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Installation of Vertical Strip Drains to Increase Storage Capacity of Craney Island Dredged Material Management Area

by Timothy D. Stark, Thomas A. Williamson
University of Illinois at Urbana-Champaign

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Prepared for U.S. Army Engineer District, Norfolk

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Installation of Vertical Strip Drains to Increase Storage Capacity of Craney Island Dredged Material Management Area

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Final report

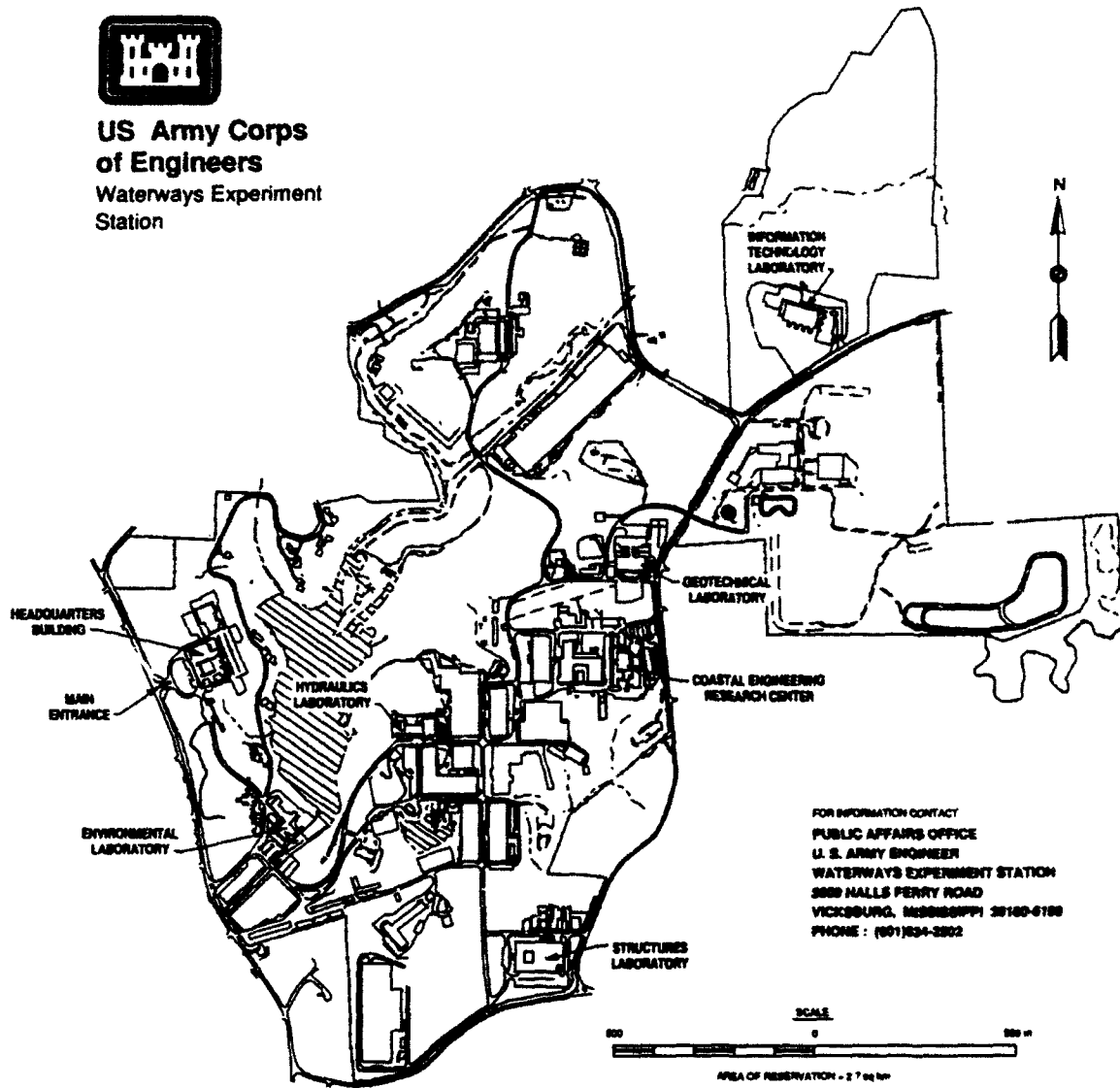
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Preface

This report investigates the feasibility of installing vertical strip drains to increase the storage capacity of the Craney Island Dredged Material Management Area. A preliminary strip drain spacing and cost for installing vertical strip drains in Craney Island are presented. A detailed plan of action and schedule for installing vertical strip drains in the northern compartment of Craney Island are also presented.

This research was conducted for the U.S. Army Engineer Waterways Experiment Station (WES), Vicksburg, Mississippi, and the U.S. Army District, Norfolk (NAO), Norfolk, Virginia, during the period June 1991 to March 1992.

General supervision of the study was carried out by Sam McGee, NAO, and Dr. Jack Fowler, Geotechnical Laboratory (GL), WES, under the guidance of Mr. Ronn G. Vann, Chief, Dredging Management Branch, and Mr. James N. Thomasson, Chief, Engineering Division, NAO. Technical information was provided by Mr. M. T. Byrne and by Mr. D. A. Pezza, Chiefs, Geotechnical Branch, NAO.

Drs. Timothy D. Stark and Thomas A. Williamson, Department of Civil Engineering, University of Illinois at Urbana-Champaign, performed the analyses and wrote this report under the direct supervision of Dr. Jack Fowler, WES. General supervision was provided by Mr. W. Milton Myers, Chief, Engineering Group, Soil Mechanics Division (SMD), Dr. D. C. Banks, Chief, SMD, and Dr. W. F. Marcuson III, Director, GL. This research was performed under Contract No. DACW39-91-M-5638 between WES and Drs. Stark and Williamson.

At the time of publication of this report, Director of WES was Dr. Robert W. Whalin. Commander was COL Bruce K. Howard, EN.

Conversion Factors, Non-SI to SI Units of Measurement

Non-SI units of measurement used in this report can be converted to SI units as follows:

Multiply	By	To Obtain
acres	4,046.873	square meters
cubic yards	0.7645549	cubic meters
Fahrenheit degrees	5/9	Celsius degree or kelvins ¹
feet	0.3048	meters
inches	2.54	centimeters
pounds (force)	4.448222	newtons
pounds (force) per square inch	6.894757	kilopascals
square feet	0.09290304	square meters
square yards	0.8361274	square meters

¹ To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use the formula: $C = (5/9)(F - 32)$. To obtain kelvin (K) reading, use: $K = (5/9)(F - 32) + 273.15$.

1 Introduction

Background

The Craney Island Dredged Material Management Area is a 2,500-acre¹ site with a storage area of approximately 2,200 acres (Figure 1). Craney Island is located near Norfolk, Virginia, in Portsmouth, Virginia. Planned in the early 1940's, construction of Craney Island began in August 1954 and was completed in January 1957. Craney Island is the long-term disposal area for material dredged from the channels and ports in the Hampton Roads area.

