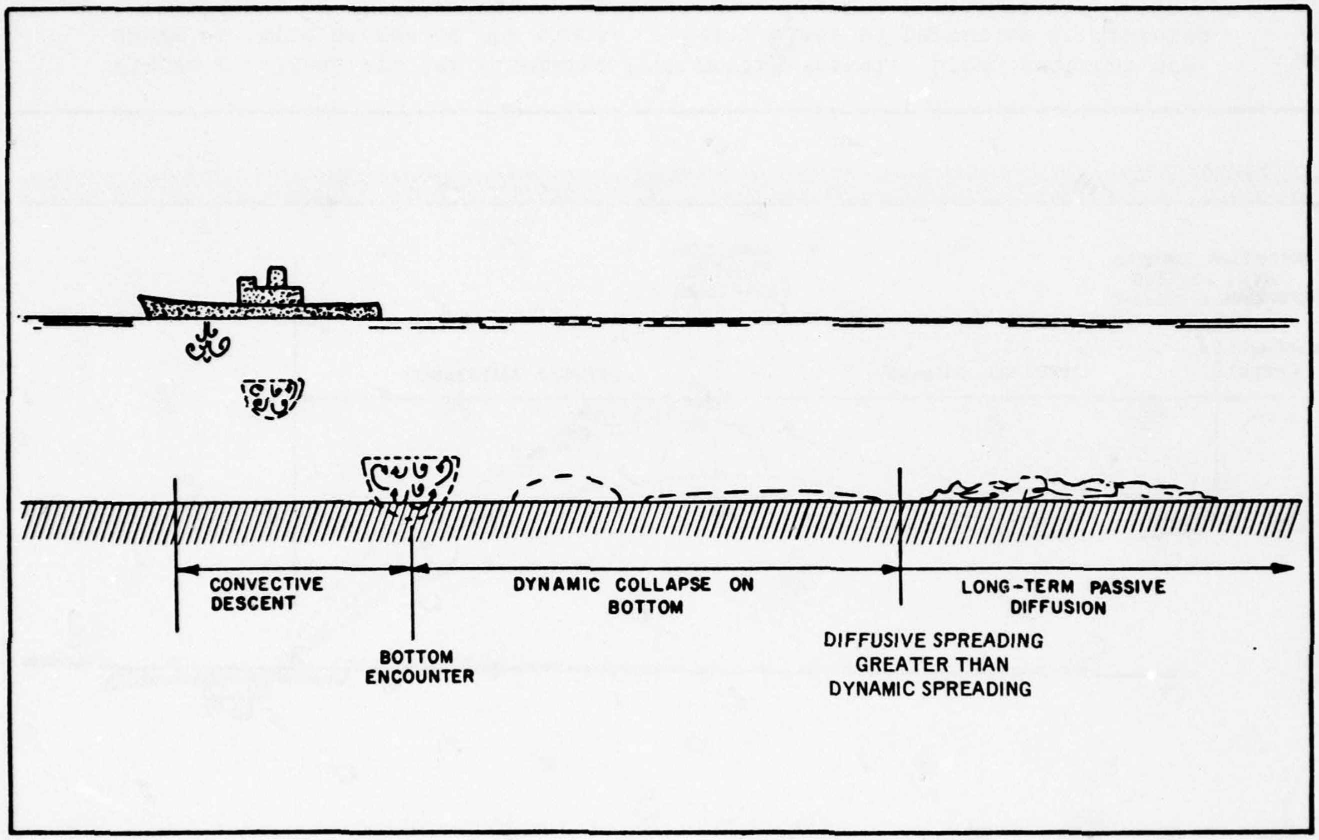


Figure 1. Illustration of idealized bottom encounter after instantaneous dump of dredged material (from Brandsma and Divoky[3])

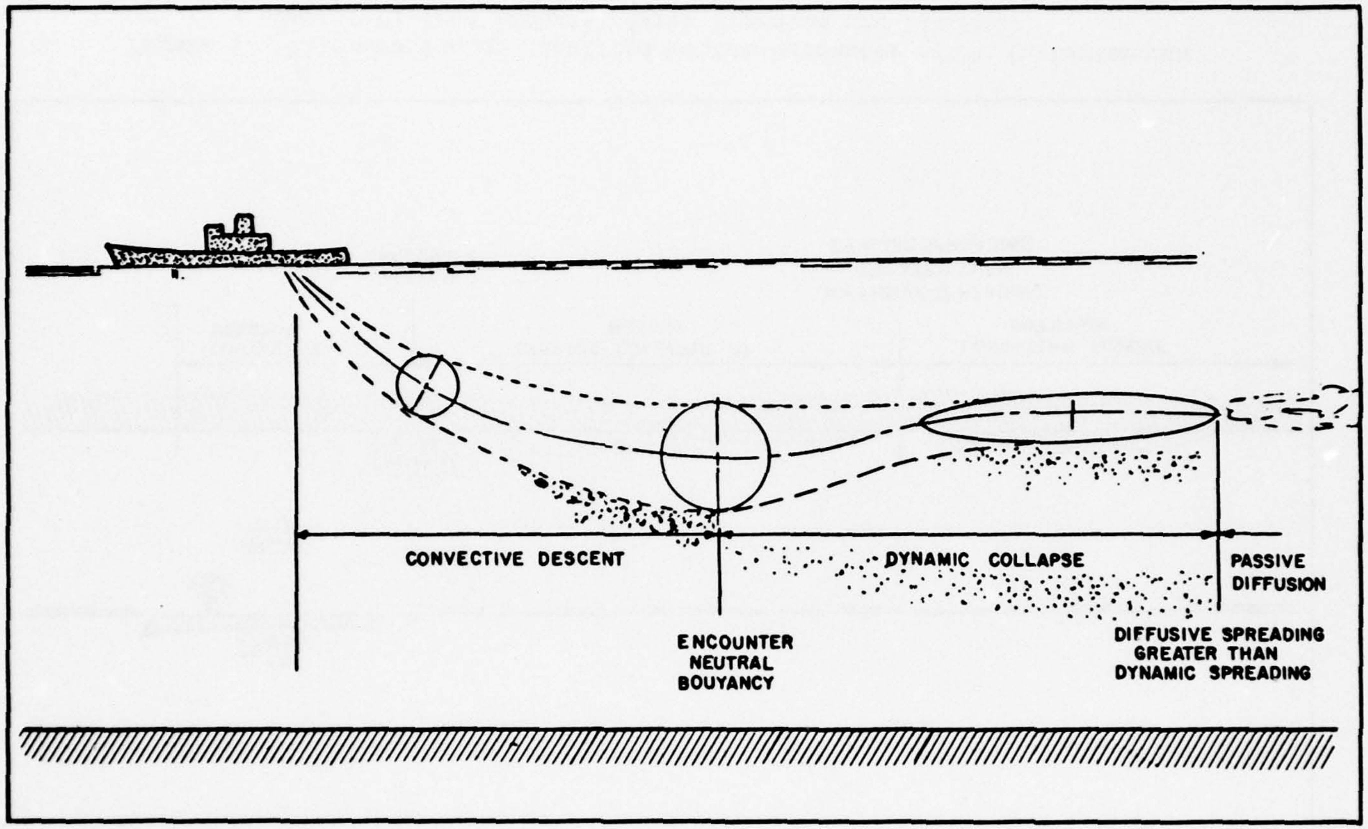


Figure 2. Idealized jet discharge from moving vessel. Cross sections are shown at three stages of the plume. A heavy class of particles is depicted settling out of the plume at an early stage. Lighter particles are shown settling during the collapse phase (from Brandsma and Divoky[3])

open one or two doors at a time, completing the disposal operation in a few minutes. A similar mode of discharge, although fixed and of a much longer duration, is a pipeline with the discharge taking place in the water column. In either case the flow phenomenon near the discharge opening is that of a sinking momentum jet in a cross current. Basic assumptions in the formulation of the conservation equations for the jet convection phase are that the jet cross section remains circular and that velocity, density, and material concentration distributions may be approximated by "top-hat" profiles. Entrainment is assumed to be composed of a combination of momentum jet entrainment and entrainment experienced by a two-dimensional thermal.

Dynamic Collapse

7. During convective descent, the dumped material cloud or jet grows as a result of entrainment. Eventually, either the material reaches the bottom, or the density difference between the discharged material and the ambient becomes small enough for a position of neutral buoyancy to be assumed. In either case, the vertical motion is arrested and a dynamic spreading in the horizontal occurs. In the bottom dump model, the hemispherical cloud is assumed to take the shape of an oblate spheroid. With the exception of vorticity, which is assumed to have been dissipated by the stratified ambient water column, the same conservation equations used in convective descent but now written for an oblate spheroid are applicable. For the case of collapse on the bottom, the only difference is the inclusion of a frictional force between the bottom and the collapsing cloud. As the jet plume of a continuous jet discharge, which does not strike the bottom, moves far downstream from the discharge point, its velocity approaches that of the ambient fluid and its behavior is more like a two-dimensional thermal than a jet. The cross section of the two-dimensional thermal is assumed to have the shape of an ellipse. As in the bottom dump model, the governing equations represent the conservation of mass, momentum, buoyancy, and solid particles, with a friction force included if the bottom is encountered.

Passive Dispersion

8. The long-term passive dispersion phase is treated the same way in both models. When the rate of horizontal spreading in the dynamic collapse phase becomes less than an estimated rate of spreading due to turbulent diffusion, the collapse phase is terminated. During collapse, solid particles can settle as a result of their fall velocity. As these particles leave the main body of material, they are stored in small clouds that are characterized by a uniform concentration, thickness, and position in the water column. These small clouds are then allowed to settle and disperse until they become large enough to be inserted into the long-term, two-dimensional passive dispersion grid positioned in the horizontal plane. Once small clouds are inserted at particular net points, those net points then have a concentration, thickness, and top position associated with them. This is the manner in which the three-dimensional nature of the problem is handled on a two-dimensional grid. Figure 3 illustrates a typical concentration profile at a net point. Computations on the passive dispersion grid are made using Fisher's backward convection concept rather than attempting a numerical solution of the governing convection-diffusion equation. In the backward convection solution technique, a massless particle at each net point at the present time level is moved backward in time by the ambient current to the position it occupied one time step before. The concentration at the net point it presently occupies is then taken as a five-point average of the points surrounding its old position (Figure 3).

9. In addition to the horizontal convection and diffusion of material, settling of the suspended solids also occurs. Therefore, in addition to computing a concentration profile at each net point, the amount of solid material deposited on the bottom and a corresponding thickness are also determined. A basic assumption in the models is that once material is deposited on the bottom it remains there, i.e., neither erosion nor bed-load movement of material are allowed. This is the primary theoretical limitation of the models that restricts their usefulness to the study of the short-term fate of discharged material.

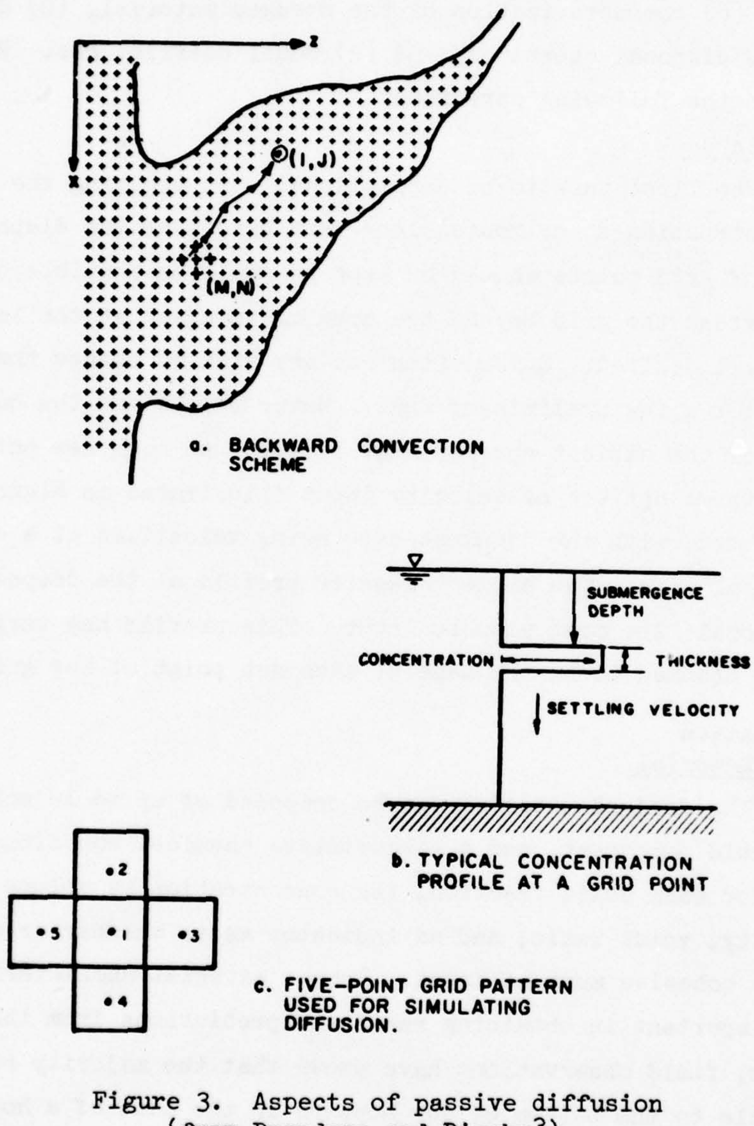


Figure 3. Aspects of passive diffusion
(from Brandsma and Divoky[3])

Model Input Requirements

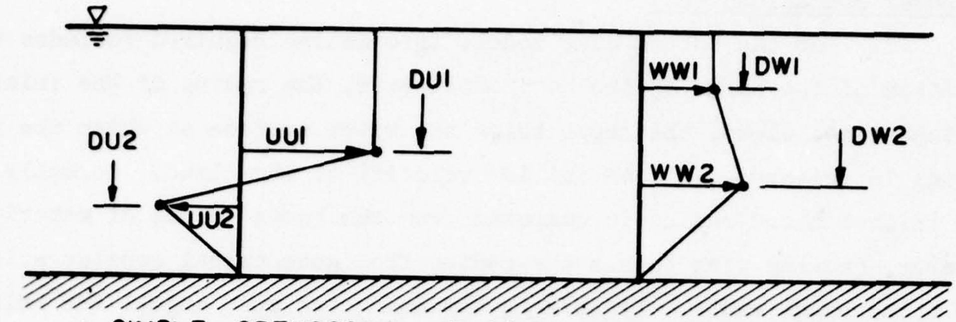
10. Input data required for the operation of the models can be grouped into (a) a description of the ambient environment at the disposal site, (b) characterization of the dredged material, (c) data describing the disposal operation, and (d) model coefficients. Each is discussed in the following paragraphs.

Disposal site data

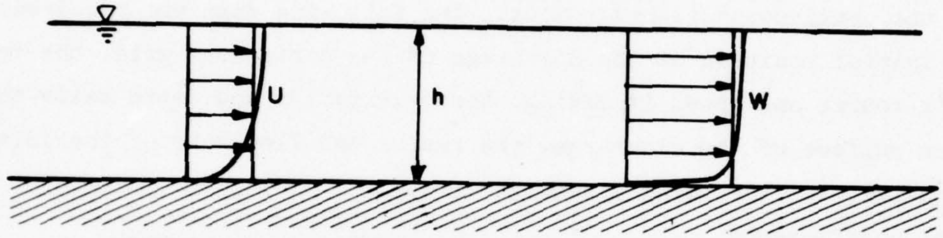
11. The first task to be accomplished when applying the models is that of constructing a horizontal long-term grid over the disposal site. The number of grid points should be kept as small as possible but large enough to extend the grid beyond the area of interest at the level of spatial detail desired. Quite often one may wish to change the horizontal grid after a few preliminary runs. Water depths and the horizontal components of the ambient current must be input at each net point. Any of the three options of velocity input illustrated in Figure 4 may be selected, with the simplest case being velocities at a constant depth disposal site. The ambient density profile at the deepest point in the disposal site must also be input. This profile may vary with time but is assumed to be the same at each net point of the grid.

Characterization of dredged material

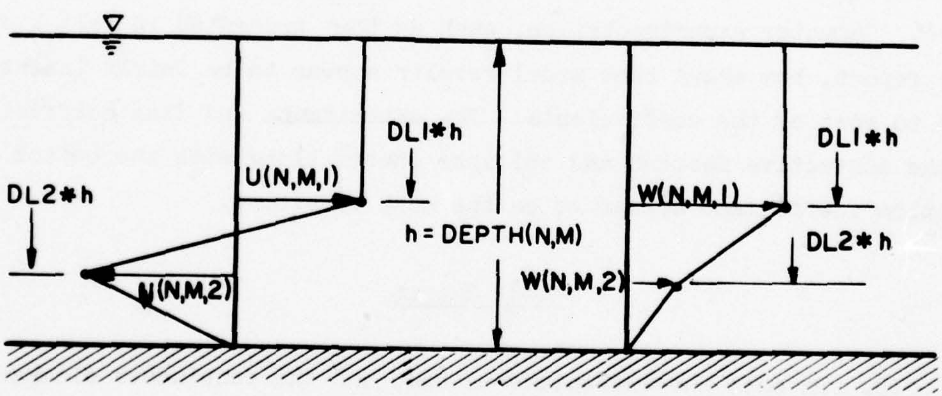
12. The dredged material can be composed of up to 12 solid fractions, a fluid component, and a conservative chemical constituent if desired. For each solid fraction, its concentration by volume, density, fall velocity, voids ratio, and an indicator as to whether or not the fraction is cohesive must be input. Proper material characterization is extremely important in obtaining realistic predictions from the models. For example, field observations have shown that the majority of the solids settle to the bottom of the hoppers in the case of a hopper dredge disposal with the resulting density of the upper portion of the hopper being almost that of the ambient water. This is discussed in more detail in Part VI. If a conservative chemical constituent is to be traced, its initial concentration and a background concentration must



a. SIMPLE ORTHOGONAL VELOCITY PROFILES FOR CONSTANT DEPTH. APPLIED EVERYWHERE IN FIELD.



b. VERTICALLY AVERAGED VELOCITY PROFILES FOR VARIABLE DEPTHS WITH EQUIVALENT LOGARITHMIC PROFILES SUPERIMPOSED.



c. TWO-LAYER PROFILES FOR VARIABLE DEPTH.