Dredged material has been placed in the disposal area almost continuously since it was completed in 1957. The original design was for an initial capacity of about 100 million cu yd at an annual dredging rate of 4 to 7 million cu yd. Therefore, Craney Island was designed for a service life of approximately 20 years (1957 to 1977) based on an annual dredging rate of 5 million cu yd. Continued dredging in the Norfolk channel has required the capacity of Craney Island to be increased through three major dike raising efforts. The initial raising from el +8 to el +17 ft mean low water (MLW) occurred around 1974 with the second increase to el +26 ft around 1980. The U.S. Army Engineer District, Norfolk (NAO), is currently raising the perimeter dike system based on recommendations presented by Fowler et al. (1987). The west dike is being raised to el +34 ft MLW but this raising required the placement of a 1,000-ft-wide underwater stability berm along the outer toe of the dike (Figure 2) to ensure stability. The perimeter dike in the northwest corner is being raised to el +34 ft MLW using a dike setback of approximately 450 ft (Figure 3). The north and east perimeter dikes are being raised to el +40 ft MLW with setbacks from the dike perimeter road of 420 and 450 ft, respectively (Figures 4 and 5). Dike setbacks have resulted in approximately 20 to 30 acres of lost storage capacity during each dike raising. Figure 1 shows the location of these dike cross sections.

Using plans developed by Palermo et al. (1981), interior dikes were built within Craney Island to create three containment areas (Figure 1) that would improve sedimentation in the compartment being filled and allow the other two compartments to desiccate and consolidate at a faster rate. Desiccation

¹ A table of factors for converting Non-SI units of measurement to SI units is presented on page vi.

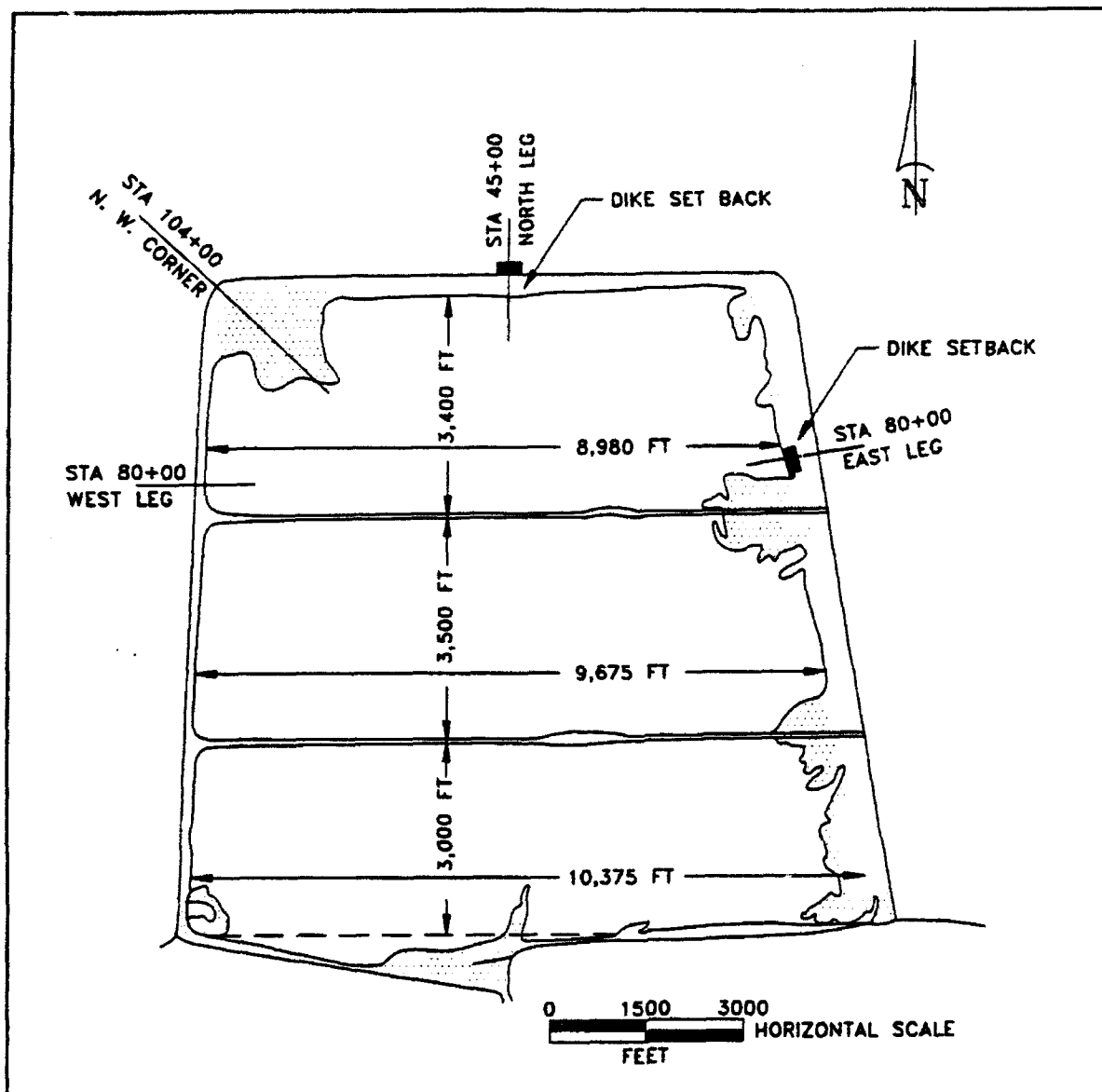


Figure 1. Plan view of Craney Island and location of dike cross sections

will be accelerated by the removal and/or evaporation of surface water, and will increase the amount of consolidation because the effective density of the soil increases as the pore water evaporates. Construction of the interior dikes was completed in 1983, and the dredged material management plan (Palermo et al. 1981) was implemented in 1984 starting with the center compartment. The management plan has resulted in each compartment being filled approximately every third year. On the average 4 to 5 million cu yd of dredged fill is placed in a compartment each year. This results in an annual increase in dredged fill thickness of 3 to 6 ft in the compartment being filled or about 1 to 2 ft over the entire disposal area (Szelest 1991).

The Environmental Laboratory at the U.S. Army Engineer Waterways Experiment Station conducted an extensive consolidation and desiccation