Figure 4. Illustration of the various velocity profiles available for use in models (from Brandsma and Divoky[3])

be given. In addition, the bulk density and aggregate voids ratio of the dredged material must be prescribed.

Disposal operations data

13. For the bottom dump model, information required includes the position of the barge on the horizontal grid, the radius of the initial hemispherical cloud, the depth below the water surface at which the material is released, and the initial velocity of the cloud. Normally, the initial cloud radius is computed from the known volume of material. However, one may wish to set the radius from geometrical considerations, e.g., the barge width. If this is the case, one must adjust the bulk density to reflect the initial dilution, making sure the resulting cloud contains the exact amount of solid material contained within the barge. For the continuous discharge model, the following data are required: the initial position of the discharge on the horizontal grid, the vessel's course and speed if moving, the orientation and depth below the water surface of the discharge, the radius and flow rate of the initial discharge, and the total discharge time.

Model coefficients

14. The models contain suggested average values for the many coefficients involved (14 in the instantaneous dump model and 17 in the continuous discharge model) but the user may input other values if desired. Computer experimentation, such as that presented in Part V of this report, has shown that model results appear to be fairly insensitive to most of the coefficients. The entrainment and drag coefficients in the convective descent and collapse phases along with the bottom friction coefficient appear to be the most sensitive.

Model Output

15. In both the instantaneous dump and the continuous discharge model, the discharged material is traced through three phases: convective descent, during which the dump cloud or discharge jet falls under the influence of gravity; dynamic collapse, occurring when the descending cloud or jet either impacts the bottom or arrives at the level of

neutral buoyance at which descent is retarded and horizontal spreading dominates; and long-term passive dispersion, commencing when the material transport and spreading is determined more by ambient currents and turbulence than the dynamics of the disposal operation. Model output is provided in both tabular and plotted form describing the movement of the material through each of the three phases.

Convective descent
and dynamic collapse

16. The time history of position in the water column, velocity, and size of the cloud or jet plume is provided at the end of both the convective descent and collapse phases. In addition, the volume of solids and the corresponding concentrations, as well as the density difference between the discharged material and the ambient, are provided. As a guide for determining dilution rates, the time history of the conservative chemical constituent concentrations is also furnished.

Passive dispersion

17. A basic assumption by which the three-dimensional aspects of the suspended sediment concentrations are represented on the two-dimensional horizontal grid is that the concentration profile in the vertical is a "top-hat" profile (Figure 3). Such a profile is characterized by a thickness, top position, and an average concentration. Therefore, in the passive dispersion phase, at each net point of the horizontal grid, the concentration, position of the top, and the thickness of each suspended solids profile, as well as the conservative chemical constituent, are output at as many time steps as requested. In addition, at each net point the amount and thickness of deposited solids on the bottom are also provided as functions of time.

PART III: DISCUSSION OF THE COMPUTATION CYCLE AND MODIFICATIONS TO THE CONTINUOUS DISCHARGE MODEL

18. As noted in the previous section, the Tetra Tech continuous discharge model allows for an unlimited continuous discharge of dredged material from either a stationary or moving source oriented at any angle below the water surface. A detailed discussion of the theoretical aspects of the numerical model can be found in the final report by Brandsma and Divoky.[3] The purpose of the discussion presented herein is to present in more detail the procession of computations through the computer model and to point out those modifications to the model that have been made, as they are encountered in the computation cycle.

19. The complete computation cycle centers around subroutine MAIN. Many of the read statements for input data plus various initialization statements are encountered upon first entering MAIN. Two subroutines, INIT and AMBC, are called from MAIN to read other input data such as discharge data and information on the dredged material plus the ambient density and velocity data. ESTGEO is then called to read water depths. This subroutine has been modified such that if the depth is constant, only one number must be input rather than having to specify the same constant depth at each grid point as previously required.

20. The major loop in MAIN within which all computations are made is on the number of tidal days (each day is 25 hr) for which the model is to be run. Embedded within this loop is a loop over the long-term passive diffusion time steps contained in each tidal day. It should be noted that this time step must be greater than the total time required for the dynamic collapse phase to terminate. The phases through which computations proceed are discussed in more detail later. Before computations in the short-term phases (convective descent and dynamic collapse) begin, UW is called to update velocities to the current long-term time step if the velocities are time dependent. VEL is then called to interpolate between grid point velocities to determine the ambient velocity at the point of discharge.

21. Immediately after discharge is initiated, the material behaves

as a sinking momentum jet in a cross current, i.e., a jet convective descent phase is entered. JET is called to control computations through this descent phase. The coordinate system is centered on the discharge point. Upon entering JET, the initial values of all dependent variables such as momentum, solid concentrations, and buoyancy are prescribed in preparation for the first solution trial. The initial integration step for numerical integration of the governing ordinary differential equations is DINCR (an input parameter) times the initial radius of the jet. Remember the model computes a steady picture of the momentum jet. At this point in the program various modifications allowing for the tracing of a conservative chemical constituent, considering a background concentration, through all phases of the model, begin to appear. Modifications allowing for these computations are found throughout remaining portions of the numerical code and are far too numerous to discuss at each point they occur.

22. JET calls RUNGS which in turn immediately calls DERIVJ to determine values of the derivatives of the dependent variables in the governing conservation equations. These are the EP's in the computer code. One major addition to the model can be found in DERIVJ. The drag force on the descending jet in the original model is assumed to always act perpendicular to the axis of the jet. If material is discharged in the vertical from a stationary vessel in essentially quiescent ambient water, little bending of the jet occurs and thus essentially no drag force acts to oppose the downward motion. From model applications in Lake Ontario, the computed time required for a jet that is nearly vertical to hit the bottom is significantly less than observed times for bottom encounter. Thus, if the angle between the jet center line and the vertical θ_2* is less than 10 deg,** an additional drag force similar to the force acting on the descending hemispherical cloud in the bottom dump model (see Brandsma and Divoky[3]) has been added in the vertical.

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* For convenience, symbols and unusual abbreviations are listed and defined in the Notation (Appendix E).

** A table of factors for converting U. S. customary units of measurement to metric (SI) units is presented on page 3.

23. After setting up the derivatives, control switches back to RUNGS for the numerical integration of the governing equations using a fourth-order Runga-Kutta integration scheme. Control then refers back to JET where the next integration step is increased over the present value by a factor of 1.1 unless the vertical position of the center of the jet is greater than 90 percent of the water depth, in which case it is decreased by a factor of 1.1.

24. Checks are now made in JET to determine if the bottom has been encountered. This occurs if any of the three expressions below are satisfied, which then results in IPLUNG = 1 . (IPLUNG is a parameter set internally as an indicator of whether or not the cloud is on the bottom.)

$$CY(ISTEP) + 0.85 * BC(ISTEP) \, SIN \, \theta_2 \geq H \quad (1)$$

$$CY(ISTEP) + DS \, COS \, \theta_2 \geq H \quad (2)$$

$$CY(ISTEP) + 0.75 * BC(ISTEP) \geq H \text{ if } \theta_2 < 30 \text{ deg} \quad (3)$$

where

CY = vertical position of jet center line

ISTEP = number of integration steps

BC = jet radius

θ_2 = angle between vertical and jet center line

H = water depth

DS = spatial integration step

Checks are now made to determine if jet convection computations are completed. If any of the three conditions below occur, this trial run is considered to be over.

$$CY(ISTEP) < CY(ISTEP - 1) \text{ - results in NUTRL} = 1 \quad (4)$$

$$IPLUNG = 1 \text{ - bottom encounter} \quad (5)$$

$$ISTEP > 600 \quad (6)$$

where

NUTRL = a parameter set internally as an indicator of whether or not diffusive spreading exceeds dynamic spreading and also of whether or not a neutrally buoyant position has been reached.

If none of the above three conditions are satisfied, the computations for this trial continue by calling RUNGS which calls DERIVJ, etc. However, if either NUTRL = 1 or IPLUNG = 1 and if the number of trial solutions does not exceed 5, and if the number of integration steps is greater than 100 but less than 190, jet convection computations are considered complete. If the number of trial solutions (NTRIAL) is less than 5 but the number of integration steps (ISTEP) is either less than 100 or greater than 190, NTRIAL is increased by 1 and the jet convection computations are completely reinitiated from the point of discharge, but with the initial integration step now set to be

$$DS = DINCR * BC(1) \tag{7}$$

where

DINCR = DINCR * FLOAT(ISTEP)/140

BC(1) = radius of the discharge point

If after five trials (NTRIAL = 5) a successful completion is not realized, the program terminates. Assume a successful completion has been realized and all output requested has been provided. Control now switches back to MAIN.

25. If the bottom has been encountered in JET, MAIN calls COLAPS to initiate computation of the dynamic collapse phase on the bottom. However, instead of hitting the bottom the jet center line may have attained a horizontal trajectory in the water column (NUTRL = 1), in which case MAIN conducts a check on the ambient density gradient. If the ambient density is uniform, dynamic collapse is completely bypassed and long-term computations are initiated. This procedure is correct for the case of a neutrally buoyant plume in a uniform ambient since the force (derived in Koh and Chang[2]) which drives collapse will be zero. In the original coding there was no such check for the case of bottom encounter. In sample runs with bottom encounter occurring in a uniform ambient,

errors were observed. A new expression for the force driving collapse on the bottom which accounts for the difference between the average plume density and the ambient density has been derived and accounted for in the program. If a neutrally buoyant position in the water column is reached, this difference is essentially zero, which as implied above was the assumption made in the original model. However, this assumption was made not only for collapse in the water column but also for collapse on the bottom which does not appear to be correct. This will be discussed in more detail later.

26. Assume that COLAPS, which controls the computation cycle for the dynamic collapse phase in the water column as well as on the bottom, has been called from MAIN. Results from the last integration step of the jet convection computations are used to initiate collapse computations. If collapse occurs in the water column the initial integration step is

$$DS = DINCR * BC(ISAV) \tag{8}$$

where ISAV is the last integration step in jet convection. However, if collapse occurs on the bottom (ISTEP = IBED) the initial integration interval is taken to be

$$DS = DINCR * DS_{jet\ conv} * \sin \theta_2 \tag{9}$$

It can be seen that if the jet is vertical, $\theta_2 = 0$ deg and DS is zero. Therefore, the model requires some bending of the jet before the bottom is encountered.

27. For now assume collapse occurs in the water column. The first computation in COLAPS is for the fall velocity of cohesive material, which is a new feature of the model. Fall velocities are assumed to be a function of only the suspended sediment concentration and are computed from*

* Personal communication, Ronjon Ariathurai, Nielsen Engineering and Research, Inc., Mountain View, Calif.

$$V_S \begin{cases} = 0.0017 & \text{if } C \le 25 \text{ mg/}\ell \\ = 0.00713\, C^{4/3}/304.8 & \text{if } 25 \le C \le 300 \text{ mg/}\ell \\ = 0.047 & \text{if } C > 300 \text{ mg/}\ell \end{cases}$$

where

V_S = settling velocity, ft/sec

C = suspended sediment concentration, mg/ℓ

Fall velocities for cohesive sediment are computed throughout the remainder of the program. These modifications are easily recognized and will not be discussed further. COLAPS now calls RUNGS which in turn calls DERIVC to compute the derivatives of the dependent variables. It should be noted that the time derivative in each of the basic conservation equations (see Brandsma and Divoky[3]) has been changed to a spatial derivative along the plume center line by employing the relation DS/DT = CU(ISTEP) where CU(ISTEP) is the center-line velocity and S is distance along the center line of the plume. As in the jet convection computations, RUNGS now performs the numerical integration of the governing equations. Control now switches back to COLAPS and a new integration step is computed as the product of the previous integration step and the ratio of the present plume velocity to that determined in the previous step.

28. Various exit checks are now made to determine whether or not there is a need to increment ISTEP in this solution trial and proceed with the computations or to increment NTRIAL and start again from the end of jet convection, but with a new initial integration step, or to transfer control back to MAIN. These checks are listed below.

<u>a</u>. If diffusive spreading is greater than dynamic spreading, NUTRL = 3 .

<u>b</u>. If CY(ISTEP) + 0.85 AA(ISTEP) $\ge$ H then IPLUNG = 2 and BOTTOM is called to continue collapse computations where AA is the major axis of elliptical cross section and H is the depth of the water column.

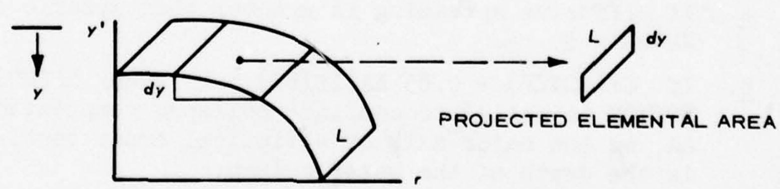
<u>c</u>. Let IDIF = (ISTEP - ISAV) where ISAV is the number of the last integration step in jet convection. If IDIF lies between 100 and 400 and NUTRL = 3 , collapse computations have been successfully completed.

d. If NUTRL $\neq$ 3 and ISTEP > 599 , NTRIAL is incremented and collapse computations are started again from the end of jet convection but with a new initial integration step. However, if NUTRL $\neq$ 3 and ISTEP < 599 , ISTEP is incremented and computations proceed with RUNGS being called, etc.

e. If NUTRL $\neq$ 3 and NTRIAL = 5 , the program terminates.

29. It has been indicated that if the bottom is encountered, either during jet convection or during collapse within the water column, BOTTOM is called. As for the case of collapse in the water column, results from previous computations (either jet convection or collapse in the water column) are used to initiate bottom collapse computations. One important note should be made. In the original model, the vertical momentum of the plume is set to zero after one integration step. Movement of the plume center line (remember that during collapse it is assumed that material is continuously being pumped into the plume) is determined from the momentum in the horizontal directions at the end of jet convection. For a bottom encounter in which the jet is almost vertical, the horizontal momentum is essentially zero and the plume center line moves very little during collapse. Based on observations in the field, this is not a very realistic representation. Returning to the discussion of the computation cycle, RUNGS is now called that in turn calls DERIVB. As in the previous DERIVE subroutines, the derivatives of the dependent variables are evaluated in DERIVB. In paragraph 25, an addition to the force driving collapse on the bottom was mentioned. Its derivation is presented below.

30. As indicated in Brandsma and Divoky,[3] consider a quadrant of the collapsing plume illustrated as follows



In the original model the density of the plume at $y' = 0$ was related to the ambient density, ρ_a as

$$\rho_o = \frac{\rho_a}{(1 - \varepsilon y')} \tag{10}$$

where

ρ_o = plume density at cloud center

ε = normalized density gradient $\left(\frac{1}{\rho_o}\right)\left(\frac{\partial \rho_o}{\partial y}\right)$

y' = vertical axis of coordinate system positioned at cloud center

Likewise, the density distribution inside the plume ρ^* was assumed to be

$$\rho^* = \rho_o\left(1 - \frac{\gamma a_o}{a}\, \varepsilon y'\right) \tag{11}$$

where the plume density gradient is assumed to be less than that in the ambient fluid by the factor $\gamma a_o/a$

where

γ = the density gradient coefficient

a_o = one half the final radius of the convective descent jet

a = semiminor axis of the collapsing plume

A basic assumption in the above was that the plume density at $y' = 0$ equals the ambient density. If the plume experiences collapse within the water column, this is a reasonable assumption; however, if collapse occurs on the bottom, it is not. Let us assume the following

$$\rho_a = \rho_o(1 - \varepsilon y') + \Delta\rho \tag{12}$$

where $\Delta\rho$ is the difference between the plume density at $y' = 0$ and the ambient. Thus the force term as originally formulated by Tetra Tech plus an additional force term due to the $\Delta\rho$ would be the correct expression for the force driving bottom collapse. Assuming hydrostatic pressures, this addition can be determined by integrating the pressure due to $\Delta\rho$ over the projected area of the rounded external surface.

Thus

$$F_{\Delta\rho} = \int_0^a \Delta\rho g y \; L \; dy \tag{13}$$

or

$$F_{\Delta\rho} = \Delta\rho g \, L \, a^2/2 \qquad (14)$$

where

$F_{\Delta\rho}$ = driving force in bottom collapse due to $\Delta\rho$

g = acceleration due to gravity

y = distance from water surface

L = length of plume element

dy = incremental vertical distance

The modification to the model can be found in the expression for EP(10) in DERIVB. RUNGS now performs the numerical integration and control switches to BOTTOM.

31. At the beginning of each integration step, a bed reaction force, FBED, is computed. If FBED < 0 , the plume rises off the bottom and the remainder of dynamic collapse is computed in the water column. When FBED < 0 , IPLUNG is set to 4. In addition to a check on FBED, at the beginning of each integration step diffusive spreading is compared to dynamic spreading. When diffusive spreading exceeds dynamic spreading, NUTRL = 3 . In several model applications, problems have been encountered with collapse on the bottom terminating too soon, especially if the jet is almost vertical at bottom encounter. Within one integration step the model has computed a negative FBED and/or set NUTRL = 3 . Some type of instability seems to be occurring since one certainly would not expect such behavior in an actual disposal operation. Therefore, two statements have been inserted into the model which force FBED to be zero and NUTRL to be 1 for the first ten integration steps in collapse on the bottom.

32. As in the case of collapse within the water column, various checks are made at the end of each integration step to determine if ISTEP is to be increased and RUNGS called again or if NTRIAL is to be increased and bottom collapse computations reinitiated with a new initial integration step. Finally control switches back to COLAPS and then to MAIN. As previously noted, if NTRIAL = 5 and diffusive spreading has not exceeded dynamic spreading, the program terminates.

Assume collapse computations have been successfully completed and all output pertaining to the collapse phase has been provided.

33. Subroutine BOOKS is now called to create small clouds in which mass is stored during the transition from the short-term computations (convective descent and dynamic collapse) to the grid upon which long-term computations are made. These are created at the end of collapse (or jet convection if the jet trajectory becomes horizontal and the ambient density is uniform) in the following manner. If the discharge time of the jet plus the time to the end of collapse is less than the long-term time step, TMAX is set equal to this sum. If the sum above is greater than the long-term time step (after the first time step this sum is compared to the total elapsed time), then TMAX is set equal to the long-term time step. Now a speed, VDIF, is defined to be the magnitude of the ambient velocity, unless the plume collapsed on the bottom in which case VDIF is set equal to the speed of the disposing vessel. However, if both speeds above are zero, VDIF is set equal to the center line velocity of the plume. Now the time increment for creating small clouds is determined from

$$DTC = 2 * BC(ISTEP)/VDIF \tag{15}$$

However, DTC may be much too large. Thus, if DTC > [TMAX - T(ISTEP)], it is set equal to [TMAX - T(ISTEP)], where T(ISTEP) is the time to the end of collapse. DTC then determines the number of small clouds to be created in this time step. If the total discharge time plus the time to the end of collapse extends over into the next time step, the material discharged during that time is inserted into small clouds at the beginning of the next long-term time step.

34. The solid material inserted into a small cloud is the product of the initial discharge flow rate, the initial concentration, and the time increment DTC. The amount of chemical constituent inserted into a small cloud is determined differently due to the entrainment of background material by the jet. The chemical constituent mass inserted is the product of the flow rate and concentration at the end of jet

convection times the time increment DTC. A modification in the computation of the horizontal dimension of the chemical cloud has been made in the model to ensure that the concentration of the chemical cloud is the same as the chemical concentration at the end of collapse. This has not been done for the solids clouds since material continually falls out of the collapse phase. However, the effect of material falling from collapse shows up only in the thickness assigned to the clouds, not in the creation of clouds.

35. After all small clouds are created, they are updated from their creation time to the end of the long-term time step. This update consists of convection by the ambient current, an adjustment of the cloud top due to convection over varying depths, horizontal diffusion, and settling. At this point if the distance between the cloud bottom and the estuary bottom is less than the fall velocity times the update time, material will be deposited on the bottom. In the original model it was assumed that the small clouds would be smaller than the long-term grid spacing. Therefore, if material were deposited from a cloud, it should be placed in a single grid square. Since quite often one desires greater refinement, the model has been modified to allow for the equal placement of deposited material in as many grid squares as covered by the cloud. If all the material in a cloud is deposited, that cloud is then erased.

36. Small clouds are now updated through vertical diffusion. Initially, the model made one vertical diffusion computation over the complete long-term time step which can create artificial diffusion. For example, if the cloud top is in an essentially uniform ambient but very close to a region of high density gradient, one computation over a large time step can result in the position of the top moving much too far into the high gradient region. The program has been modified so that vertical diffusion computations are made in increments of one tenth the long-term time step.

37. After computations on small clouds are made, as well as long-term computations that will be discussed later, a check is made to ensure that the bottom of the cloud does not fall below the bottom of the

estuary nor does the top extend above the water surface. Some of these checks existed in the original model while others have since been added.

38. After updating the small clouds created in BOOKS, control switches back to MAIN that now calls MAD to control the long-term computations. The first operation in MAD is to call ACAD if there are small clouds that have not been inserted into the long-term grid. ACAD moves and diffuses small clouds as well as handles the insertion of clouds into the long-term grid when they become large enough. If the horizontal dimension of a cloud is greater than Δx but less than $2\Delta x$, it is inserted in one manner; whereas, if the cloud dimension is greater than $2\Delta x$, it is inserted differently.

39. Previously, the approach for insertion of clouds with sides less than $2\Delta x$ but greater than Δx was to proportion the cloud mass to the nearest four points and to assign the cloud thickness to each of the four points. This, however, resulted in artificial dilution strictly as a result of the manner in which clouds were inserted since the volume associated with each of the four pieces of mass is Δx^2 times the cloud thickness. Modifications have been made which eliminate this problem by adjusting the thickness associated with each of the four points. The volume after insertion of the cloud is then such that the grid concentrations immediately after insertion of the cloud are the same as the cloud concentration.

40. As noted, clouds with a horizontal dimension greater than $2\Delta x$ are handled in a different manner. In the original model a distribution of the material among grid points was attempted; however, mass conservation problems seemed to be associated with this technique. Therefore, the model has been modified so that the cloud mass is equally distributed among the points covered by the cloud. This approach seems to be reasonable since small clouds are assumed to be uniformly mixed. Once again the thickness is adjusted to ensure that no artificial dilution results from inserting a small cloud into the long-term grid.

41. As previously indicated, if there are small clouds that are not large enough to be placed in the long-term grid, they are updated in ACAD to the end of the current long-term time step. As in BOOKS,

this update consists of convection, a variation of the position of the cloud top due to convection over variable depths, settling and the corresponding deposition of material on the bottom, and, finally, vertical diffusion. Once again, the program has been modified to perform vertical diffusion computations in steps of one tenth of a long-term time step. After the update of small clouds, control transfers back to MAD.

42. The basic function of MAD is to control computation of concentrations on the long-term grid. As discussed in detail in Brandsma and Divoky,[3] rather than attempting a finite difference solution of the governing convective-diffusion equation, Fischer's backward convection scheme is used. In the original model the vertical coordinate YY used in the interpolation of the ambient velocity was

$$YY = TOP(NST,MST) + 0.5 * THICK(NST,MST) \tag{16}$$

where TOP(NST,MST) and THICK(NST,MST) are initially set to zero. In subroutine VEL, if YY = 0 , the velocity is returned with its surface value. However, the grid point ambient velocity corresponding to the vertical position of nonzero concentrations is the velocity which should be used in the backward convection scheme. This problem has been corrected by determining the average vertical position of the centroids of all points at which concentrations are not zero and setting YY equal to this value.

43. TRANSPT is called to determine the position one time step ago of a massless particle occupying the particular grid point in question. As presented in Brandsma and Divoky,[3] this is the basis of Fischer's backward convection scheme. After returning particle coordinates to MAIN, MAD determines the four grid points of the square within which the particle was located. AVE5PT is then called for each of the four points to determine a special five-point average concentration at each. The top position associated with the five-point average concentration is merely an arithmetic average of the five points unless one or more of the values is zero, in which case it is not included in the averaging. The thickness associated with the five-point average concentration is the

maximum of the five points. It should be noted that before the five-point average concentration is determined, each of the individual concentrations is multiplied by the ratio of its thickness to the maximum thickness noted above to ensure mass conservation.

44. AVE5PT has been modified slightly. In initial experimentation of the model, it was observed that mass conservation problems were encountered in the long-term computations for a variable depth disposal site. This has been corrected by forcing the thickness at each of the five points used in the averaging procedure in AVE5PT to be the value assigned upon entering AVE5PT.

45. After being called four times, AVE5PT returns a five-point average concentration, a top position, and a thickness for each of the four corners of the square from which the particle occupying the grid point in question originated one time step ago. An interpolation of the values associated with the four points yields the concentration and top position assigned to the grid point in question for the current time step. The thickness, however, is again set to be the maximum associated with the four points. This complete process of calling TRANSPT, AVE5PT, etc., is repeated for each point in the long-term horizontal grid.

46. The next operation in MAD is a mass conservation check of the material in the long-term grid. Various modifications can be found which account for the background concentration of the chemical constituent. The long-term grid is now updated to allow for a variation in top position of the concentration profile at each grid point as a result of convection over variable depths. The profiles are then allowed to settle with a subsequent deposition of material. It might once again be noted that settling velocities for cohesive material are computed before settling of the profiles. These velocities vary over the long-term grid as well as with time. Vertical diffusion is then computed at each grid point in increments of one tenth the long-term time step. An additional modification to the manner in which vertical diffusion is handled has been made. Vertical diffusion was considered to be dependent upon the Richardson number based upon only the ambient density gradient. However, the suspended solids density would seem to have a stabilizing

effect which was not accounted for. Therefore, the model has been modified to compute a Richardson number based upon a density gradient that accounts for the suspended solids density. All computations for this time step are now completed and control transfers back to MAIN.

47. All of the above is the basic computation cycle of the continuous discharge model. After output is provided, MAIN is now ready to begin the loop through long-term time steps again. If the discharge is still continuing, both the jet convection and dynamic collapse phases are recomputed. If the discharge was discontinued in the last time step but all the material has not been accounted for, BOOKS is called again to create small clouds for storage of the remaining material. If all discharged material has been accounted for, either in small cloud storage or in the long-term grid, MAIN goes directly to MAD.

PART IV: DISCUSSION OF THE COMPUTATION CYCLE AND MODIFICATIONS TO THE INSTANTANEOUS DUMP MODEL

48. The Tetra Tech bottom dump numerical model traces dredged material dumped from a barge from the moment it enters the water column until deposition on the bottom occurs. As indicated in the previous discussion, detailed theoretical aspects of the modeling can be found in Brandsma and Divoky,[3] with the purpose of the discussion herein being to describe in detail the computation cycle of the computer program and to note modifications to the original model that have been made. The manner in which this is accomplished is to present the modifications as they occur in the computation cycle.

49. The basic structure of the bottom dump code is essentially the same as the jet or continuous discharge model, with the long-term computations being identical. As in the jet model, the computation cycle centers around subroutine MAIN. In addition to those in MAIN, various read statements for input data are encountered in subroutines INIT, AMBC, and ESTGEO. As in the jet model, ESTGEO has been modified in the dump model for easier input of water depths for a constant depth estuary. Subroutine UW is called to read ambient velocities from an external storage device for model application to disposal operations in variable depth estuaries. After input data have been read and various variables initialized, the convective descent phase is ready for computations.

50. As noted in previous discussion, the dumped material is assumed to fall through the water column as a hemispherical cloud during the convective descent phase with subroutine DUMP called from MAIN to control computations. After reading in the discharge characteristics, DUMP initializes the dependent variables for the first solution trial. As in the continuous discharge model, many modifications have been made throughout the computer program to allow computations through long-term diffusion on a conservative chemical constituent, taking into account a uniform background concentration.

51. Before continuing with the convective descent computation

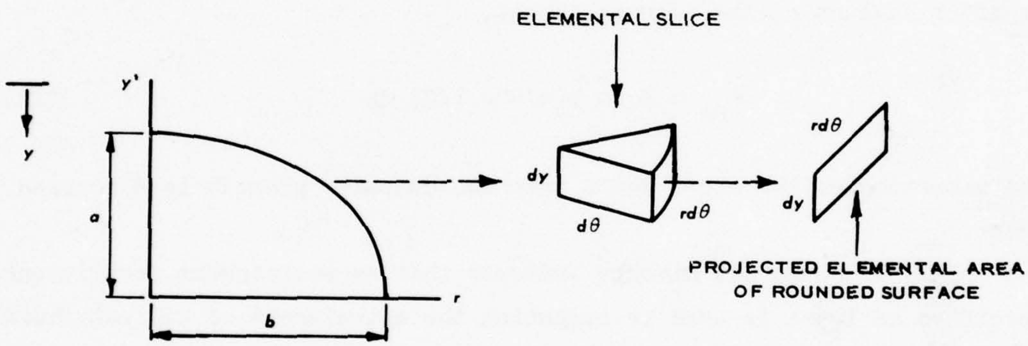
cycle, it should be noted that the short-term dynamic computations are made only once in the bottom dump model and thus are completely outside the long-term time step loop. To initiate computations, RUNGS is called from DUMP which then calls DERIVD to set up the time derivatives of the dependent variables involved in the conservation equations presented in Brandsma and Divoky.[3] Control then switches back to RUNGS for the numerical solution of the governing equations. RUNGS is identical to the subroutine by the same name discussed in the continuous discharge model. The counter, ISTEP, that keeps up with the number of integration steps is now incremented by 1 in DUMP and computations are repeated for the next time step.

52. At the end of each integration step various checks are encountered in DUMP to determine whether the convective descent phase has been successfully computed or if a new solution trial with a different initial integration step is required. If the sum CY(ISTEP) + 3/8 AA(ISTEP) is greater than the water depth, the bottom has been encountered and IPLUNG is set to 1. If bottom encounter has occurred and ISTEP lies between 100 and 200, convective descent is considered to have been successfully computed. If ISTEP does not lie between 100 and 200, the number of the solution trial, NTRIAL, is incremented by 1 and computations begin over with ISTEP = 1 and with a different integration step. Five solution trials are allowed before program termination. Rather than striking the bottom, the hemispherical cloud may reach a neutrally buoyant position in the water column. If this occurs with ISTEP lying between 100 and 200, convective descent is again assumed to have been successfully computed. Assuming that one of the conditions above has been met and that all output requested has been provided, control now reverts back to MAIN.

53. If IPLUNG = 1 (i.e., the bottom has been encountered), subroutine COLAPS is called to control computations through the dynamic collapse of the cloud on the bottom. If a level of neutral buoyancy is encountered during convective descent, a check on the ambient density is made before COLAPS is called to control dynamic collapse computations in the water column. If the ambient density is uniform, dynamic collapse

computations are bypassed and the material moves directly into the long-term diffusion computations. The original program contained an error which did not allow this; however, it has now been corrected.

54. Similar to the discussion in the continuous discharge model, the force derived in Brandsma and Divoky[3] that drives the collapse of the cloud should have an additional term reflecting the difference between the average cloud density and the ambient density when collapse occurs on the bottom. As previously discussed, if collapse occurs in the water column, the expression derived in Brandsma and Divoky[3] is probably appropriate, since for that case the average cloud density is essentially the same as the ambient density. This additional driving force is derived below. As in Brandsma and Divoky,[3] consider a quadrant of the collapsing elipsoidal cloud on the bottom



Assuming hydrostatic pressures, the additional driving force due to the difference between the cloud density at $y' = 0$ and the ambient $\Delta\rho$ is determined by integrating the pressure due to $\Delta\rho$ over the projected area of the rounded external surface. Thus,

$$F_{\Delta\rho} = \int_{y=0}^{y=a} \Delta\rho g y r(y)\, dy\, d\theta \qquad (17)$$

where

y' = the minor axis of the elliptical cross section that varies from 0 to a

r = the major axis of the elliptical cross section that varies from 0 to b

$d\theta$ = the incremental angle of an elemental slice and

$$\frac{y'^2}{a^2} + \frac{r^2}{b^2} = 1 \qquad (18)$$

but, since $y' = y - a$, the above can be solved for $r(y)$ to yield

$$r(y) = \sqrt{\frac{2b^2}{a} y - \frac{b^2}{a^2} y^2} \qquad (19)$$

therefore,

$$F_{\Delta\rho} = {}_0\int^a \Delta\rho g y \left(\frac{2b^2}{a} y - \frac{b^2}{a^2} y^2 \right)^{1/2} dy \, d\theta \qquad (20)$$

or after evaluating the integral above,

$$F_{\Delta\rho} = \Delta\rho g a^2 b(\pi/4 - 1/3) \, d\theta \qquad (21)$$

The insertion of the above force into the computer program is discussed later.

55. Brandsma and Divoky[3] indicate that an entrainment coefficient specified as input is used in computing the entrainment of ambient fluid during collapse on the bottom. However, the computer code actually employs a computed entrainment coefficient that appears to be set to zero in practically all cases. The model has been modified to use the input entrainment coefficient, which, as will be discussed in Part VI, has resulted in a much better representation of the bottom collapse phase based upon observations at disposal sites in Lake Ontario.

56. At this point assume the cloud has attained a level of neutral buoyancy in the water column and collapse occurs. As noted above, COLAPS is now called from MAIN. Results from the end of convective descent are used to initialize collapse computations. Using the same basic equations as presented in the discussion of the continuous discharge model, a fall velocity for cohesive sediment is now computed as a function of the suspended sediment concentration. Subroutine RUNGS is now called

which in turn calls DERIVC. The various derivatives in the governing equations are set up in DERIVC and control then switches back to RUNGS where the numerical integration of the equations is performed. A return to COLAPS then follows. Various checks are now made to determine if the computations have been completed. If the vertical position of the cloud centroid plus three eighths of the cloud radius is greater than the water depth, the bottom has been encountered and IPLUNG is set equal to 2. If IPLUNG = 2 , and the number of collapse time steps lies between 100 and 400, BOTTOM is called. If an estimated diffusive spreading is greater than the computed dynamic spreading, NUTRL is set equal to 3. If NUTRL = 3 and the number of collapse time steps lies between 100 and 400, the collapse phase has been successfully computed. However, if either IPLUNG = 2 or NUTRL = 3 and the number of collapse time steps is less than 100 or greater than 400, the time integration step DT is changed from its old value to the expression below

$$DT_{new} = DT_{old} * \frac{DINCR * FLOAT\ (No.\ Time\ Steps)}{250} \tag{22}$$

and a new trial solution, with NTRIAL increased by 1, is initiated. If neither IPLUNG = 2 nor NUTRL = 3 and the number of collapse time steps is less than 400, the integration step counter, ISTEP, is increased by 1 and computations continue with RUNGS being called which in turn calls DERIVC, etc. As in the short-term dynamic phases of the continuous discharge model, five solution trials are allowed.

57. If the bottom is encountered during either convective descent or during dynamic collapse in the water column, BOTTOM is called. The only modifications to BOTTOM are those associated with computations on a conservative chemical constituent and computation of a fall velocity for cohesive sediments. As in COLAPS, RUNGS is called which in turn calls DERIVB to set up the derivatives in the governing conservation equation presented in Brandsma and Divoky.[3] Previously, an additional driving force for collapse on the bottom was derived. In the computer program, this force is inserted into the expression for EP(10) in subroutine DERIVB.

58. As for collapse in the water column, various checks are made after computations for each integration step are completed. Bottom computations continue with ISTEP incremented by 1 after each step forward in time until either diffusive spreading exceeds dynamic spreading (NUTRL = 3), or the reaction force on the bottom becomes negative, in which case the cloud is assumed to have left the bottom (IPLUNG = 4), or ISTEP becomes greater than 599. Remember, ISTEP is the sum of the number of convective descent integration steps and the number of collapse time steps. Once again, up to five solution trials are allowed before control switches back to MAIN. In summary, in order for collapse to be successfully computed, diffusive spreading must exceed dynamic spreading with the number of collapse time steps lying between 100 and 400.