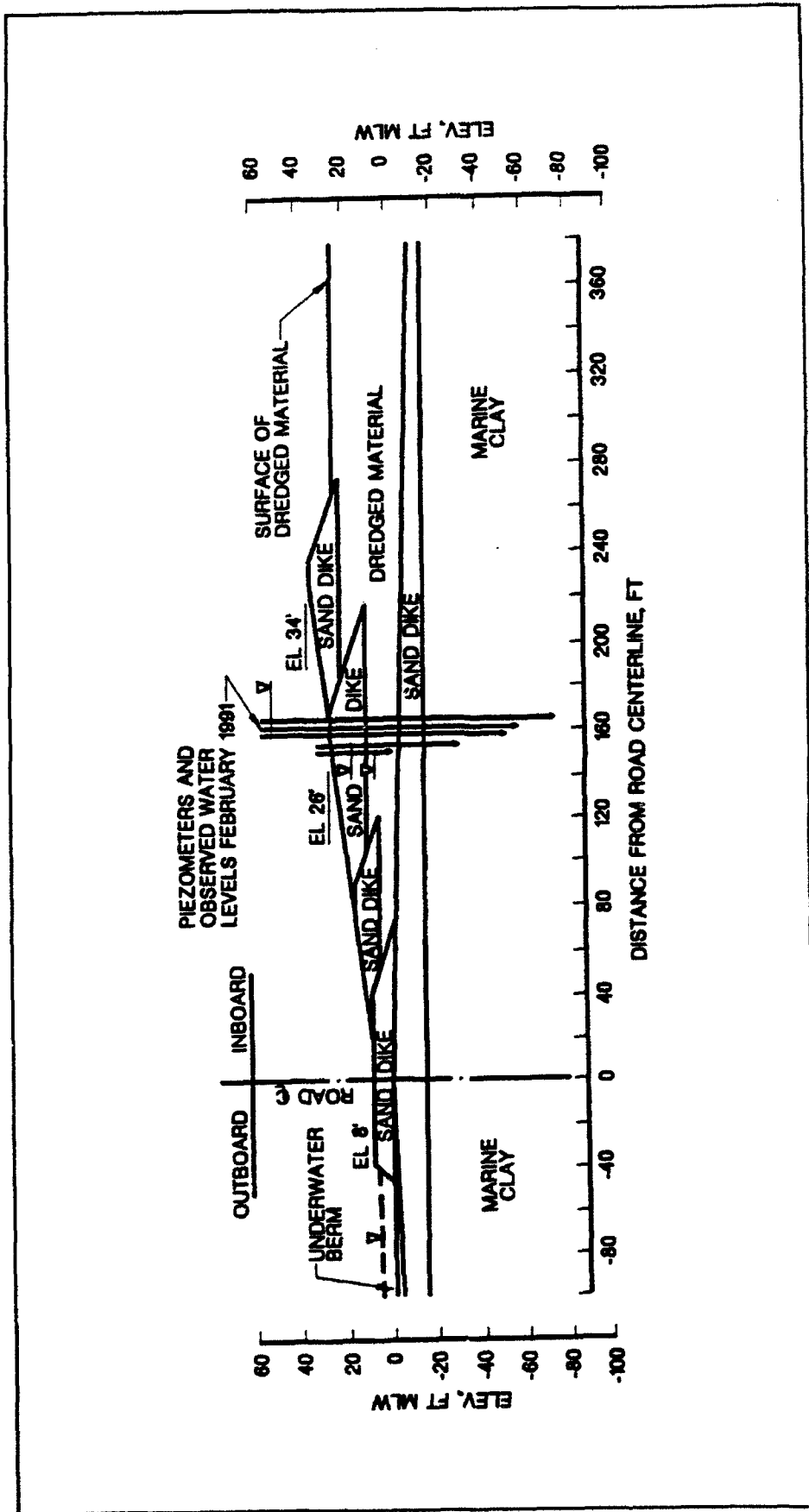


Figure 2. Generalized cross-section, West Perimeter Dike

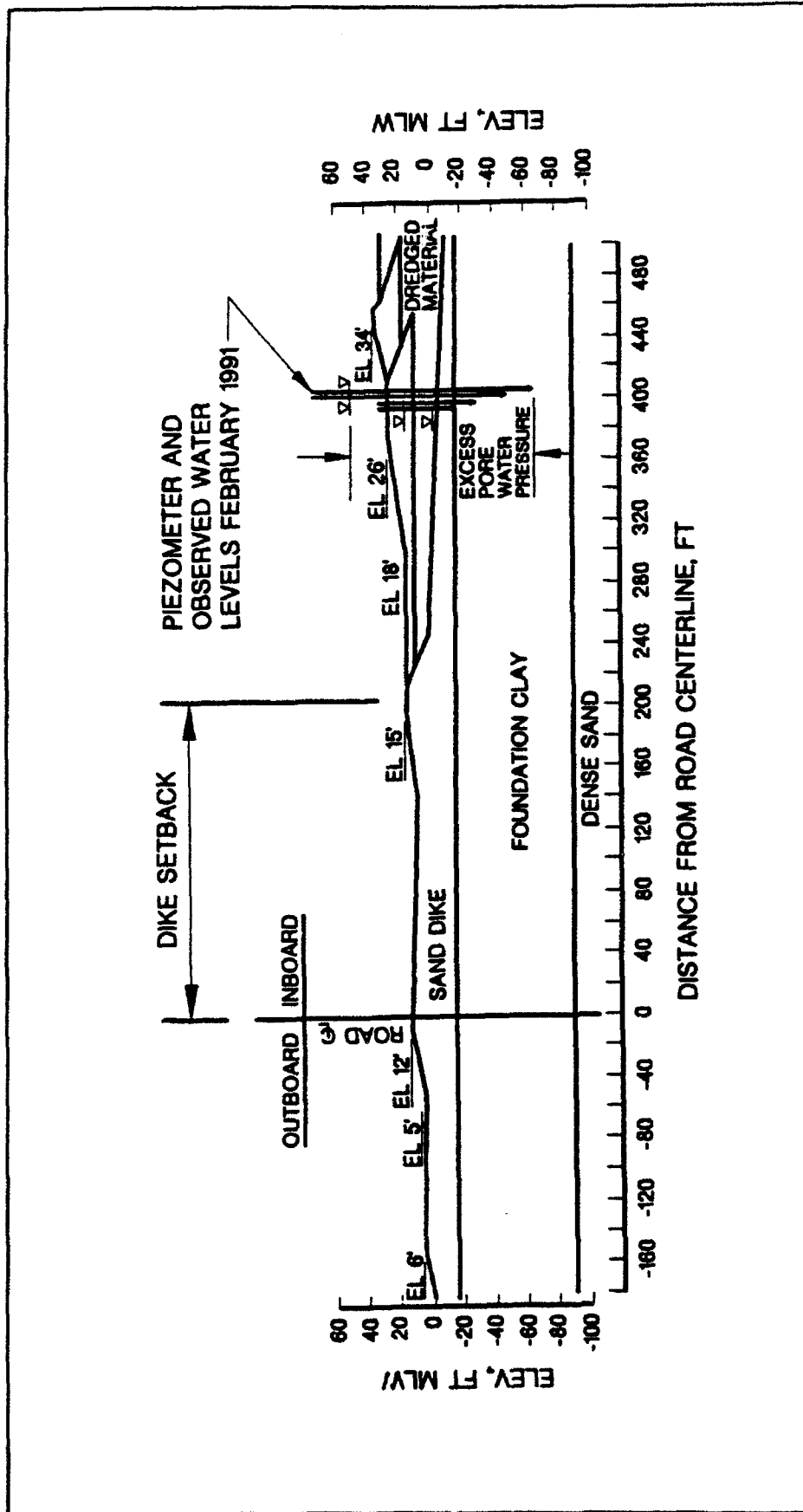


Figure 3. Generalized cross-section, Northwest Corner Perimeter Dike

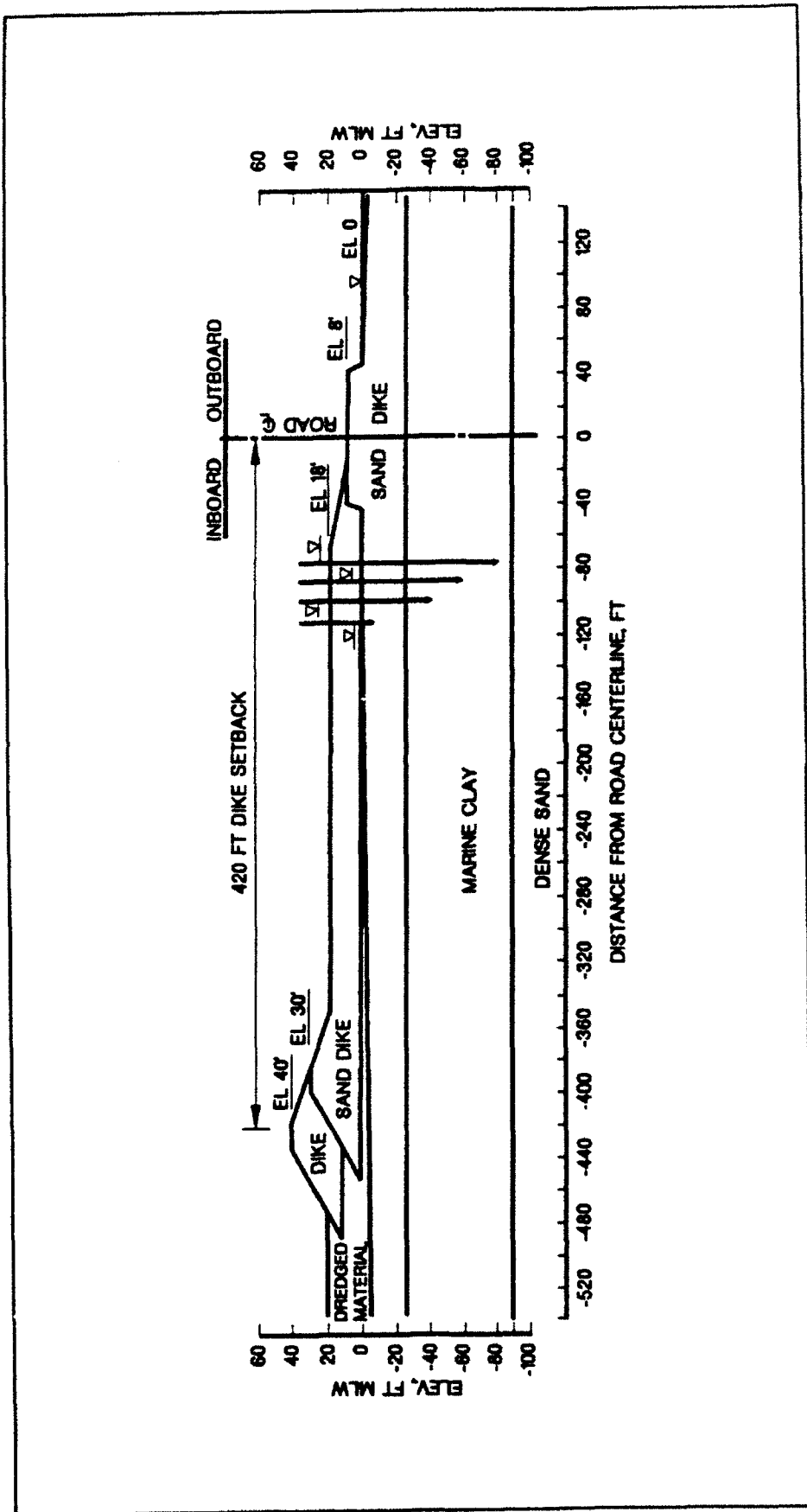


Figure 4. Generalized cross-section, North Perimeter Dike

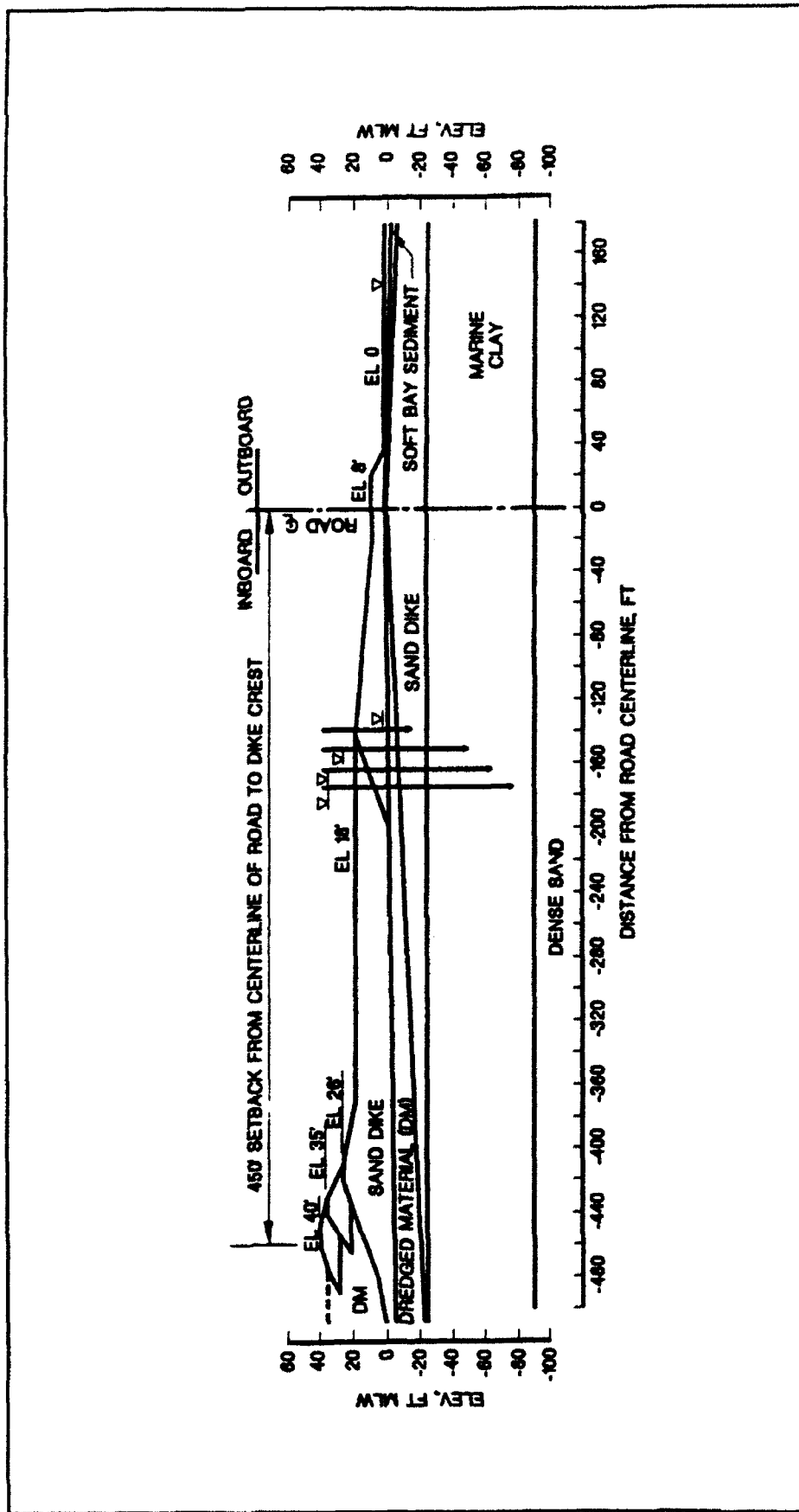


Figure 5. Generalized cross-section, East Perimeter Dike

analysis to predict the life expectancy of Craney Island (Palermo and Schaefer 1990). This study utilized the finite strain consolidation micro computer program PCDDF (Stark 1991, Stark and O'Meara 1991) and revealed that the current capacity of Craney Island will be exhausted by the year 2000. As a result, the Norfolk District (NAO) started investigating new techniques for increasing the storage capacity of Craney Island.

Alternatives for Increasing Storage Capacity at Craney Island

The studies by Fowler et al. (1987) showed that the perimeter dikes are at their maximum height. However, if the undrained shear strength of the dredged fill and underlying marine clay was increased through consolidation, the perimeter dikes could be raised again. The time required for this strength gain would be substantial and thus would not alleviate the short-term storage problem.

An extensive study was conducted by Spigolon and Fowler (1987) on the feasibility of expanding Craney Island. Six expansion configurations were considered by Spigolon and Fowler (Figure 6). However, in 1991 the Virginia State Legislature ruled that Craney Island could not be expanded or replaced. Therefore, the feasibility of restricting the usage of Craney Island to disposal of contaminated dredged material and ocean dumping the remainder of the material was investigated. The cost of ocean dumping is approximately \$7.00 per cu yd whereas deposition in Craney Island is approximately \$0.90 per cu yd (Szelest 1991). NAO is still dredging at a rate of approximately 5 million cu yd per year. Therefore, the difference between disposal in Craney Island and ocean dumping is approximately \$30 million per year. As a result, additional alternatives for increasing the storage capacity of Craney Island were sought.