59. Assume all short-term computations have been successfully computed, output has been provided, and MAIN is ready to initiate tracing of the material through the long-term diffusion computations. These computations are made on one component at a time (i.e., each component's time history is computed for as long as computations are requested, separately from all others). This, of course, is different from the manner in which the various components are traced in the continuous discharge model. Thus, the basic loop found in MAIN is on the dredged material components. The first operation is that of calling BOOKS for the transfer of material from the short-term dynamic computations into small cloud storage.

60. The manner in which these clouds are determined is as follows. The total number of short term time steps, ISTEP, is divided into 10 increments and a check is made at the end of each increment to determine if mass has been lost from the basic dynamic cloud. If solid particles have settled out by the end of the first increment, a small cloud is created for storage of the mass. If no mass has been lost at the end of this increment, the next increment is checked. This continues until at the end of the tenth or last increment all remaining material is inserted into a final small cloud. Note that with this procedure only one chemical constituent cloud is created.

61. As each cloud is created, it is updated to the end of the long-term time step. This update consists of horizontal convection by the ambient current, variation of the cloud depth due to convection over varying depths, horizontal diffusion, and vertical diffusion. As in the jet model, the program has been modified to compute vertical diffusion in increments of one tenth of a long-term time step. The cloud is then allowed to settle at its fall velocity. As in the jet model, modifications have been made to allow for the placement of deposited material equally among all grid squares covered by the cloud rather than placing all material in the one square associated with the cloud centroid. After all clouds are created and updated, control switches back to MAIN.

62. A second loop in MAIN is now encountered. This loop, which is embedded within the loop on the components, is a loop over the tidal days and corresponding long-term time steps. Computations from this point until the end of the long-term diffusion phase are the same as in the continuous discharge model and are not discussed here. All the modifications in MAD, ACAD, and AVE5PT discussed previously apply to the bottom dump model also.

63. After all long-term diffusion computations are completed for the particular component in question, the same set of computations, i.e., the calling of BOOKS, MAD, etc., is performed for the next component. This process is repeated until all solid components as well as the conservative chemical constituent have been tracked for as long as requested by the user.

PART V: SENSITIVITY OF MODEL OUTPUT TO MODEL COEFFICIENTS

64. The instantaneous dump model contains 14 coefficients and the continuous discharge model contains 17 coefficients (16 in the original model plus the additional drag force coefficient previously discussed). The models contain suggested default values by the model developers that the user can request in case better values are not available. However, most of these default values are merely "best guesses" and thus some idea of the sensitivity of model output to each coefficient is required.

Instantaneous Dump Model

65. To provide some guidance on the importance of the various coefficients in the instantaneous dump model, several runs were made for a typical disposal from a bottom dumping scow in the New York Bight. The input data describing the disposal operation and the ambient environment are presented in Table 1. Appendix A provides a general formatted list of input required.

66. The sensitivity of model output to the various coefficients was determined by individually increasing the value of each coefficient, with all others held constant at the default values suggested by Tetra Tech. These are presented in Table 2. It should be realized that the sensitivity of most coefficients will vary with the input conditions. Therefore, the results obtained and presented in Table 3 for a scow disposal operation in the New York Bight would not necessarily be applicable to instantaneous disposal operations in which the water depth and material characteristics were substantially different from those listed in Table 1.

67. Table 3 presents an illustration of the dependence of model output from all three phases, i.e. convective descent, dynamic collapse, and long-term dispersion, on each of the 14 coefficients contained in the instantaneous dump model. As can be seen, the most important

coefficients appear to be α_o , CDRAG, CFRIC, α_c , FRICTN, F1, and λ_H . Each of these is discussed below.

<u>α_o - Entrainment coefficient for a turbulent thermal</u>

68. Actually α , which is a function of α_o and is given by the expression below, is the entrainment coefficient governing entrainment of ambient fluid during convective descent of the hemispherical cloud.

$$\alpha = \alpha_o \left[\tanh \left(\frac{B}{2\pi g C_1 K^2 \alpha_o} \right)^2 \right]^{1/2} \tag{23}$$

where

α_o = entrainment coefficient for a turbulent thermal

B = buoyancy

C_1 = a constant = 0.16

K = vorticity

During the initial descent of the cloud, the vorticity is large which results in α approaching the value for the entrainment coefficient of a vortex ring given by

$$\alpha = \frac{B}{2\pi g C_1 K^2} \tag{24}$$

However, as the cloud descends the vorticity approaches zero and α approaches α_o . No real justification has been given by Tetra Tech for the functional form of α other than it does have the proper limits for large and small vorticity and does provide a smooth transition from one to the other. As noted by JBF Scientific,[4] α should be related to the percent moisture of the material being disposed, with α increasing as the moisture content increases. With the present representation of the convective descent entrainment coefficient, some variation of α_o will be required in any calibration of the instantaneous dump model.

CDRAG - Collapse drag coefficient

69. Collapse of the oblate spheriodal cloud is governed by the driving force arising from the difference in the density structure and resistive forces consisting of (a) the inertia force, (b) the form drag of the collapsing cloud, and (c) the skin friction drag of the cloud. CDRAG is the coefficient associated with the form drag and thus has been suggested as being similar to the drag coefficient for a wedge, which results in the suggested value of 1.0. However, there is significant uncertainty associated with CDRAG to warrant changing the value of CDRAG as deemed necessary to improve the comparison between computed rates of spreading on the bottom and recorded bottom surge data during calibration of the model.

CFRIC - Collapse
skin friction coefficient

70. As previously discussed, the collapsing cloud experiences a resistive skin friction force. CFRIC is the skin friction coefficient and thus is very similar to the kinematic viscosity of the ambient fluid. The kinematic viscosity of water at $50^{o}F$ is 0.013 cm^2/sec which is approximately the default value of 0.01 listed in Table 2. Since there is a greater physical reasoning behind the default value of CFRIC, it is suggested that very little variation of this coefficient should be undertaken in a calibration effort, even though model output in the collapse phase is moderately sensitive to it.

α_c - Collapse
entrainment coefficient

71. As the cloud collapses, additional fluid is entrained. As previously noted, in the initial model, for the case of collapse on the bottom, an entrainment coefficient was computed which in most cases appeared to be set to zero. One of the modifications to the model has been that of setting the bottom collapse entrainment coefficient to α_c , as is the case for collapse in the water column. The default value has been set to 0.001, although no basis for this selection was noted by Brandsma and Divoky.[3] Therefore, when attempting a calibration of the model, one should not be overly concerned about a substantial variation

of α_c from its default value, if such is required.

FRICTN - Bottom
friction coefficient

72. FRICTN is the bottom-cloud interface friction coefficient. Its value should depend upon the character of the bottom being impacted. Its default value is 0.01, but the value required in a calibration effort may be substantially different.

F1 - Bottom modification factor

73. F1 is a modification factor used in computing the resistance of the friction force to the collapse of an arc of a half ellipsoid. Since F1 is multiplied by FRICTN, increasing F1 by some factor has the same effect as increasing FRICTN by the same factor. Thus, rather than increasing both in a calibration effort, only FRICTN will be varied.

λ_H - Horizontal turbulent dissipation parameter

74. The horizontal turbulent diffusion coefficient E is assumed to be a function of a characteristic length to the four-thirds power, i.e.,

$$E = \lambda_H (\Delta X)^{4/3} \qquad (25)$$

where λ_H is the dissipation parameter and ΔX is taken as the characteristic length. The influence of λ_H is primarily restricted to long-term computations, although it does influence when the collapse phase terminates.

75. Based upon computer experimentation with the instantaneous dump model, the major coefficients that might be varied from their default values during calibration efforts of short-term results for disposal operations similar to a scow dump in the New York Bight are α_o, α_c, CDRAG, and FRICTN. It should be noted that for a different ambient stratification and/or longer periods of simulation, the vertical and the horizontal diffusion coefficients would take on added importance.

Continuous Discharge Model

76. As previously done with the instantaneous dump model, several runs were made with the continuous discharge model to determine the importance of the model coefficients. A typical hopper dredge disposal operation in the New York Bight was selected. The input data describing the disposal operation and the ambient environment are presented in Table 4. Appendix B provides a general formatted list of input required. Again, it should be realized that the sensitivity of most coefficients will vary with input conditions and thus the results obtained herein will not necessarily be applicable to significantly different continuous operations under different environmental conditions.

77. The sensitivity of model output to the various coefficients was determined by individually increasing the value of each coefficient with all others held constant at the default values suggested by Tetra Tech and listed in Table 5. Table 6 presents an illustration of the dependence of model output from all three phases, i.e., convective descent, dynamic collapse, and long-term dispersion, on each of the 16 coefficients contained in the continuous discharge model. The most important coefficients appear to be α_1, CD, CDRAG, CFRIC, α_4, FRICTN, F1, CM, and λ_H. Each is discussed below. It should be noted that the drag coefficient (ADDRAG) associated with the additional drag force discussed in paragraph 22 did not influence the model results since the additional drag force acts to inhibit the vertical descent of the jet only for a vertical stationary discharge.

α_1 - Jet convection entrainment coefficient

78. The convective descent phase of the continuous discharge is similar to the motion of a momentum jet. However, as the jet bends in the direction of the ambient current, the rise or fall of the plume more closely resembles a two-dimensional thermal. The expression for entrainment of the ambient fluid during the convective descent phase is composed of two parts: namely, entrainment similar to that experienced by a momentum jet and entrainment experienced by a two-dimensional thermal.

The entrainment coefficient associated with the initial or momentum jet stage of the convective descent phase is α_1 .

CD, ADDRAG - Jet
convection drag coefficients

79. In the presence of a cross current, a force arises due to the unbalanced pressure field at the upstream and downstream faces of the convective descent jet. A gross drag force perpendicular to the trajectory of the jet has been assumed, with CD being the associated drag coefficient. In a calibration effort, one can expect to vary CD from its default value of 1.3. The default value of ADDRAG has been set to 1.0. However, it should be realized that no importance should be attached to this value, since the representation of the additional drag force was simply taken to be similar to the drag force acting on the descending hemispherical cloud in the instantaneous dump model. In the calibration effort at Lake Ontario, discussed in the next section, it was found that increasing ADDRAG from 0 to 1.0 (for the run with a bulk density of 1.17 g/cc) resulted in approximately twice as much time being required for the jet to strike the bottom. It might be noted that an instability in the computations occurs for even small values of ADDRAG when the difference between the jet density and the ambient density becomes less than about 0.025 g/cc. Therefore, the model has been programmed to set ADDRAG = 0 when this occurs.

CDRAG - Collapse
drag coefficient

80. As discussed in the instantaneous dump analysis, collapse is governed by a driving force arising from the difference in the plume and ambient density structure and resistive forces consisting of (a) the plume inertia force, (b) the form drag of the collapsing plume, and (c) the skin friction drag of the plume. CDRAG is the drag coefficient associated with the resistive form drag of the collapsing plume that is assumed to take the shape of an elliptical cylinder. Thus, a default value of 1.0 has been set which, of course, is subject to change when attempting a calibration of the model.

CFRIC - Collapse skin friction coefficient

81. CFRIC is the same coefficient as CFRIC in the instantaneous dump model. Statements previously made about CFRIC in connection with the instantaneous dump model are also applicable to the continuous discharge model.

α_4 - Collapse entrainment coefficient

82. Entrainment of the ambient fluid during collapse occurs due to convection as well as a result of the collapse itself. α_4 is the coefficient associated with the latter. It appears that great uncertainty exists concerning α_4 and thus significant variation from its default value of 0.001 seems justifiable.

FRICTN - Bottom friction coefficient

83. FRICTN is the same coefficient as FRICTN in the instantaneous dump model. Statements previously made about FRICTN in connection with that model are also applicable here.

F1 - Bottom modification factor

84. As with FRICTN, F1 is the same coefficient as F1 in the instantaneous dump model.

CM - Apparent mass coefficient

85. The apparent mass of a body moving at velocity V_o is a virtual mass moving at the same velocity with the same kinetic energy as that of the actual body plus the kinetic energy of the displaced fluid. Some variation of CM appears justified based upon the sensitivity demonstrated in Table 6.

λ_H - Horizontal turbulent dissipation parameter

86. The long-term computations in the continuous discharge model are performed in the same manner as in the instantaneous dump model. Therefore, statements previously made concerning λ_H are applicable here.

87. Based upon computer experimentation with the continuous

discharge model, the major coefficients that might be varied from their default values during calibration efforts of short-term results for disposal operations similar to the hopper dredge disposal modeled are α_1 , CD, ADDRAG, CDRAG, α_4 , FRICTN, and CM. If one attempts to match long-term results, λ_H might be varied also.

88. As a final note, the importance of the vertical diffusion coefficient is quite dependent upon the ambient stratification. In the example problems, the ambient density was assumed relatively uniform for about 23 ft up from the bottom. This explains the vertical diffusion of the tracer cloud up to this height (see Table 6). Note, however, that in some instances the cloud diffuses upwards for 37 ft. The reason is because the computations were such that the top of the cloud managed to extend past the first region of stratification occurring from 22.3 to 24.3 ft from the bottom into another region of uniform density. When this occurred, the model allowed the top of the cloud to rapidly diffuse upward to the next region of stratification (occurring at about 37 ft from the bottom). At this point, as can be seen in Table 6, the vertical diffusion was essentially stopped.

PART VI: CALIBRATION EFFORTS USING FIELD DATA COLLECTED BY YALE UNIVERSITY

89. In order to evaluate techniques for predicting the fate of dredged material released in the water column, it is necessary to determine the significance of the controlling physical processes affecting the deposition of this material on the bottom. Consequently, a field study was initiated with Yale University by the DMRP to investigate the mechanics of the placement of dredged material at various open-water disposal sites.[5] Their objectives were to follow the path of the dredged material, determine how much material reaches the bottom and in what form, document how much sediment is dispersed into the ambient water, and measure how long. Some results from this work are used herein to attempt a calibration of the Tetra Tech models, albeit a very limited calibration due to a lack of the type of data needed from these studies.

90. Model calibration has centered around determining the most realistic way to apply the models to a particular disposal operation, within the framework of the idealized conditions assumed in the models, and a subsequent variation of model coefficients to match computed results with data collected during the field disposal operations by Yale. A discussion of these efforts and results attained are presented below.

Model Calibration for Instantaneous Dump Operations

91. When attempting to apply the dredged material models to real disposal operations, a basic problem is that of determining how to apply the models so that an actual operation can be represented by the idealized methods of disposal considered in the models. For example, there are no dredged material disposals in which all the material leaves the disposal vessel instantaneously. However, for the case of a barge dump, all of the material leaves fairly quickly, e.g., perhaps 15 to 20 sec. If the water depth is sufficiently large, such a dump does resemble a hemispherical cloud falling through the water column by the time the

bottom is encountered and thus can be adequately modeled by the instantaneous dump model. If the volume of the dump is of such magnitude and/or the water depth is too shallow so that collapse occurs on the bottom before all the material leaves the disposal vessel, it is obvious that the instantaneous model will not yield an accurate description of the disposal process.

92. Proper material characterization is extremely important in obtaining realistic predictions from the models, particularly when collapse of the disposal cloud in the water column is a real possibility. In some dumps, it has been observed that even the cohesive solids settle to the bottom of the vessel before disposal, with the resulting bottom material possessing a low water content and corresponding high bulk density. It is believed that a large portion of the material then falls from the collapsing cloud as clumps with fall velocities of perhaps 1.0 to 2.0 ft/sec. This is, of course, quite different from a characterization of the material where various solid types are assumed to settle at essentially particle fall velocities.

93. There are 14 coefficients in the instantaneous dump model. As previously discussed, the model contains default values, but the user has the option of prescribing these as input. As noted in Part V, computer experimentation with the Tetra Tech models indicates that model output is most sensitive to entrainment and drag coefficients in both the convective descent and collapse phases, as well as the bottom friction coefficient. Therefore, when attempting to calibrate the model using data collected at a disposal site, these provide a good starting point in the variation of coefficients to match computed and recorded data.

Duwamish site

94. During February 1976, Yale University collected data during and after several dumps over a 2-week period at the Duwamish disposal site in Elliott Bay near Seattle, Washington. All dumps were made from a 530-cu-yd barge; thus, the instantaneous dump model with an initial radius of 19.0 ft for the hemispherical cloud with a bulk density of 1.50 g/cc was selected to best represent the disposal operation. A

depth-averaged velocity field over the varying depth disposal site was constructed, making sure to satisfy mass conservation of the flow field. This was accomplished as follows. At one point near the disposal site current data averaged over the water column were available as a function of time over a 25-hr cycle. Water depths were available at each of the net points of the horizontal grid constructed over the disposal site. Assuming that the known current and associated water depth are V^* and h^*, respectively, one can then compute the current at the net point (i,j) as

$$V_{ij} = \frac{V^* h^*}{h_{ij}} \tag{26}$$

to ensure the conservation of mass of the flow field. The magnitude and direction of V^* as a function of time are presented in Table 7. The depth grid, i.e. h_{ij}, is given in Table 8 where M is the number of spatial steps in the X-direction and N is the number of spatial steps in the Z-direction. The computer program used to perform the computations noted above and to subsequently create the velocity tape is listed in Appendix C. The remaining input data required for operation of the instantaneous dump model are presented in Table 9.