Recently installed piezometers in the perimeter dikes at Craney Island revealed that large excess pore-water pressures exist in the dredged fill and underlying marine clay. It can be seen in Figures 2 through 5 that the excess pore-water pressure levels in February 1991 exceed the ground surface elevation by 25 ft in some locations. The dissipation of these excess pore-water pressures would result in substantial consolidation settlement, and thus increased storage capacity. In addition, the consolidation of the marine clay and dredged fill would cause a significant increase in the undrained shear strength of these materials. This would allow the perimeter dikes to be constructed to higher elevations without setbacks or stability berms.

The time required for 90 percent consolidation to occur can be estimated using Terzaghi's one-dimensional consolidation equation:

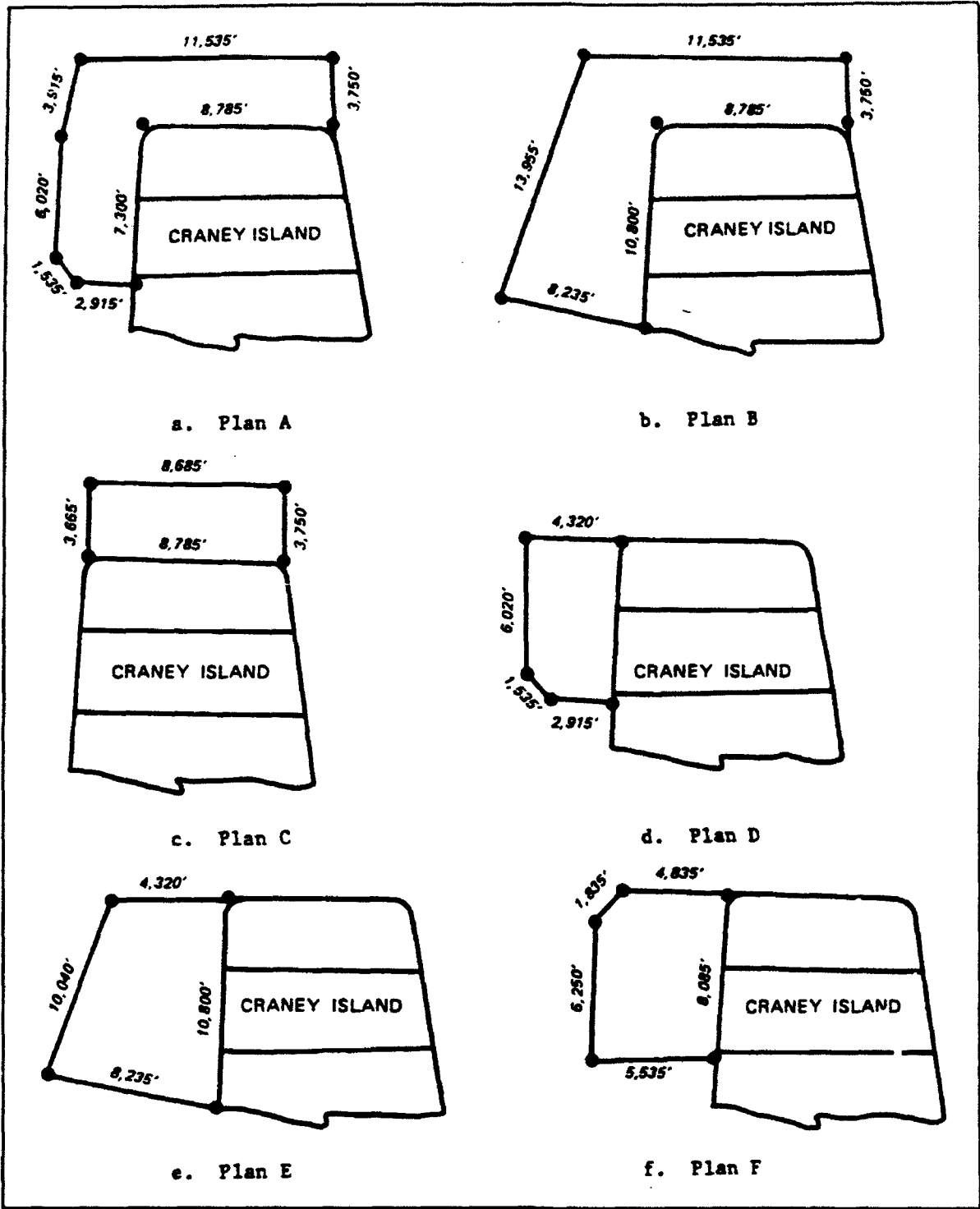


Figure 6. Dimensions of Crane Island Enlargement Alternatives (from Spigolon and Fowler 1987)

$$t_{90\%} = \frac{0.848 \times H_{dr}^2}{C_v} \quad (1)$$

where H_{dr} is the maximum length of the drainage path and C_v is the vertical coefficient of consolidation. This equation shows that the time required for consolidation is controlled by the coefficient of consolidation, that is, permeability, of the soil and the maximum drainage length that water must travel to exit the soil deposit. Since altering the permeability of a soil in situ is not practical, techniques were sought to decrease the drainage path to accelerate consolidation.

Use of Strip Drains to Increase Storage Capacity

Figure 7 shows the generalized subsurface profile at Craney Island. It can be seen that the average surface elevation of the dredged fill is +23 ft MLW and the thickness of the dredged fill and marine clay is approximately 123 ft. Since the site appears to be doubly drained, the maximum length of the vertical drainage path to either the top surface or the sands underlying the marine clay is 61.5 ft or approximately 62 ft. However, the thickness of the marine clay varies throughout the site. For example, in the north compartment the marine clay is approximately 105 ft thick where an old river channel is located. For illustrative purposes the marine clay will be assumed to be 90 ft thick. Recent piezocone penetration tests (Stark 1992) in the north compartment suggest that the underlying dense sand and silty sand is permeable. Therefore, the site is assumed to be doubly drained.

Figure 8 shows that the installation of vertical strip drains will result in radial flow instead of vertical flow. As a result, the maximum drainage path will be reduced to one-half of the strip drain spacing, that is, 6 ft instead of one-half of the compressible layer thickness which is 62 ft. This reduction in drainage path is extremely significant since the time rate of consolidation is a function of the length of drainage path squared (Equation 1). Therefore, the installation of vertical strip drains will result in a substantial reduction in the time required to consolidate the dredged fill and underlying marine clay. This will yield a rapid increase in storage capacity and undrained shear strength of the dredged fill and marine clay.

It is proposed that the strip drains be installed throughout the disposal area and subsequently the perimeter dikes. The strip drains will consolidate the dredged fill and underlying marine clay in the disposal area, which may permit future development of this site. Installing strip drains in only the perimeter dikes would be less expensive and may also result in more settlement because of the additional surcharge applied by the dikes. The strip drains would accelerate consolidation of the marine clay underlying the perimeter dikes and allow the dikes to be constructed to higher elevations. However, the strip drains would not consolidate the disposal area and thus not reduce the elevation of the disposal area. NAO is interested in consolidating the disposal

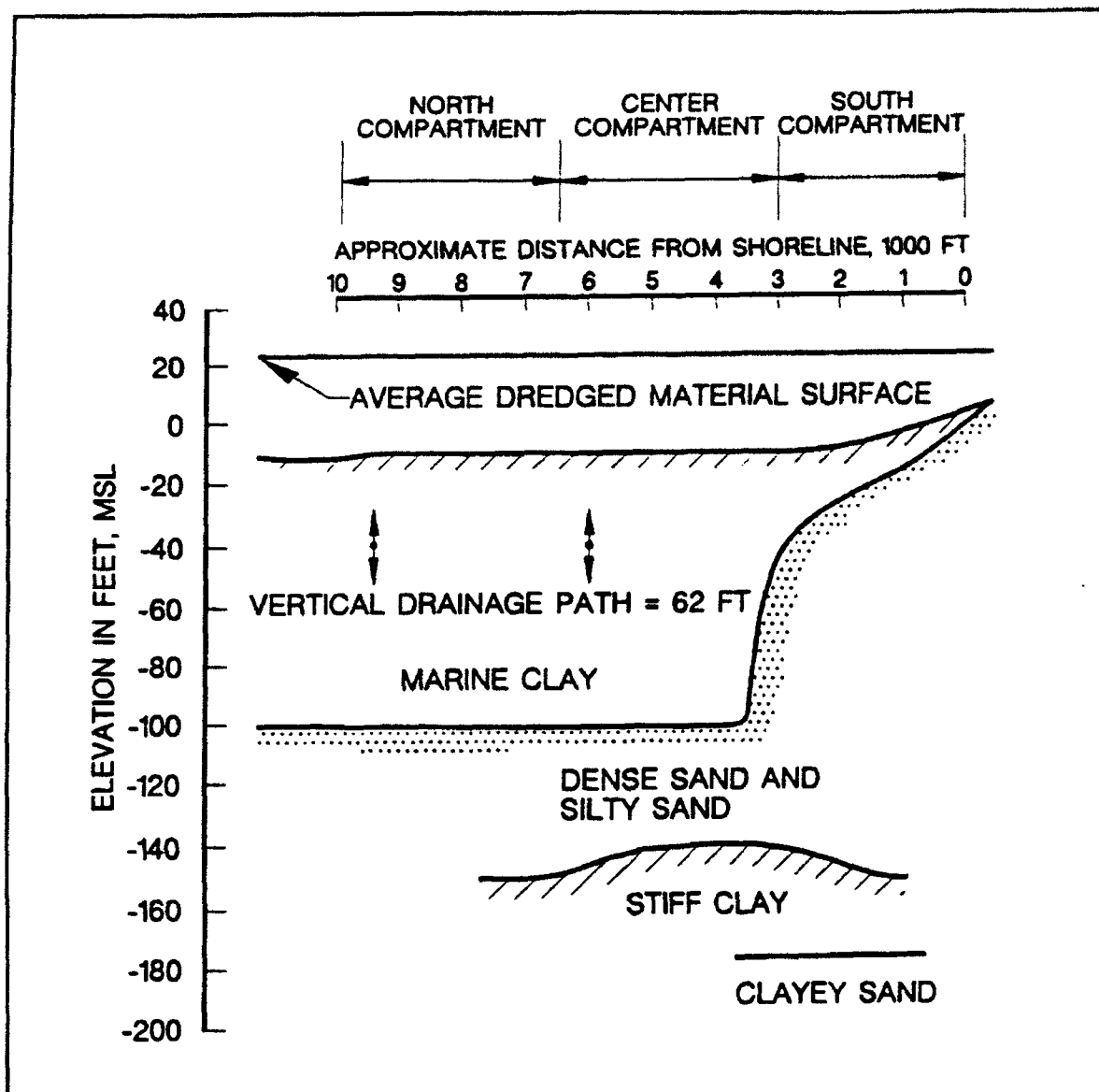


Figure 7. Generalized subsurface profile at Craney Island

Objective

The objectives of the study reported herein were to: (a) investigate the feasibility of using vertical strip drains to increase the storage capacity of the Craney Island Dredged Material Management Area; (b) develop a preliminary design of the vertical strip drains; (c) develop a preliminary cost estimate for the strip drains; and (d) develop a detailed plan of action for design, construction, and monitoring of the vertical strip drains in the northern compartment of Craney Island.

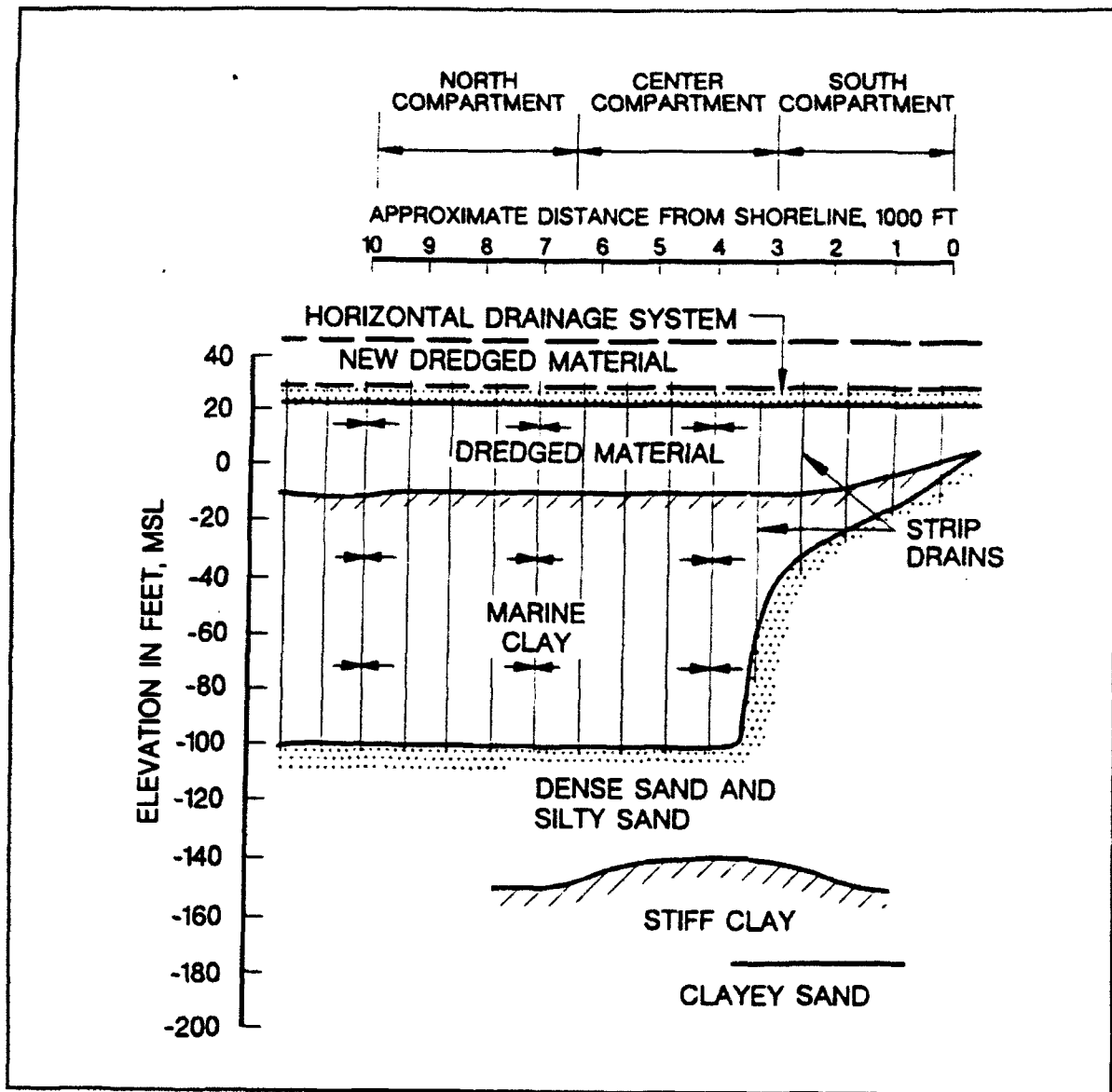


Figure 8. Radial drainage pattern using vertical strip drains

Craney Island Dredged Material Management Area; (b) develop a preliminary design of the vertical strip drains; (c) develop a preliminary cost estimate for the strip drains; and (d) develop a detailed plan of action for design, construction, and monitoring of the vertical strip drains in the northern compartment of Craney Island.