95. Upon release of the material during the field tests, a time of 25 to 30 sec was normally observed for the cloud to strike the bottom. With the convective descent drag coefficient increased from its suggested value of 0.5 to 1.0, the model computes a time of 24 sec with a final radius of 59 ft at bottom encounter. The speed of the front of the surge in the field at 160 ft from the point of dump was estimated to be 20 cm/sec. With an increase in the drag coefficient in the collapse phase from 1.0 to 1.75, the model computes a corresponding speed of 19 cm/sec. During the field test, suspended solids data were recorded at 3 ft from the bottom at only one point, which was 300 ft downstream of the dump point. At 600 sec after the dump, the recorded suspended sediment concentration was 64 mg/ℓ. After 1000 sec the computed concentration of the suspended material was 42 mg/ℓ, extending 8 ft up from the bottom. The times could not be compared due to a restriction on the

long-term time step in the model, the restriction being that the long-term time step must be greater than the time required for the collapse phase to terminate. Based upon recorded data at 300 ft downstream of the dump point, it took 1800 sec for the suspended sediment concentration to decrease from 94 to 35 mg/ℓ, i.e., a rate of decrease of 0.0328 mg/ℓ/sec. From the model computations, 1000 sec was required to reduce the suspended sediment concentration at the same point from 42 to 11 mg/ℓ, i.e., a rate of decrease of 0.0310 mg/ℓ/sec. A summary of these results is presented in Table 10.

New York Bight site

96. As a second example of application of the instantaneous dump model, data collected during a scow dump in the New York Bight were utilized. The solids of the 3000-m^3 dump were assumed to be composed of 30 percent cohesive "clumps" with a fall velocity of 2.0 ft/sec and 70 percent silty-clay with a fall velocity of 0.01 ft/sec. The water depth was 85 ft and the bulk density of the material was 1.60 g/cc. The basic model input data were previously presented in Table 1. There were two prototype data points in the bottom surge available for comparison with computed results. Based upon transmissometer data, the front of the surge arrived at about 300 ft from the dump 70 sec after initiation of the dump, whereas, after about 250 sec, a current meter recorded the arrival of the surge at approximately 800 ft from the dump. From the transmissometer data, the suspended sediment concentration at 3 ft from the bottom was 7.5 g/ℓ after 138 sec, 1.5 g/ℓ after 558 sec, and was down close to background levels after approximately 1000 sec.

97. Various combinations of the more sensitive coefficients were tried in the attempted calibration of the model. In all runs, the drag coefficient in the convective descent phase (CD) was increased to 1.0. As previously noted, the most sensitive coefficients in the bottom collapse are a drag coefficient (CDRAG), an entrainment coefficient (α_c) and the bottom friction coefficient (FRICTN). The default values of these coefficients, as presented in Table 2, are 1.0, 0.001, and 0.01, respectively. However, very little is known about these coefficients

and thus no great significance should be attached to these default values. In addition, it should be realized that the bottom collapse entrainment coefficient has gained added significance due to the modification previously discussed.

98. It became obvious early in the computer experimentation that, as in the Duwamish simulation, CDRAG had to be increased in order to match the arrival time of the surge front 300 ft from the dump. However, unlike the Duwamish simulation, in addition to matching an early surge arrival time, the spread after 250 sec in the New York Bight simulation also had to be considered. Values of CDRAG = 5.0 , $\alpha_c = 0.04$, and FRICTN = 0.075 resulted in a computed spread of 350 ft after 70 sec and 685 ft after 250 sec. The computed cloud thickness after 250 sec was approximately 3 ft which, based upon similar surge observations at a hopper dredge disposal operation in Lake Ontario, probably comes close to approximating the proper surge volume. These hopper dredge disposal observations are discussed in more detail in the next section. After 450 sec, the computed average suspended sediment concentration over the cloud was 6.2 mg/ℓ and had fallen to essentially zero after 900 sec. It should be remembered that the recorded concentrations of 7.5 mg/ℓ after 138 sec and essentially background after 1000 sec were point values rather than averages over the collapsing cloud. A summary of these results is presented in Table 11.

Model Calibration for Continuous Discharge Operations

99. As previously noted, a major question when attempting to apply these disposal models is how best to model the particular disposal operation with the idealized disposal methods simulated by the models. For example, the continuous discharge model allows for only one discharge opening, whereas, most hopper dredges have eight doors, all of which discharge continuously for a discrete period of time but not necessarily concurrently. Of course, for the case of a pipeline discharge, there is no problem with representing the disposal operation, although, other problems such as very shallow water depths may exist.

100. The purpose of the discussion below is to demonstrate the

manner in which hopper dredge disposal operations might be modeled as well as to present calibration results. Although the applications are for actual disposal operations in the New York Bight and Lake Ontario, the data from the New York Bight site were not sufficient for model calibration.

New York Bight disposal site

101. The disposal in the New York Bight was accomplished by a hopper dredge moving at over 4 ft/sec. The dredge contained four pairs of doors, with disposal occurring by alternating between first a pair of forward doors and then a pair of aft doors, etc., until the complete load was discharged. Normally, the discharge from one pair of doors was essentially complete by the time the next pair opened. The continuous discharge model was used to simulate this disposal operation by making the assumption that the operation could be represented as a continuous discharge through a circular opening with an area equivalent to a pair of doors. Model input data have previously been presented in Table 4. Although no field data collected at the site were considered suitable for comparison with model predictions, the approach did appear to provide a reasonable qualitative description of the short-term fate of disposed material. However, a note of caution must be raised concerning the concept of representing the outflow from several openings by a single discharge. In the New York Bight case combining a pair of doors into one discharge decreases the densimetric Froude number by about 20 percent. Since the Froude numbers are quite small, this change probably will not significantly alter the hydrodynamic similarity. However, if a case should arise where one wished to combine several openings into a single opening, the change in the densimetric Froude number might be so large that the hydrodynamic similarity would be altered. In addition, problems with the initial Koh-Chang computer model were often encountered when attempting to apply the model to a large initial opening. Thus, combining several openings of a hopper dredge into a single opening is not recommended.

Lake Ontario disposal site

102. The disposal operation at Rochester, N. Y., in Lake Ontario

was accomplished from a stationary hopper dredge discharging simultaneously from eight doors. As previously discussed, the continuous discharge model applied to a stationary, vertical discharge does not behave well at bottom encounter. Based upon observations by Yale University, the eight individual jets grew fairly quickly and at some point in the water column had grown enough to mix together. From this point, the material falling through the water column resembled the type of disposal operation that could be simulated with the instantaneous dump model. However, the discharge continued for about 45 sec; whereas, the bottom was encountered within 15 to 20 sec. Thus, although the dump model will yield the radial outflow pattern on the bottom, some mechanism for accounting for the material still being discharged had to be developed. This was accomplished as follows. From field observations it was estimated that the majority of the solids settled to the bottom of the hoppers, with the resulting material in the lower one third of the hoppers having a bulk density of 1.5 g/cc and the material in the upper two thirds having an average bulk density of about 1.17 g/cc. The continuous discharge model was first run assuming a release density of 1.50 g/cc. Input data are presented in Table 12. Results from this run were then used to initiate the instantaneous dump model, taking into account the case of all eight doors being opened. The continuous model was then rerun assuming a release density of 1.17 g/cc to arrive at a resulting flow rate near the bottom. The instantaneous dump model was then modified to accept this flow rate as entrained fluid into the collapsing cloud on the bottom for as long as the discharge continued. The steps for modeling such a disposal operation are summarized below.

- a. Apply the continuous discharge model to a single door using an average bulk density corresponding to the material occupying the lower one third of the hopper.
- b. Results from step a enable one to compute the volume of the instantaneous hemispherical cloud and the position of its centroid. An example is presented in Appendix D.
- c. Before application of the instantaneous dump model, rerun the continuous discharge model for a single door using the average density of the material occupying the upper two thirds of the hopper. From this run, the entrainment flow rate and density of the entrained fluid are determined for input to the instantaneous dump model.

d. Apply the instantaneous dump model, using results from steps b and c, to obtain the best representation of the radial bottom surge.

It is believed this approach yields the most realistic representation possible with the current structure of the models. Input data for the instantaneous dump run are presented in Table 13.

103. A major question that must be answered in the calibration phase is that of which of the computed results should be compared with recorded field values. For example, comparing computed and recorded times to bottom encounter certainly seems justified, whereas attempting a direct comparison of cloud thickness at some point on the bottom does not seem justified since the computed results of bottom collapse are more or less averaged results over the spatial extent of the cloud. It was finally decided that perhaps the most important information to be gained from the models was time to bottom encounter, spread of material through the water column, and lateral extent and total volume of the bottom surge versus time. Therefore, these were the quantities compared in the calibration phase.

104. Two dump sites were monitored by Yale University in Lake Ontario with the major difference between the two being the water depth, 58 ft at one and 87 ft at the other. Results from the 58-ft site were used for calibration purposes due to more detailed data having been collected there.

105. With a drag coefficient of 1.50 for the additional vertical drag force previously discussed and a convective descent jet entrainment coefficient of $\alpha_1 = 0.20$, the front of the descending jet reached 42 ft below the surface in 10 sec, which was essentially the time recorded by Yale. After initiating the instantaneous dump model, the total computed elapsed time until bottom encounter was 17 sec, whereas Yale recorded 18 sec.

106. A comparison between computed and recorded bottom surge volumes and arrival times for different combinations of CDRAG, α_c , FRICTN, ADDRAG, α_o , and α_1 , are presented in Figures 5 and 6, respectively. Values of CDRAG = 5.0 , $\alpha_c = 0.04$, and FRICTN = 0.10

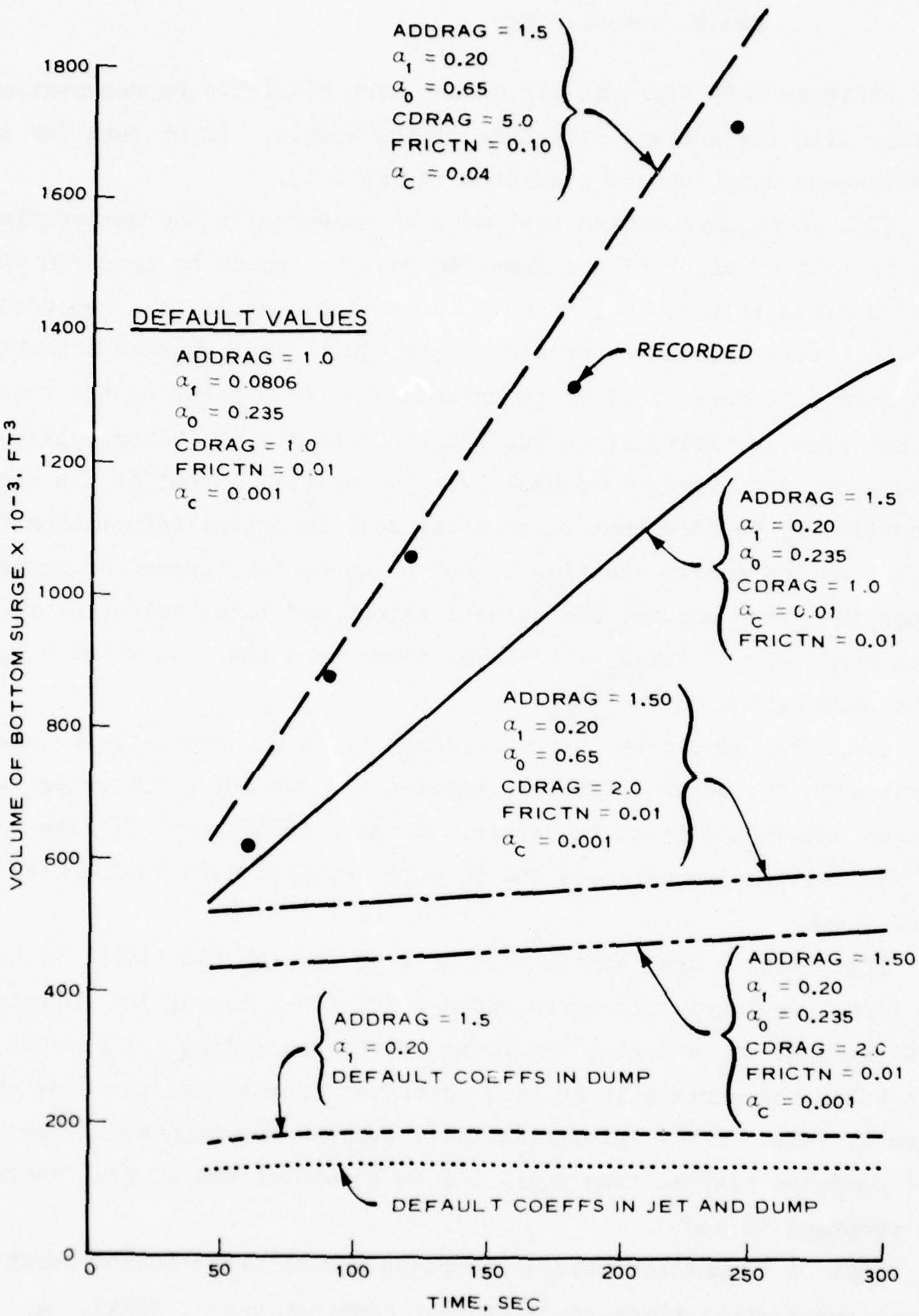


Figure 5. Surge volume versus time after disposal at the Lake Ontario 58-ft site

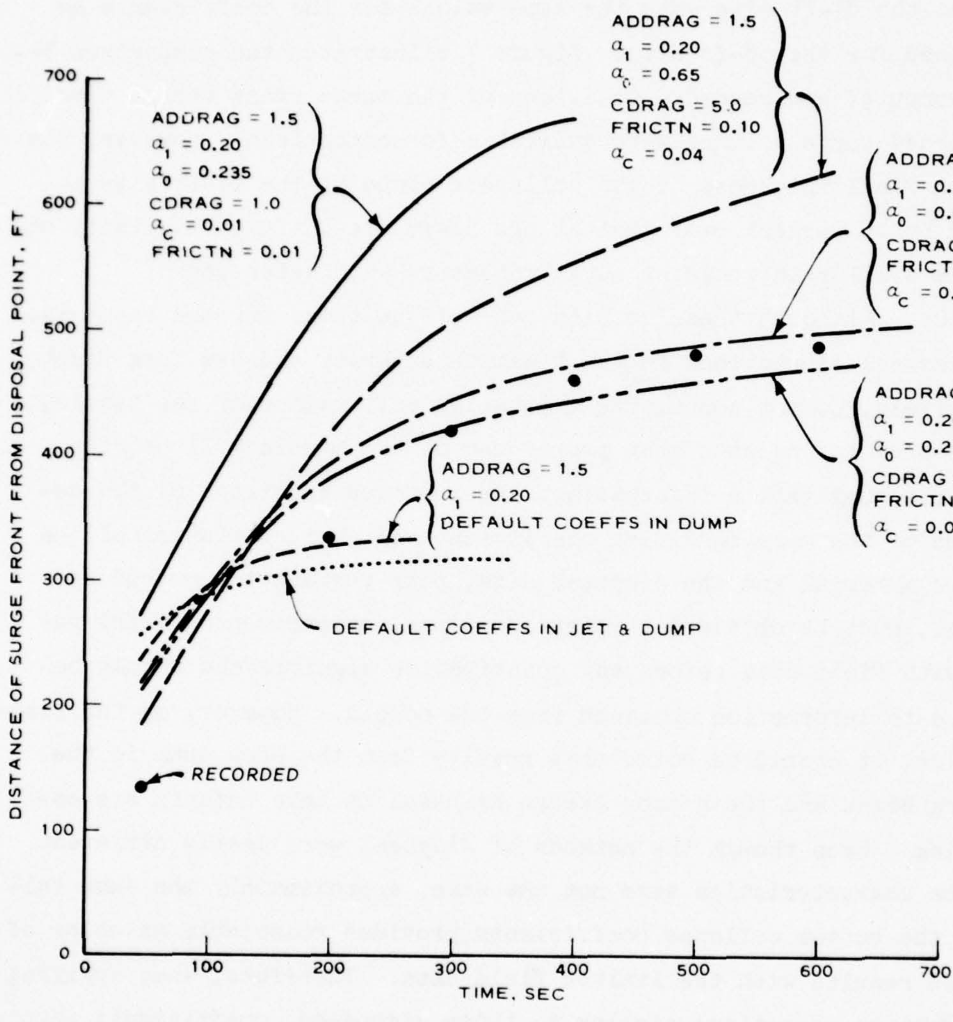


Figure 6. Surge spread versus time after disposal at the Lake Ontario 58-ft site

along with ADDRAG = 1.5 , α_o = 0.65 , and α_1 = 0.20 appear to be the best combination to make computed values approximate both measured surge spread and surge volume simultaneously.

107. The models were then applied in the same manner to the disposal at the 87-ft site with the same values for the coefficients as determined for the 58-ft site. Figure 7 illustrates the comparison between computed and recorded positions of the surge front versus time. No recorded surge volumes were available for comparison. However, the computed final thickness of the collapsed cloud at the 87-ft site increased by 40 percent over that at the 58-ft site. Yale University observed a similar increase of surge thickness with water depth.

108. Although these results, as well as those for the barge and scow disposal simulations in the Duwamish Waterway and New York Bight, respectively, do not constitute a detailed calibration of the models, they do seem to indicate that proper use of the models will provide reasonable qualitative information. An improved knowledge of the dependence of the more sensitive coefficients on characteristics of the disposed material and the disposal site, plus perhaps the method of disposal, must be obtained through additional comparison of model results with field data before any quantitative significance should be attached to information obtained from the models. However, on the positive side, it should be noted that results from the scow dump in the New York Bight and the hopper dredge disposal in Lake Ontario are encouraging. Even though the methods of disposal were vastly different and site characteristics were not the same, approximately the same values of the bottom collapse coefficients provided reasonable matching of computed results with the limited field data. Therefore, when applying the models to operations similar to those discussed, coefficients should be selected close to those determined here to yield the best results at the New York Bight and Lake Ontario sites. Table 14 presents a summary of the variation of coefficients in the calibration effort discussed.