Scope of Work

The completion of the study objectives was accomplished in the following steps:

- a. Available geotechnical and related information was assembled from conferences with Waterways Experiment Station (WES) and NAO personnel and from existing literature, both published and unpublished.
- b. A single cross-section geometry and set of consolidation material properties were adopted for the preliminary design of the vertical strip drains.
- c. A micro computer program entitled "VDRAIN" was developed to design the vertical strip drains. The interactive computer program is included in Appendix A and was used to develop a preliminary spacing, pattern, and cost estimate for installing the strip drains at Craney Island. A relationship between consolidation settlement and cost per increased storage volume was developed based on the preliminary spacing and pattern of the strip drains. This relationship can be used to evaluate the economic feasibility of installing vertical strip drains against other disposal alternatives, such as ocean dumping.
- d. A detailed plan of action was developed for the design, construction, and monitoring of the vertical strip drains. Specific tasks were recommended for WES and NAO, and a time table for completing these tasks is also presented.

2 Vertical Strip Drain Technology

In the last 5 to 10 years, vertical strip drains have replaced conventional sand drains as the preferred method to speed up the consolidation of soft cohesive soils. This is primarily due to the ease of installation, higher flexibility and reliability, less environmental impact, and reduced cost of the strip drains. Most vertical strip drains are modelled after the cardboard strip drain developed by Kjellman in 1948 (a and b). Strip drains are band-shaped and have a rectangular cross section of approximately 4 in. wide and 0.15 to 0.20 in. thick. A plastic core with grooves, studs, or channels is surrounded by a filter fabric. The fabric is most commonly a nonwoven geotextile. The core carries the excess pore-water to the ground surface, and/or the underlying drainage layer, and the filter fabric keeps soils particles from entering the core. Vertical strip drains have been used to accelerate consolidation of soft cohesive soils in many projects throughout the United States, including the recent expansion of the Port of Los Angeles, the Seagirt project in Baltimore Harbor, the construction of a dredge material containment area in the Delaware River near Wilmington, Delaware, and the New Bedford Superfund Site near New Bedford, Massachusetts.

Vertical strip drains are easily installed using equipment (Figure 9) that exerts a ground pressure as low as 2 to 3 psi. It is anticipated that a well-developed desiccated crust will support this equipment. The installed cost of strip drains is usually \$0.40 to \$1.00 per lin ft depending on the quantity of strip drains installed. In contrast, the installed cost of conventional sand drains is \$3.50 to \$6.50 per lin ft. The time required for consolidation of the dredged fill and foundation clay is controlled by the spacing of the strip drains. Therefore, value engineering can be used to determine the optimal spacing of the drains to produce a certain increase in settlement, that is, storage capacity, in a specified time.

The strip drains arrive at the site in large rolls and are installed using a hollow mandrel. The end of the strip drain is threaded down the inside of the mandrel, which must be as long as the depth to which the strip drains are to be installed. At the bottom of the mandrel, the strip drain is threaded through a baseplate and inserted into the mandrel (Figure 10). The baseplate is used to keep the strip drain at the bottom of the mandrel, to prevent soil from entering the mandrel during the insertion process, and to keep the strip drain

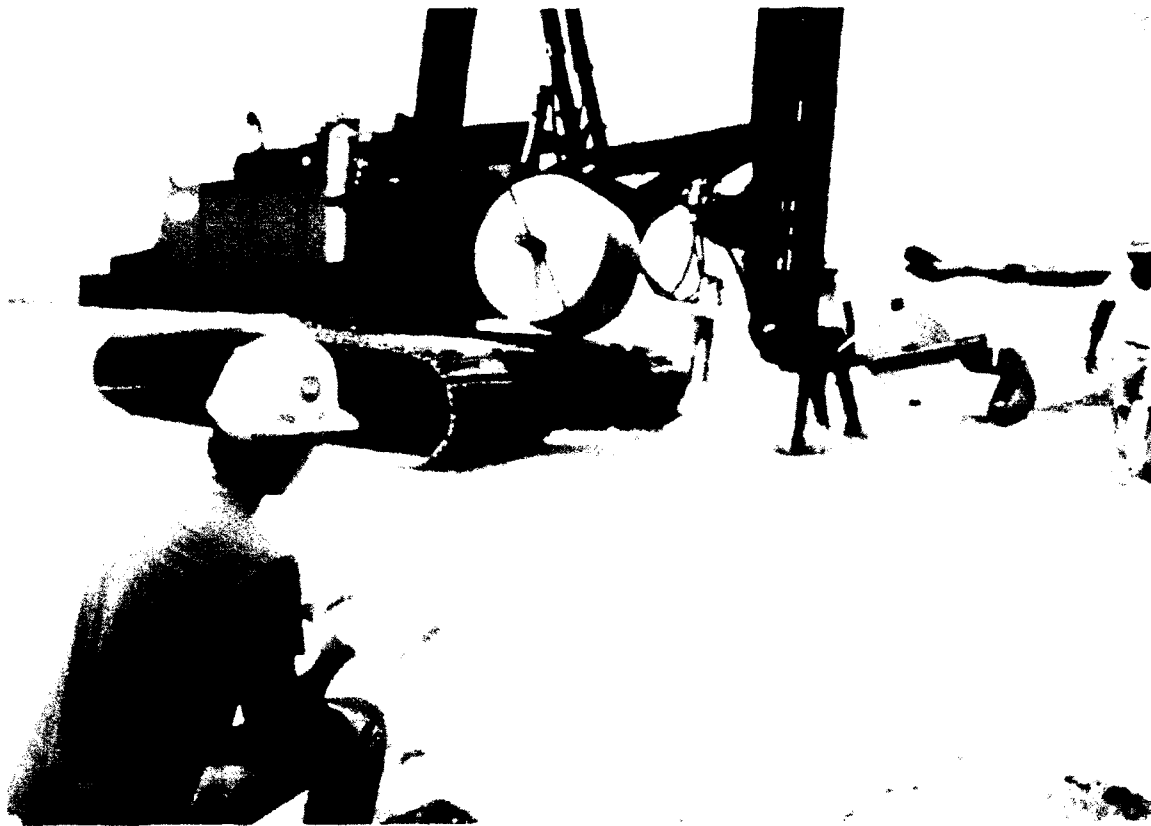


Figure 9. Typical strip drain installation equipment

at the desired depth as the mandrel is withdrawn. When the mandrel is withdrawn from the ground, the strip drain is cut, and the process is repeated at the next location. This insertion cycle is rapid (1 to 5 min depending on insertion depth) and only strip drains, baseplates, and a cutting tool are required.

At Craney Island it is anticipated that strip drains will be installed in one compartment while the other compartments are used for disposal and desiccation. After the strip drains accelerate consolidation in the first compartment, this compartment will be used for disposal while strip drains are installed in another compartment, and the third compartment undergoes desiccation to support the strip drain equipment. Installation of strip drains will continue until strip drains have been installed in all three compartments.