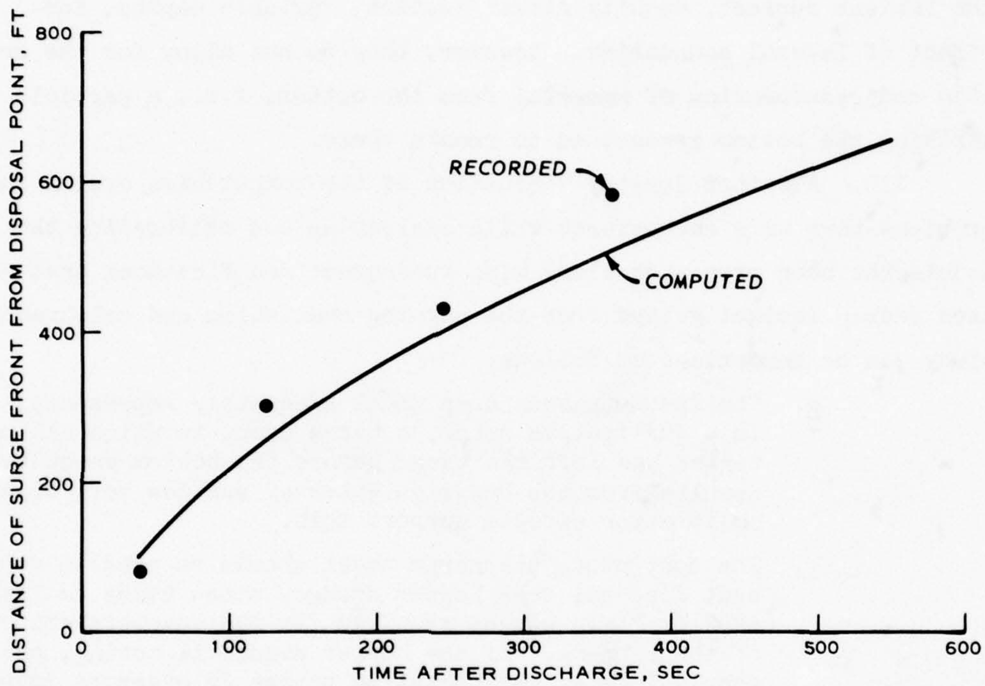


Figure 7. Surge spread versus time after disposal at the Lake Ontario 87-ft site

PART VII: SUMMARY AND CONCLUSIONS

109. A discussion of modifications made to and calibration of the Tetra Tech dredged material disposal models for the physical fate prediction of dredged material discharged in an aquatic environment has been presented. One model is for an instantaneous bottom dump and the other is for a continuous discharge from either a fixed or moving source. The models allow for the temporal and spatial dependence of the ambient current, density stratification, variable depths, and effect of lateral boundaries. However, they do not allow for the erosion and resuspension of material from the bottom, i.e., a particle striking the bottom is assumed to remain there.

110. A rather lengthy discussion of the computation cycles and problems that were encountered while evaluating and calibrating the models has been presented along with subsequent modifications that have been made. Insight gained from the ongoing evaluation and calibration study can be summarized as follows:

- a. The instantaneous dump model adequately represents, in a qualitative sense, a barge dump, in which all material has left the barge before the bottom encounter. Results from the Duwamish Waterway and New York Bight calibration efforts support this.
- b. The continuous discharge model should be used to represent disposal from hopper dredges since times as large as 2 or 3 min may be required for the complete emptying of the hoppers. If the hopper dredge is moving, one should look at the operating scheme in order to determine the best approach to take, keeping in mind that combining too many individual hopper gate openings into a single opening may alter the hydrodynamic similarity. If the hopper dredge is stationary, one should not attempt to apply the continuous discharge model alone since it does not provide a realistic representation of a vertical jet bottom encounter. The approach used in the Lake Ontario calibration effort should be considered.
- c. Proper material characterization is extremely important in obtaining realistic predictions from the models, particularly when collapse in the water column is a real possibility. One should attempt to classify not only solid particle fractions such as coarse sandy material but also that fraction of the material that falls as "clumps."

d. Entrainment and drag coefficients in the descent and collapse phases plus the bottom friction coefficient appear to be the most sensitive coefficients in the models. When attempting to calibrate the models using data collected at a disposal site, these coefficients provide a good starting point in the variation of coefficients to match computed and recorded data. For disposal operations similar to those discussed, the values of the coefficients should be selected close to those determined to yield the best matching of computed and recorded results at the New York Bight and Lake Ontario sites.

e. No quantitative significance should be attached to predictive computations from either model until knowledge of the required coefficients is improved.

111. Major modifications made to the Tetra Tech models other than correcting minor programming errors in the computer codes include:

a. Allowing for the computation of a conservative chemical constituent through the passive dispersion phase taking into account a background concentration.

b. Computing settling velocities for cohesive fractions beginning with the collapse phase and extending through the passive dispersion phase.

c. Removal of the excessive dilution experienced in transferring small clouds to the long-term transport grid and also in the vertical diffusion computations.

d. Inclusion of an additional driving force in the bottom collapse phase.

e. Allowing for extra entrainment into the collapsing cloud on the bottom.

112. Although these models still have not undergone sufficient calibration and subsequent verification to warrant confidence in a quantitative sense, the limited calibration discussed herein and the in-depth evaluation the models have received do justify confidence in a qualitative sense, especially if the material is properly characterized and the models are judiciously applied to adequately represent a real disposal operation.

113. From the evaluation and testing program including the data collected from the field studies, the following conclusions can be made concerning the short-term models at this time:

a. The models can realistically simulate what happens in the water column during the release. The limiting factor determining which model or models to apply is the relationship between the time required for the leading edge of the descending cloud to impact the bottom and the time required to empty the hopper dredge or barge.

b. These models cannot accurately describe the detailed structure of the impact and subsequent bottom surge as observed and discussed in Bokuniewicz et al.[5] However, with proper selection of coefficients, the lateral spread and the rate of change in the total volume of the radially expanding surge can be estimated.

c. A reasonable description of the concentrations within the surge and long-term phase is dependent on an adequate characterization of the sediment properties of the dredged material.

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Table 1

Model Input for New York Scow Disposal Operation

Number of grid points in z-direction = 25

Number of grid points in x-direction = 25

Grid spacing = 100 ft

Constant depth of 85.3 ft

Dump made at x = 700 ft and z = 1500 ft

Ambient Conditions

Depth ft	Density g/cc	x Velocity ft/sec	z Velocity ft/sec
0	1.021		
2.5		1.170	0.250
40	1.022		
51	1.023		
61	1.023		
63	1.025		
65	1.026		
75	1.026		
82		0.280	-0.280
85.3	1.026		

Long-term time step = 450 sec

Initial radius of cloud = 36.97 ft

Initial depth of cloud centroid = 19.68 ft

Initial cloud velocity = $0.0\hat{i} + 2.0\hat{j} + 0.0\hat{k}$

Bulk density of disposal material = 1.60 g/cc

Characterization of Material

Description	Density g/cc	Concentration ft^3/ft^3	Fall Velocity ft/sec
Silty-clay	2.60	0.2570	0.01
Clumps	2.60	0.1100	2.0
Fluid	1.020	0.6330	0.0

Table 2

Default Values of Instantaneous Dump Model Coefficients

Coefficient	Default Value
α_o	0.235
β	0.0
Cm	1.0
CD	0.50
γ	0.25
CDRAG	1.0
CFRIC	0.01
CD_3	0.10
CD_4	1.0
α_c	0.001
FRICTN	0.01
F1	0.10
λ_H	0.005
λ_V	0.05

Table 3

Sensitivity Results for Instantaneous Scow Dump in New York Bight

Coefficient	t_{CONV}	V_{CONV}	R_{CONV}	t_{COLL}	$A \times B_{COLL}$	% Solids on Bottom @450 sec	Area of TR Cloud @900 sec	Avg. Thick. of TR Cloud @900 sec	Max. Conc of TR Cloud @900 sec	Area of TR Cloud @1350 sec	Avg. Thick. of TR Cloud @1350 sec	Max. Conc of TR Cloud @1350 sec
Default Values	3.35	19.2	48.2	92.5	0.65 × 949	99.0	100×10^4	22	0.23	110×10^4	22	0.23
α_o = 0.650	3.91	11.2	64.2	182.1	0.90 × 1245	89.8	144×10^4	23	0.15	156×10^4	23	0.15
β = 0.50	3.35	19.2	48.2	93.6	0.63 × 973	100.0	100×10^4	22	0.23	110×10^4	22	0.23
CM = 1.50	3.99	16.3	48.2	95.2	0.65 × 943	100.0	100×10^4	22	0.23	110×10^4	22	0.23
CD = 2.0	3.91	14.1	48.2	97.2	0.66 × 938	100.0	100×10^4	22	0.23	110×10^4	22	0.23
γ = 0.75	3.35	19.2	48.2	92.5	0.65 × 949	99.0	100×10^4	22	0.23	110×10^4	22	0.23
CDRAG = 2.0	3.35	19.2	48.2	155.2	0.81 × 791	97.1	72×10^4	24	0.35	80×10^4	24	0.35
CFRIC = 0.02	3.35	19.2	48.2	70.6	0.78 × 826	100.0	81×10^4	23	0.28	90×10^4	23	0.28
CD_3 = 0.50	3.35	19.2	48.2	92.5	0.65 × 949	99.0	100×10^4	22	0.23	110×10^4	22	0.23
CD_4 = 4.0	3.35	19.2	48.2	92.5	0.65 × 949	99.0	100×10^4	22	0.23	110×10^4	22	0.23
α_c = 0.005	3.35	19.2	48.2	190.5	0.92 × 1402	87.6	168×10^4	21	0.11	182×10^4	21	0.11
FRICTN = 0.10	3.35	19.2	48.2	71.6	0.75 × 846	100.0	81×10^4	23	0.29	90×10^4	23	0.29
F1 = 1.0	3.35	19.2	48.2	71.6	0.75 × 846	100.0	81×10^4	23	0.29	90×10^4	23	0.29
λ_H = 0.05	3.35	19.2	48.2	68.5	0.66 × 932	94.4	169×10^4	23	0.12	182×10^4	23	0.12
λ_V = 0.50	3.35	19.2	48.2	92.5	0.65 × 949	94.0	100×10^4	26	0.20	110×10^4	26	0.20

Table 4

Model Input for New York Hopper Dredge Disposal Operation

Number of grid points in z-direction = 25

Number of grid points in x-direction = 25

Grid spacing = 150 ft

Constant depth of 85.3 ft

Disposal initiated at x = 1200 ft and z = 2250 ft

Course = 225 deg

Hopper dredge velocity = 4.63 ft/sec

Volume rate of discharge = 1750 ft^3/sec

Initial radius of jet = 5.05 ft

Depth of discharge point = 27 ft

Angle of discharge = 90 deg

Duration of discharge = 120 sec

Long-term time step = 450 sec

Bulk density of disposed material = 1.30 g/cc

Characterization of Material

Description	Density gm/cc	Concentration ft^3/ft^3	Fall Velocity ft/sec
Silty-clay	2.60	0.1880	0.01
Fluid	1.00	0.8120	0.0

Ambient Conditions

Depth ft	Density g/cc	x Velocity ft/sec	z Velocity ft/sec
0	1.021		
2.5		1.170	0.250
40	1.022		
51	1.023		
61	1.023		
63	1.025		
65	1.026		
75	1.026		
82		0.280	-0.280
85.3	1.026		

Table 5

Default Values of Continuous Discharge Model Coefficients

Coefficient	Default Value
α_1	0.0806
α_2	0.3536
β	0.0
CD	1.3
γ	0.25
CDRAG	1.0
CFRIC	0.01
CD_3	0.20
CD_4	2.0
α_3	0.3536
α_4	0.001
FRICTN	0.01
F1	0.10
CM	1.0
λ_H	0.005
λ_V	0.05

Table 6

Sensitivity Results for Continuous Hopper Dredge Disposal in New York Bight

Coefficient	t_{CONV}	V_{CONV}	R_{CONV}	t_{COLL}	$A \times B_{COLL}$	% Solids on Bottom @450 sec	Area of TR Cloud @900 sec	Avg. Thick. of TR Cloud @900 sec	Max. Conc of TR Cloud @900 sec	Area of TR Cloud @1350 sec	Avg. Thick. of TR Cloud @1350 sec	Max. Conc of TR Cloud @1350 sec
Default Values	2.90	15.1	11.02	27.90	0.24 × 263.5	100	324×10^4	23	0.11	380×10^4	23	0.11
α_1 = 0.20	3.72	9.8	18.8	51.94	0.34 × 441	100	504×10^4	24	0.086	648×10^4	24	0.086
α_2 = 0.75	2.97	13.8	12.20	31.35	0.25 × 296.6	100	324×10^4	24	0.10	380×10^4	24	0.10
β = 0.50	2.90	15.1	11.02	29.21	0.22 × 280	100	324×10^4	37	0.07	380×10^4	37	0.07
CD = 3.0	2.97	14.7	11.40	34.0	0.35 × 176	100	182×10^4	24	0.31	202×10^4	24	0.31
γ = 0.75	2.90	15.1	11.02	27.90	0.24 × 263.5	100	324×10^4	23	0.11	380×10^4	23	0.11
CDRAG = 2.0	2.90	15.1	11.02	32.48	0.29 × 183.4	100	202×10^4	37	0.17	222×10^4	37	0.17
CFRIC = 0.02	2.90	15.1	11.02	24.29	0.31 × 223	100	247×10^4	37	0.10	*	*	*
CD_3 = 1.0	2.90	15.1	11.02	27.92	0.24 × 265	100	324×10^4	23	0.11	380×10^4	23	0.11
CD_4 = 4.0	2.90	15.1	11.02	27.90	0.24 × 263	100	324×10^4	23	0.11	380×10^4	23	0.11
α_3 = 0.75	2.90	15.1	11.02	27.90	0.24 × 263.5	100	324×10^4	23	0.11	380×10^4	23	0.11
α_4 = 0.005	2.90	15.1	11.02	22.72	0.17 × 598	100	607×10^4	37	0.045	726×10^4	37	0.045
FRICTN = 0.10	2.90	15.1	11.02	28.44	0.35 × 176	100	182×10^4	23	0.32	202×10^4	23	0.32
F1 = 1.0	2.90	15.1	11.02	25.98	0.33 × 200	100	247×10^4	24	0.15	322×10^4	24	0.15
CM = 1.5	2.90	15.1	11.02	46.74	0.20 × 296	100	504×10^4	23	0.089	648×10^4	23	0.089
λ_H = 0.05	2.90	15.1	11.02	27.26	0.25 × 263	100	504×10^4	37	0.055	855×10^4	37	0.055
λ_V = 0.50	2.90	15.1	11.02	27.90	0.24 × 263.5	100	324×10^4	24	0.10	380×10^4	24	0.10

* Computer run "blew up."

Table 7

Current Data at the Duwamish Disposal Site

Time sec	Direction deg from N	Magnitude knots	Time sec	Direction deg from N	Magnitude knots
0	340	6.73	45,600	332	5.04
1,200	357	6.30	46,800	355	5.04
2,400	302	8.02	48,000	1	7.59
3,600	335	6.73	49,200	1	5.04
4,800	347	6.73	50,400	356	2.52
6,000	345	6.30	51,600	242	8.88
7,200	354	8.02	52,800	250	2.52
8,400	8	12.32	54,000	197	6.30
9,600	9	6.73	55,200	137	8.02
10,800	65	7.16	56,400	164	6.73
12,000	67	2.52	57,600	166	7.59
13,200	57	3.78	58,800	122	7.16
14,400	42	7.16	60,000	73	8.45
15,600	25	8.45	61,200	52	9.74
16,800	34	10.60	62,400	14	8.02
18,000	17	3.78	63,600	14	7.59
19,200	2	6.30	64,800	0	7.59
20,400	0	3.78	66,000	340	8.02
21,600	307	8.02	67,200	337	6.73
22,800	265	12.32	68,400	315	8.45
24,000	270	11.89	69,600	285	11.89
25,200	272	11.46	70,800	275	14.90
26,400	274	11.03	72,000	265	13.18
27,600	280	8.88	73,200	267	12.75
28,800	280	8.45	74,400	272	8.45
30,000	283	10.17	75,600	277	7.59
31,200	289	7.16	76,800	277	6.73
32,400	298	5.04	78,000	282	6.73
33,600	313	3.78	79,200	289	5.04
34,800	332	7.16	80,400	290	5.04
36,000	57	8.02	81,600	290	5.04
37,200	54	6.30	82,800	275	6.73
38,400	51	8.45	84,000	291	8.02
39,600	49	8.02	85,200	317	8.45
40,800	37	7.59	86,400	340	8.88
42,000	24	7.16	87,600	2	8.45
43,200	317	6.30	88,800	7	8.45
44,400	337	6.30	90,000	27	8.02

Table 8

Water Depths at the Duwamish Disposal Site

M	N = 1	N = 2	N = 3	N = 4	N = 5	N = 6	N = 7	N = 8	N = 9	N = 10	N = 11
1	198	194	199	200	200	200	199	198	199	201	206
2	197	198	199	200	199	199	199	199	198	200	204
3	198	200	200	200	200	200	199	198	198	199	201
4	198	198	199	199	198	198	198	198	198	198	200
5	198	198	198	199	198	198	198	198	198	197	200
6	196	198	198	200	198	198	198	199	197	196	197
7	196	197	198	198	199	199	198	198	198	197	196
8	196	196	198	198	198	198	198	198	198	197	197
9	195	195	197	198	198	198	198	197	198	197	197
10	194	194	194	195	196	196	196	196	196	196	196
11	195	195	194	195	195	195	195	195	195	194	194
12	195	194	194	194	194	194	194	194	194	192	193
13	191	192	192	193	192	192	192	193	192	192	193
14	184	184	185	187	187	189	190	189	189	190	192
15	181	180	181	182	183	183	184	185	186	188	189
16	179	178	180	179	180	180	180	182	183	185	186
17	178	178	178	178	179	179	179	180	180	183	185
18	177	176	174	176	176	178	178	179	180	182	183
19	176	175	173	174	174	173	175	176	177	178	178
20	176	173	173	172	172	172	173	173	175	176	176
21	175	173	173	171	171	171	171	172	173	173	175

M	N = 12	N = 13	N = 14	N = 15	N = 16	N = 17	N = 18	N = 19	N = 20	N = 21
1	216	221	223	224	225	226	227	228	229	230
2	210	215	220	223	223	223	225	226	227	228
3	206	213	218	220	222	223	223	223	225	226
4	204	209	216	218	219	220	220	221	220	222
5	204	209	215	217	218	218	219	219	220	221
6	199	206	214	218	218	217	217	219	219	219
7	198	203	211	219	219	217	217	218	218	219
8	199	203	210	219	219	218	217	217	216	217
9	199	204	210	217	216	216	216	216	216	214
10	197	200	206	213	215	214	215	214	213	213
11	194	196	199	208	214	215	214	213	213	212
12	195	197	202	208	212	211	212	210	210	210
13	194	197	201	204	209	210	209	209	208	208
14	193	194	197	200	206	207	206	206	205	205
15	190	191	192	196	200	205	205	204	202	203
16	187	188	190	192	195	201	202	201	200	200
17	186	186	189	190	195	199	198	197	196	196
18	183	185	187	190	195	198	198	197	196	195
19	180	181	182	185	188	192	192	192	191	192
20	176	178	181	184	185	187	187	187	188	188
21	176	176	179	182	182	183	183	184	184	184

Table 9

Input Data for Application of the Instantaneous Dump Model at the Duwamish Diposal Site

Number of long-term grid points in x-direction = 21

Number of long-term grid points in z-direction = 21

Grid spacing = 100 ft

Dump made at x = 1,100 ft and z = 1,150 ft

Time of dump = 65,000 sec into tidal cycle

Duration of simulation = 1,500 sec

Long-term time step = 500 sec

Ambient Conditions

Depth, ft	Density, g/cc
0	1.018
20	1.018
80	1.019
125	1.022
171	1.022
189	1.023
231.3	1.023

Initial radius of cloud = 19 ft

Initial depth of cloud centroid = 5 ft

Initial cloud velocity = $0.0\hat{i} + 2.0\hat{j} + 0.0\hat{k}$

Bulk density of disposed material = 1.50 g/cc

Characterization of Material

Description	Density g/cc	Concentration ft^3/ft^3	Fall Velocity ft/sec
Sand	2.60	0.1395	0.07
Silty-clay	2.60	0.1705	0.02
Fluid	1.00	0.6900	0.0

Table 10

Summary of Calibration Results at the Duwamish Disposal Site

Event	Computed	Recorded
Time to bottom encounter	24 sec	25-30 sec
Speed of surge front at 160 ft from point of dump	19 cm/sec	20 cm/sec
Suspended sediment concentration after 600 sec at 300 ft from the point of dump	--	64 mg/ℓ
Suspended sediment concentration after 1000 sec at 300 ft from the point of dump	42 mg/ℓ	--
Rate of decrease in suspended sediment concentration	0.0310 mg/ℓ/sec	0328 mg/ℓ/sec

Table 11

Summary of Calibration Results at the New York Bight Disposal Site

Event	Computed	Recorded
Distance of bottom surge front from the point of dump after 70 sec	350 ft	300 ft
Distance of bottom surge front from the point of dump after 250 sec	685 ft	800 ft
Suspended sediment concentration after 138 sec at 300 ft from point of dump	--	7.5 g/ℓ
Average suspended sediment concentration of the cloud after 450 sec	6.2 g/ℓ	--
Suspended sediment concentration after 900 sec at 300 ft from point of dump	≈0.0	--
Suspended sediment concentration after 1000 sec at 300 ft from point of dump	--	≈ 0.0

Table 12

Input Data for the Continuous Discharge Model at the Lake Ontario Site

Number of grid points in x-direction = 20

Number of grid points in z-direction = 20

Grid spacing = 100 ft

Constant depth = 58 ft

Duration of simulation = 100 sec

Duration of discharge = 10 sec (first run)
= 30 sec (second run)

Long-term time step = 100 sec

Volume rate of discharge = 51.97 ft^3/sec

Initial radius = 2.11 ft

Depth of discharge = 12.75 ft

Angle of discharge = 90 deg

Disposal initiated at x = 1000 ft and z = 1000 ft

Hopper dredge velocity = 0.0

Density of disposed material = 1.50 g/cc (first run)
= 1.17 g/cc (second run)

Characterization of Material

Description	Density g/cc	Concentration ft^3/ft^3	Fall Velocity ft/sec
Clumps	2.60	0.0780	2.00
Sand	2.60	0.0470	0.07
Silt	2.60	0.1870	0.01
Fluid	1.00	0.6880	0.0

Ambient Conditions

Depth ft	Density g/cc	x Velocity ft/sec	z Velocity ft/sec
0	1.000		
30		0.180	0.180
57		0.110	0.110
58	1.000		

Table 13

Input Data for the Instantaneous Dump Model at the Lake Ontario Site

Number of grid points in x-direction = 20

Number of grid points in z-direction = 20

Grid spacing = 100 ft

Constant depth = 58 ft

Dump initiated at x = 1000 ft and z = 1000 ft

Duration of simulation = 1300 sec

Time step = 650 sec

Initial radius of cloud = 27.6 ft

Initial depth of cloud centroid = 30.6 ft

Initial cloud velocity = $0.0\hat{i} + 2.61\hat{j} + 0.0\hat{k}$

Bulk density = 1.091 g/cc

Characterization of Material

Description	Density g/cc	Concentration ft^3/ft^3	Fall Velocity ft/sec
Sand	2.60	0.0090	0.07
Silty-clay	2.60	0.0480	0.0017
Fluid	1.00	0.9430	0.0

Entrainment rate = 3728 ft^3/sec

Density of entrained fluid = 1.0106 g/cc

Time entrainment continues = 31.1 sec

x-velocity of entrained fluid = 0.0

z-velocity of entrained fluid = 0.0

Ambient Conditions

Depth ft	Density g/cc	x Velocity ft/sec	z Velocity ft/sec
0	1.000		
30		0.180	0.180
57		0.110	0.110
58	1.000		

Table 14

Summary of Calibration Coefficients

Location of Operation	Mode of Disposal and Volume	Water Depth	Material Description	Convective Descent Coefficients Varied			Bottom Collapse Coefficients Varied		
				Coeff	Default	Final	Coeff	Default	Final
Duwamish Waterway	Instantaneous barged dump of 530 cu yd	≈ 200 ft	14% Sand 17% Clay Bulk density = 1.50 g/cc	CD	0.50	1.0	CDRAG	1.0	1.75
New York Bight	Instantaneous scow dump of 3900 cu yd	85 ft	11% "Clumps" 26% Silt-clay Bulk density = 1.60 g/cc	CD	0.50	1.0	CDRAG α_c FRICTN	1.0 0.001 0.01	5.0 0.04 0.075
				Jet Convection Coefficients					
Lake Ontario	Continuous discharge from stationary hopper dredge for 45 sec @ 365 cfs, modeled by using both models.	Two disposal operations at 58 and 87 ft, respectively	Bulk density ranged from 1.07 g/cc at the top of the hoppers to 1.70 near the bottom	α_1 ADDRAG	0.0806 "New Coeff" · (1.0)	0.20 1.50	CDRAG α_c FRICTN	1.0 0.001 0.01	5.0 0.04 0.10
				Instantaneous Descent Coefficients					
				α_o	0.235	0.650			

APPENDIX A: INSTANTANEOUS DUMP INPUT

1. NMAX, MMAX, NS, NVL, NSC (16I5)

    NMAX - Number of grid points in z-direction of long-term grid

    MMAX - Number of grid points in x-direction of long-term grid

    NS - Number of solid components

    NVL - Number of velocity layers

    NSC - Number of small clouds allowed for each solid component (value of 20 suggested)

2. KEY1, KEY2, KEY3, KEY4 (16I5)

    KEY1 = 1 - Use default coefficients
    = 2 - Read coefficients as input

    KEY2 = 1 - Computations stop at end of convective descent
    = 2 - Computations stop at end of dynamic collapse
    = 3 - Computations stop at end of long-term diffusion

    KEY3 = 1 - Long-term diffusion for chemical constituent
    = 0 - No long-term diffusion for chemical constituent

    KEY4 = 0 - No action
    = 1 - Input specified time steps for convective descent and collapse

3. IGCN, IGCL, IPCN, IPLT (16I5)

    IGCN = 0 - No graphs of convective descent
    = 1 - One line printer graph of convective descent
    = 2 - Extra graphs of concentrations for convective phase

    IGCL = 0 - No graphs of dynamic collapse
    = 1 - One line printer graph

    IPCN = 0 - No printed record of convective descent phase
    = 1 - Printed output included

    IPCL = 0 - No printed record of dynamic collapse phase
    = 1 - Printed output included

    IPLT = 0 - Print long-term results at default times (1/4, 2/4, 3/4, 4/4 of TSTOP)
    = n - Number of values to be read in of times to print long-term results (up to 12)

4. ID (8A10)

ID - Free-form alphanumeric description of run

5. DX (8E10.0)

DX - Spatial step (ft) for long-term grid

6. IDEP, DEPC (I10,F10.0)

IDEP = 1 - This is a constant depth run and DEPC = the depth
= 0 - Variable depths will be read as input

DEPC - If IDEP = 1, set = constant depth

NOTE: Omit cards 7 if IDEP = 1

7. ((DEPTH(N,M), M = 1, MMAX), N = 1, NMAX) (16F5.0)

DEPTH(N,M) - Depths at grid points of horizontal grid - Read in row by row, left to right, top to bottom

8. XBARGE, ZBARGE (8E10.0)

XBARGE - X-coordinate of discharging vessel in estuary

ZBARGE - Z-coordinate of discharging vessel in estuary

9. NROA (16I5)

NROA - Number of points (in depth) where ambient density is specified

10. (Y(I), I = 1, NROA) (8E10.0)

y(I) - Depths (feet from surface) where density is specified (the final value should equal the deepest depth in the estuary)

11. (ROA(I), I = 1, NROA) (8E10.0)

ROA(I) - Density (g/cc) of ambient water

12. IFORM (16I5)

IFORM - This is an indicator of the ambient velocity interpretation. Set to one of the following values. See Brandsma and Divoky[3] for more details*

---

* See text for references and figures cited in appendices.

= 1 - One-layer flow variable in horizontal and in time. Vertically averaged velocities are read from logical unit 7 (LUN7) at each long-term time step

= 2 - Same as above except that velocity profiles are assumed to be logarithmic such that the average over the vertical equals the read in value

= 3 - Two-layer flow variable horizontally, vertically, and in time. These are interpreted as described in Brandsma and Divoky.[3]

= 4 - Two-layer flow, constant depth case. Velocity specification is one pair of velocity profiles as shown in Figure 4. These profiles are assumed constant in the horizontal and invariant in time

NOTE: Omit card 13 if IFORM ≠ 4

13. DU1, DU2, UU1, UU2, DW1, DW2, WW1, WW2 (8E10.0)

NOTE: See Figure 4

DU1 - Depth (ft) to upper U velocity (x-direction)

DU2 - Depth (ft) to lower U velocity

UU1 - Upper U velocity (ft/sec)

UU2 - Lower U velocity (ft/sec)

DW1 - Depth (ft) to upper W velocity (z-direction)

DW2 - Depth (ft) to lower W velocity

WW1 - Upper W velocity (ft/sec)

WW2 - Lower W velocity (ft/sec)

14. TDUMP, TSTOP, DTL (8E10.0)

TDUMP - Time of dump to nearest DTL seconds after start of tidal cycle (sec)

TSTOP - Duration to nearest DTL seconds of simulation after dump (sec)

DTL - Long-term time step (sec) - Time varying velocities are specified at this interval

NOTE: Omit card 15 if KEY4 = 0

15. DT1U, DT2U (8E10.0)

DT1U - User-specified time step for convective descent phase (used for repeated runs)

DT2U - User-specified time step for dynamic collapse (used for repeated runs)

NOTE: Omit card 16 if IDLT = 0

16. (TPRT (I), I = 1, IPLT) (8E10.0)

TPRT(I) - Values of times in seconds to print long-term results (must be integer multiples of the long-term time step)

17. RB, DREL, CU(1), CV(2), CW(1), ROO, BVOID (8E10.0)

RB - Radius of initial hemispherical waste cloud (ft)

DREL - Depth of centroid of initial cloud at release (ft)

CU(1) - Initial velocity components of the cloud in x-, y-, and
CV(1) z-directions
CW(1)

ROO - Bulk density of initial cloud (g/cc)

BVOID - Voids ratio of aggregate solids

18. PARAM(K), ROAS(K), CS(K), VFALL(K), VOIDS(K), ICOHES(K) (A10,4F10.0,I5)

PARAM(K) - Alphanumeric description of solid (10 characters maximum)

ROAS(K) - Solid density (g/cc, dry weight) of particle

CS(K) - Concentration of these particles in volume ratio

VFALL(K) - Fall velocity of these particles (ft/sec)

VOIDS(K) - Voids ratio of these particles

ICOHES(K) = 1 - This solid fraction is cohesive
= 0 - Noncohesive

NOTE: Card 18 will be repeated for each solid fraction

19. TRACER, CINIT, CBACK (A10,2E10.0)

TRACER - Alphanumeric description of conservative chemical tracer in initial fluid fraction

CINIT - Concentration of tracer in initial fluid (mg/ℓ)

CBACK - Background concentration in ambient fluid (mg/ℓ)

NOTE: If the model is not being used in conjunction with the continuous discharge model, insert a blank card for card 20

20. ERATE, EROO, ECON, ETIME, EUA, EWA (6F10.0)

DRATE - Rate (in ft^3/sec) at which fluid from the continuous discharge is fed into the bottom collapse

EROO - Density (in g/cc) of the entrained fluid

ECON - Concentration (in mg/ℓ) of the conservative chemical constituent in the entrained fluid

ETIME - Total time (in sec) for entraining fluid from the continuous discharge

EUA - X-velocity (in ft/sec) of the entrained fluid

EWA - Z-velocity (in ft/sec) of the entrained fluid

NOTE: If KEY1 ≠ 2, omit cards 21, 22, 23, 24

21. DINCR1, DINCR2 (8E10.0)

DINCR1 - Factor used for estimating time step in convective descent

DINCR2 - Factor used for estimating time step in dynamic collapse

22. ALPHAO, BETA, CM, CD (8E10.0)

ALPHAO - Entrainment coefficient for turbulent thermal

BETA - Settling coefficient

CM - Apparent mass coefficient

CD - Drag coefficient for a sphere

23. GAMA, CDRAG, DFRIC, CD3, CD4, ALPHAC, FRICTN, F1 (8E10.0)

GAMA - Density gradient factor in the cloud

CDRAG - Form drag coefficient for the quadrant of a collapsing oblate spheroid

CFRIC - Skin friction coefficient for the quadrant of a collapsing oblate spheroid

CD3 - Drag coefficient for an ellipsoidal wedge

CD4 - Drag coefficient for a plate

ALPHAC - Entrainment coefficient for collapse

FRICTN - Friction coefficient between cloud and estuary bottom

F1 - Modification factor used in computing the resistance of the friction force to the collapse or a quadrant of an oblate spheroid

24. ALAMDA, AKYO (8E10.5)

ALAMDA - Dissipation factor used in computing horizontal diffusion coefficients by four-thirds law

AKYO - Maximum value of vertical diffusion coefficient

APPENDIX B: CONTINUOUS DISCHARGE INPUT

1. NMAX, MMAX, NS, NVL, NSC (16I5)

NMAX - Maximum dimension of long-term passive diffusion grid in z-direction

MMAX - Maximum dimension of long-term passive diffusion grid in x-direction

NS - Number of solid components in discharge (not greater than 12)

NVL - Number of velocity levels in velocity arrays (must be 1 or 2)

NSC - Maximum number of small clouds allowed per component for transition from short term to long term (value of 50 suggested)

2. KEY1, KEY2, KEY3 (16I5)

KEY1 = 1 - Use default coefficients suggested by Tetra Tech
= 2 - Use coefficients suggested by user

KEY2 = 1 - Fixed pipeline discharge
= 0 - Discharge from moving vessel

KEY3 = 1 - Long-term diffusion for fluid component
= 0 - No long-term diffusion for fluid component
= 2 - Computations terminate at end of collapse

3. IGCN, IGCL, IPCN, IPCL, IPLT (16I5)

IGCN = 0 - No graphs of convective descent phase
= 1 - Two line printer graphs of convective descent
= 2 - Extra graphs of concentrations for convective descent

IGCL = 0 - No graphs of dynamic collapse
= 1 - Two-line printer graphs of dynamic collapse

IPCN = 0 - No printed record of convective descent phase
= 1 - Printed output included

IPCL = 0 - No printed record of dynamic collapse phase
= 1 - Printed output included

IPLT = 0 - Print long-term results at default times (1/4, 2/4, 3/4, 4/4 of TSTOP)
= n - Number of values to be read in of times to print long-term results (up to 12)

4. ID (8A10)

ID - Free-form alphanumeric description of run

5. DX (8E10.0)

DX - Spatial step (in ft) for long-term grid

6. IDEP, DEPC (I10,F10.0)

IDEP = 1 - This is a constant depth run and DEPC = the depth
= 0 - Variable depths will be read as input

DEPC - If IDEP = 1, set = constant depth

NOTE: Omit cards 7 if IDEP = 1

7. ((DEPTH(N,M), M = 1, MMAX), N = 1, NMAX) (16F5.0)

DEPTH(N,M) - Depths at grid points of horizontal grid. Read in row by row, left to right, top to bottom

8. TSJ, TSTOP, DTL, TJET (8E10.0)

TSJ - Time that jet discharge begins (measured in sec from start of tidal cycle). Barge is at position (XBARGE, ZBARGE) at this time

TSTOP - Duration of simulation (in sec)--the maximum time elapsed from beginning of jet discharge to which material will be tracked (this is an integer multiple of DTL).

DTL - Long-term time step (sec). This is the time increment for passive diffusion. DTL should be set so that it is greater than the maximum time required for the discharged material to go through convective descent and dynamic collapse

TJET - Duration of jet discharge (sec)

9. VDOT, BC(1), DJET, ANGLE, ROI, BVOID (8E10.0)

VDOT - Volume rate of jet discharge of dredged material slurry (ft^3/sec)

BC(1) - Initial radius of jet (ft)

DJET - Depth of discharge nozzle (ft)

ANGLE - Vertical angle of discharge (deg below horizontal). The azimuth of discharge is assumed to be 180 deg away from the vessel course SAI on card 10

ROI - Bulk density of dredged material slurry at discharge nozzle (g/cm^3)

BVOID - Aggregate voids ratio

10. XBARGE, ZBARGE, SAI, UB (8E10.0)

XBARGE - X-coordinate of discharging vessel in estuary coordinates at time of start of discharge

ZBARGE - Z-coordinate of discharging vessel in estuary coordinates at time of start of discharge

SAI - Straight course maintained by discharging vessel during discharge (measured in degrees anti-clockwise from positive X axis)

UB - Constant speed of discharging vessel (measured in ft/sec with respect to surface water). This parameter should be set to 0 for a fixed discharge

11. PARAM(K), ROAS(K), CS(K), VFALL(K), VOIDS(K), ICOHES(K) (A10,4F10.0,I5)

PARAM(K) - Alphanumeric description of solid (10 characters maximum)

ROAS(K) - Solid density (g/cm^3, dry weight) of these particles

CS(K) - Concentration of these particles in volume ratio

VFALL(K) - Fall velocity of these particles (ft/sec)

VOIDS(K) - Voids ratio of these particles (used only in estimating final thickness on bottom)

ICOHES(K) = 1 - This solid fraction is cohesive
= 0 - Noncohesive

NOTE: Card 11 is repeated for each solid fraction

12. TRACER, CINIT, CBACK (A10,2E10.0)

TRACER - Alphanumeric description of conservative chemical tracer in initial fluid fraction

CINIT - Concentration of tracer in initial fluid (mg/ℓ)

CBACK - Background concentration in ambient fluid (mg/ℓ)

NOTE: <u>Omit cards 13, 14, 15, and 16 if KEY1 = 1</u>

13. DINCR1, DINCR2 (8E10.0)

DINCR1 - Trial value used in obtaining distance steps DS for the integration in the jet convection phase. DS = DINCR x (initial jet radius)

DINCR2 - Trial value used in obtaining initial distance step DS for the integration in the dynamic collapse phase. DS = DINCR2 x (jet radius at end convective descent)

14. ALPHA1, ALPHA2, BETA, CD (8E10.0)

ALPHA1 - Entrainment coefficient for momentum jet

ALPHA2 - Entrainment coefficient for two-dimensional thermal

BETA - Settling coefficient for solid particles

CD - Drag coefficient for a cylinder

15. GAMA, CDRAG, CFRIC, CD3, CD4, ALPHA3, ALPHA4, FRICTN, F1, CM (8E10.0)

GAMA - Density gradient factor in collapsing plume. Density gradient inside plume at start of collapse is assumed to be BAMA times local ambient density gradient

CDRAG - Form drag coefficient for the quadrant of a collapsing elliptical cylinder

CFRIC - Skin drag coefficient for the quadrant of a collapsing elliptical cylinder

CD3 - Drag coefficient for an elliptical wedge

CD4 - Drag coefficient for a two-dimensional plate

ALPHA3 - Entrainment coefficient in collapse phase associated with convection of the cloud

ALPHA4 - Entrainment coefficient in collapse phase associated with spreading of the cloud

FRICTN - Friction coefficient between cloud and ocean bottom

F1 - Modification factor used in computing the resistance of the friction force to the quadrant of an elliptical cylinder

CM - Apparent mass coefficient

16. ALAMDA, AKYO, ADDRAG (8E10.0)

ALAMDA - Dissipation factor used in computing horizontal diffusion coefficient by four-thirds law

AKYO - Maximum value of vertical diffusion coefficient

ADDRAG - Drag coefficient for the additional drag force for the case of a stationary vertical discharge. Default value is set to 1.0

17. NPROF, NROA, DTROA (2I5,E10.0)

NPROF - Number of successive long-term time steps for which density profiles are to be read. Each profile is that perceived from the discharging vessel at the start of a particular time step. If the vessel continues to discharge after the last DTL for which a profile is given, the most recent profile will be used. NPROF = 1 implies a constant profile over time (maximum value 50)

NROA - Number of points in each profile. This is the same for all profiles. Range is from 2 through 8

DTROA - Time interval (sec) between density profiles (must be integer multiple of DTL)

18. (YROA(I,N), I = 1, NROA) (8E10.0)

YROA(I,N) - Depths (in ft) below water surface at which densities are specified for the N'th density profile

19. (ROAP(I,N), I = 1, NROA) (8E10.0)

ROAP(I,N) - Densities (in g/cc) at the points above

NOTE: Cards 18 and 19 are repeated as pairs for each density profile

20. IFORM (16I5)

IFORM - This is an indicator of the ambient velocity interpretation. Set to one of the following values

= 1 - One-layer flow variable in the horizontal and in time. Vertically averaged velocities are read from logical unit 7 (TAPE7) at each long-term time step

= 2 - Same as above except that velocity profiles are assumed to be logarithmic such that the average over the vertical equals the read in value

= 3 - Two-layer flow variable horizontally, vertically, and in time. These are interpreted as described in Brandsma and Divoky[3]

= 4 - Two-layer flow, constant depth case. Velocity specification is one pair of velocity profiles as shown in Figure 4. These profiles are assumed constant in the horizontal and invariant in time

NOTE: Omit card 21 if IFORM ≠ 4

21. DU1, DU2, UU1, UU2, DW1, DW2, WW1, WW2 (8E10.0)

DU1 - Depth (ft) to upper U velocity (x-direction)

DU2 - Depth (ft) to lower U velocity

UU1 - Upper U velocity (ft/sec)

UU2 - Lower U velocity (ft/sec)

DW1 - Depth (ft) to upper W velocity (z-direction)

DW2 - Depth (ft) to lower W velocity

WW1 - Upper W velocity (ft/sec)

WW2 - Lower W velocity (ft/sec)

NOTE: If IPLT = 0, omit card 22

22. (TPRT(I), I = 1, IPLT) (8E10.0)

TPRT(I) - Values of times (in sec) to print long-term results

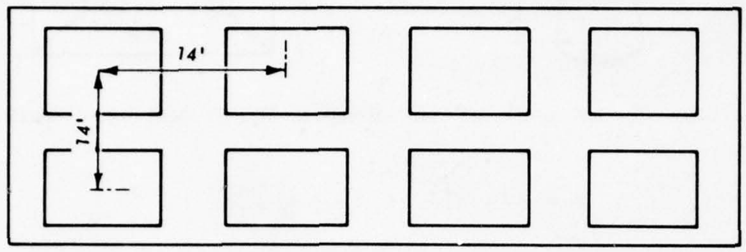
APPENDIX C: LISTING OF PROGRAM TO GENERATE THE VELOCITY TAPE AT THE DUWAMISH DISPOSAL SITE

```
      PROGRAM VTAPE(INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT,TAPE7)
C     ********************************IMPORTANT  ******************************
C     THE COORDINATE SYSTEM IN THIS PROGRAM IS  THE STANDARD RECTANGULAR
C     CARTESIAN SYSTEM.  DONOT FORGET TO ADJUST VELOCITY DATA TO THIS SYSTEM
C     *************************************************************************
      DIMENSION U(31,31),W(31,31),DEG(150),VEL(150),DEPTH(31,31),
     1UP(31,31),WP(31,31),TR(150),PRINT(100)
      READ(5,10)TITLE
   10 FORMAT(A80)
      WRITE(6,10)TITLE
      READ(5,15)NMAX,MMAX,NPRINT
   15 FORMAT(3I5)
      READ(5,20)HI,DT,DTRVEL
   20 FORMAT(3F10.0)
      DO 30 M=1,MMAX
      READ(5,200)(DEPTH(N,M),N=1,NMAX)
      WRITE(6,26)(DEPTH(N,M),N=1,NMAX)
   26 FORMAT(//,3H H ,25F5.0,/,3X,6F5.0)
   30 CONTINUE
  200 FORMAT(16F5.0)
      IR=90000./DTRVEL+0.0001
      TR(1)=0.0
      IR1=IR+1
      DO 35 I=1,IR1
      READ(5,20) DEG(I),VEL(I)
      DEG(I)=DEG(I)*0.01749
      VEL(I)=VEL(I)*1.69
   35 CONTINUE
      READ(5,5)(PRINT(I),I=1,NPRINT)
    5 FORMAT(8F10.0)
      DO 37 I=2,IR1
   37 TR(I)=TR(I-1)+DTRVEL
      DTL=DT
      DAY=90000.
      NT=DAY/DTL+0.0001
C     LOOP ON TIME VALUES
      T=-DTL
      K=1
      DO 100 L=1,NT
      T=T+DTL
      IF(ABS(T) .LT. 0.01)T=0.
      WRITE(7)T
C     SET VELOCITIES FOR THIS TIME STEP
      DO 150 I=1,IR1
      J=I
      IF(T .LE. TR(I))GO TO 160
  150 CONTINUE
  160 CONTINUE
      DO 300 M=1,MMAX
      DO 302 N=1,NMAX
      IF(J .GT. 1)U(N,M)=(VEL(J)*SIN(DEG(J))*(DTRVEL-(TR(J)-T))+
     1VEL(J-1)*SIN(DEG(J))*(TR(J)-T))/DTRVEL
      IF(J .GT. 1)W(N,M)=(VEL(J)*COS(DEG(J))*(DTRVEL-(TR(J)-T))+
     1VEL(J-1)*COS(DEG(J))*(TR(J)-T))/DTRVEL
      IF(J .EQ. 1)U(N,M)=VEL(1)*SIN(DEG(1))
      IF(J .EQ. 1)W(N,M)=VEL(1)*COS(DEG(1))
      UP(N,M)=U(N,M)*HI/DEPTH(N,M)
      UP(N,M)=-UP(N,M)
  302 WP(N,M)=W(N,M)*HI/DEPTH(N,M)
      IF(T .NE. PRINT(K))GO TO 300
      IF(M .EQ. MMAX)K=K+1
      IF(M .EQ. 1)WRITE(6,110)T
```

```
  110 FORMAT(//,2X,5HTIME=,F10.0,2X,3HSEC)
      WRITE(6,36)(UP(N,M),N=1,NMAX)
      WRITE(6,38)(WP(N,M),N=1,NMAX)
  300 CONTINUE
  36  FORMAT(/,3H U ,25F5.2,/,3X,6F5.2)
  38  FORMAT(/,3H W ,25F5.2,/,3X,6F5.2)
C     WRITE VELOCITIES ON TAPE
      WRITE(7)((UP(N,M),N=1,NMAX),M=1,MMAX),
     1  ((WP(N,M),N=1,NMAX),M=1,MMAX)
  100 CONTINUE
      WRITE(7)DAY
      ENDFILE7
      REWIND7
      CALL EXIT
      END
```

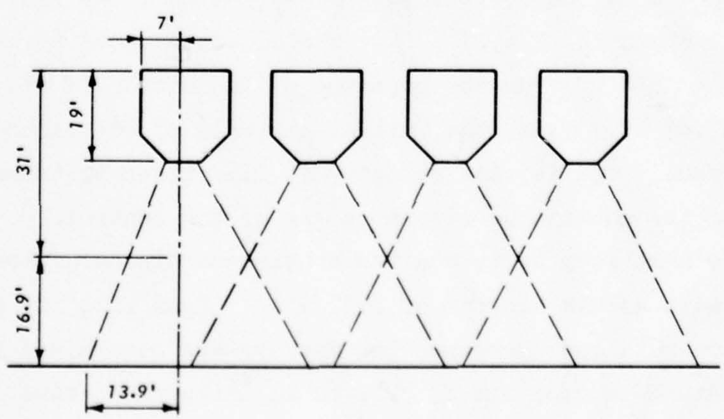
APPENDIX D: EXAMPLE PROBLEM COMBINING RESULTS FROM BOTH DREDGED MATERIAL MODELS

1. The following is a plan view of the hopper dredge.



Assume the total load discharged is 575 cu yd; also assume that the average density of the material in the lower one third of each hopper is 1.50 g/cc, while that of the upper two thirds is 1.17 g/cc and that 45 sec is required for the complete disposal operation. Remember that the dredge is stationary and all eight doors are opened simultaneously.

2. The first step is to run the continuous discharge model for the case of a single door being open, using 1.50 g/cc as the bulk density of the material. From this run the position in the water column where the jets interact can be determined. In addition, an estimate of the area impacted at the bottom is provided. For the example problem considered, i.e., disposal at the Lake Ontario site, the following results were obtained.



AD-A059 991 ARMY ENGINEER WATERWAYS EXPERIMENT STATION VICKSBURG MISS F/G 13/2
EVALUATION AND CALIBRATION OF THE TETRA TECH DREDGED MATERIAL D--ETC(U)
AUG 78 B H JOHNSON, B W HOLLIDAY
UNCLASSIFIED WES-TR-D-78-47 NL

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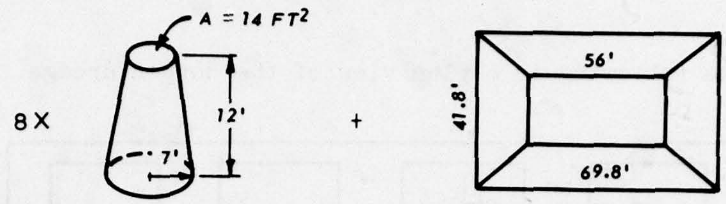
3. The volume of the hemispherical cloud is then computed from



where the volume V of each of the shapes above can be determined from

$$V = 1/3\, h\left(A_1 + A_2 + \sqrt{A_1 A_2}\right) \qquad \text{(D1)}$$

where

h = the perpendicular distance between the two faces.

A_1 and A_2 = areas of the upper and lower faces.

Therefore, the total volume computed is 44,109 ft^3.

4. To account for all the solids, it is assumed that the complete volume of solids contained in all hoppers is contained in the computed volume above. Therefore, based upon 376 ft^3 of sand and 2129 ft^3 of silt, the solids concentrations to be input to the instantaneous dump model are

Sand - 0.009 ft^3/ft^3

Silt - 0.048 ft^3/ft^3

The bulk density of the cloud can then be computed to be 1.091 g/cc.

5. Based upon the above volume of 44,109 ft^3, the radius of the hemispherical cloud is $R = 27.6$ ft. The cloud centroid is determined by subtracting $5/8\, R$ from the position of the bottom of the cloud located at 47.87 ft. Thus, the initial centroid of the cloud is 30.6 ft from the surface. The initial velocity of 2.6 ft/sec is taken to be the velocity from the continuous discharge run at the centroid position.

6. The next step is to run the continuous discharge model as before except with a bulk density of 1.17 g/cc. From this run the entrainment flow rate and corresponding density are determined for input to the instantaneous dump model. The total entrainment time is

determined as the difference between the total discharge time and the time required for the 1.50 g/cc continuous run to encounter the bottom. For the present example the entrainment time is 31 sec with a flow rate of 5809 ft^3/sec and a density of 1.0106 g/cc.

7. The final step is to use the results above to run the instantaneous dump model to yield a reasonable representation of the radial surge of material on the bottom.

APPENDIX E: NOTATION

a	Minor axis of elliptical cross section
a_o	Half the final radius of the convective descent jet
AA	Major axis of elliptical cross section
A_1	Area of top face of a general frustum
A_2	Area of bottom face of a general frustum
B	Buoyancy
BC	Jet radius
BC(1)	Radius of the discharge point
C	Suspended sediment concentration, mg/ℓ
C_1	A constant equal to 0.16
CY	Vertical position of cloud center line
dy	Incremental distance in vertical direction
DS	Spatial integration step
DT	Time integration step
DTC	Time increment for creating small clouds
E	Turbulent diffusion coefficient
$F_{\Delta\rho}$	Driving force in bottom collapse due to $\Delta\rho$
g	Acceleration due to gravity
h	Height of general frustum
$h;H;h_{i,j};h^*$	Water depths
ISTEP	Number of integration steps
K	Vorticity
L	Plume length
U	Ambient velocity in x-direction
V	Volume of a general frustum
V_S	Settling velocity of suspended solids, ft/sec
$V^*;V_{i,j}$	Ambient current
W	Ambient velocity in Z-direction
x,y	Cartesian coordinates with origin at water surface
y'	Vertical axis of coordinate system attached to the collapsing cloud
YY	Vertical coordinate used in interpolation of ambient velocity

Z	Cartesian coordinate with origin at water surface
Δx	Spatial step in horizontal grid
$\Delta \rho$	Difference in cloud and ambient densities at center of cloud
ε	Normalized density gradient - $\left(1/\rho_o\right)\left(\partial\rho_o/\partial y\right)$
θ_2	Angle between center line of the jet and the vertical
ρ_a	Ambient density
ρ_o	Cloud density at cloud center
ρ^*	Density distribution inside the cloud

In accordance with letter from DAEN-RDC, DAEN-ASI dated 22 July 1977, Subject: Facsimile Catalog Cards for Laboratory Technical Publications, a facsimile catalog card in Library of Congress MARC format is reproduced below.

Johnson, Billy Harvey
  Evaluation and calibration of the Tetra Tech dredged material disposal models based on field data / by Billy H. Johnson and Barry W. Holliday. Vicksburg, Miss. : U. S. Waterways Experiment Station ; Springfield, Va. : available from National Technical Information Service, 1978.
  61, [33] p. : ill. ; 27 cm. (Technical report - U. S. Army Egineer Waterways Experiment Station ; D-78-47)
  Prepared for Office, Chief of Engineers, U. S. Army, Washington, D. C., under DMRP Work Unit Nos. 1B06 and 1B07.
  References: p. 61.

1. Calibrating. 2. Computer programming. 3. Dredged material. 4. Dredged material disposal. 5. Estuarine environment. 6. Evaluation. 7. Field data. 8. Mathematical models. 9. Waste disposal sites. I. Holliday, Barry W., joint author. II. United States. Army. Corps of Engineers. III. Series: United States. Waterways Experiment Station, Vicksburg, Miss. Technical report ; D-78-47.
TA7.W34 no.D-78-47