The length of the strip drains will vary in each compartment with the longest strip drains (approximately 123 ft) being installed in the north compartment. A number of contractors, e.g., Joiner (1991), have installed vertical strip drains to similar depths. For example, 120, 130, and 140 ft long strip drains were recently installed in New York, Utah, and Connecticut, respectively (Joiner 1991). However, the existing strip drain equipment will have to be modified to reduce the ground pressure to successfully operate on confined dredged material. Geotechnics America, Inc. utilizes a pontoon mounted crane to support the strip drain equipment instead of a track mounted



Figure 10. Strip drain installation procedure

crane (Figure 9). The pontoons reduce the ground pressure and will provide flotation if the desiccated crust cannot support the strip drain equipment. Therefore, it appears that installation of 123 ft long vertical strip drains in Craney Island is feasible.

A horizontal drainage system at the ground surface may be required to remove the water expelled from the consolidating soil and preserve the desiccated crust to support the strip drain equipment. In addition, the drainage system would also act as a drainage layer for future dredged material. It is anticipated that the pontoon mounted crane will not require a drainage system to successfully operate on the desiccated crust, and thus significantly reduce the cost of the project. However, if a drainage system is required, the strip drains will be connected to the drainage system (Figure 8). This installation procedure will allow the expelled water to exit the strip drains and enter the surface drainage system and the underlying foundation sands.

3 Preliminary Design of Vertical Strip Drains at Craney Island

Vertical Strip Drain Design Theories

The design of vertical strip drains is generally based on the theoretical solution for radial consolidation developed by Barron (1948) in which the drains are assumed to be of infinite permeability. Hansbo (1979 and 1981) simplified Barron's solution and accounted for well resistance and the effects of smear due to drain installation (Figure 11). It can be seen that the degree of consolidation is a function of G and $F(n,s)$. The variable G describes the effect of well resistance on the rate of consolidation and $F(n,s)$ describes the effect of the smear zone. The well resistance is controlled by the influx of water to the strip drain and the flow along the drain. Therefore, G depends on the drain diameter, drain spacing, and the maximum drainage length of the strip drain. When strip drains are installed, the soil adjacent to the drain is disturbed and a smear zone is created. The extent of the smear zone depends on the installation procedure and the sensitivity of the soil. The overall effect of the smear zone is to reduce the permeability of the soil and slow the rate of consolidation.

Yoshikuni and Nakanodo (1974) and Onoue (1988) have presented rigorous solutions to the radial flow problem that also account for the effects of smear and well resistance. However, these solutions are complicated, and thus difficult to use in practice. Lo (1991) simplified the rigorous solutions, which resulted in the solution shown in Figure 12. It should be noted that Zeng and Xie (1989) also developed a simplified solution that has a slightly different expression for the effect of well resistance.

It can be seen from Figure 12 that the main differences between Lo's and Hansbo's solution are the expressions for G and $F(n,s)$ and the effect of vertical consolidation is considered. Review of several case histories has shown that these modifications provide excellent agreement with field case histories. The case histories revealed that the importance of vertical drainage increases with increased drain spacing. The preliminary drain spacing for Craney Island is large (12 ft), and thus some vertical drainage will probably occur.

$$U_h = 1 - \exp\left(\frac{-8 C_h t}{(d_e)^2 \times [F(n,s) + G]}\right) \quad (2)$$

$$F(n,s) = \ln\left(\frac{n}{s}\right) + \left(\frac{K_h}{K_s}\right) \ln(s) - 0.75 \quad (3)$$

$$G = 4 \left(\frac{K_h}{K_w}\right) \left(\frac{l_m}{d_w}\right)^2 = \left(\frac{K_h (l_m)^2}{q_w}\right) \quad (4)$$

- where
- U_h = average degree of consolidation for radial flow;
 - t = time;
 - C_h = horizontal coefficient of consolidation;
 - d_e = sphere of influence of the strip drain (triangular pattern = 1.05S where S = strip drain spacing);
 - d_w = equivalent strip drain diameter = $\frac{2 * (b - l)}{\pi}$
 - b = width of strip drain (typically 0.305 - 0.328 ft, used 0.31 ft);
 - l = thickness of strip drain (typically 0.01 - 0.013 ft, used 0.0115 ft);
 - n = ratio of drain diameters = $\frac{d_e}{d_w}$
 - $F(n,s)$ = term describing smear zones;
 - s = ratio of smear zone diameter to drain diameter = $\frac{d_s}{d_w}$
 - d_s = outer radius of the smear zone;
 - K_h = horizontal coefficient of permeability of the undisturbed soil;
 - K_s = horizontal coefficient of permeability of the smeared soil;
 - K_w = coefficient of permeability of the strip drain;
 - G = term describing well resistance;
 - q_w = discharge capacity of strip drain = $\frac{\pi}{4} K_w d_w^2$
 - l_m = maximum drainage length of strip drain.

Figure 11. Strip drain design theory presented by Hansbo (1981)

The solution proposed by Lo (1991) and described in Figure 12 was coded into a micro computer program. The interactive program is entitled "VDRAIN" and executes on any IBM or compatible micro computer. The program prompts the user for the variables shown in Figure 12, and the program estimates the drain spacing to achieve the specified degree of consolidation and time. The user will also be prompted for the depth to which the drains will be installed and the area to be consolidated. The resulting lineal footage of strip drains will be used to calculate the total cost of installing strip drains and the cost per cubic yard of increased storage capacity.

$$U = 1 - \exp\left(-\left(\frac{8 C_h}{d_e^2 \times [F(n,s) + G]} + \frac{4 C_v}{H_{dr}^2}\right) t\right) \quad (5)$$

$$F(n,s) = \frac{n^2}{n^2-1} \left[\ln\left(\frac{n}{s}\right) + \left(\frac{K_h}{K_s}\right) \ln(s) - 0.75 \right] + \frac{s^2}{n^2-1} \left[1 - \left(\frac{s^2}{4n^2}\right) \right] + \frac{K_h}{K_s} \left(\frac{1}{n^2-1}\right) \left[\frac{(s^4-1)}{4n^2} - (s^2+1) \right] \quad (6)$$

$$G = 2.5 \left(\frac{K_h}{K_w}\right) \left(\frac{l_m}{d_w}\right)^2 = 2 \left(\frac{K_h (l_m)^2}{q_w}\right) \quad (7)$$

- where
- U = average degree of consolidation for vertical and radial flow;
 - t = time;
 - H_{dr} = length of drainage path;
 - C_h = horizontal coefficient of consolidation;
 - C_v = vertical coefficient of consolidation;
 - d_e = sphere of influence of the strip drain (triangular pattern = 1.05S where S = strip drain spacing);
 - d_w = equivalent strip drain diameter = $\frac{2 * (b + l)}{\pi}$
 - b = width of strip drain (typically 0.305 - 0.328 ft, used 0.31 ft);
 - l = thickness of strip drain (typically 0.01 - 0.013 ft, used 0.0115 ft);
 - n = ratio of drain diameters = $\frac{d_e}{d_w}$
 - $F(n,s)$ = term describing smear zones;
 - s = ratio of smear zone diameter to drain diameter = $\frac{d_s}{d_w}$
 - d_s = outer radius of the smear zone;
 - K_h = horizontal coefficient of permeability of the undisturbed soil;
 - K_s = horizontal coefficient of permeability of the smeared soil;
 - K_w = coefficient of permeability of the strip drain;
 - G = term describing well resistance;
 - q_w = discharge capacity of strip drain = $\frac{\pi}{4} K_w d_w^2$
 - l_m = maximum drainage length of strip drain.

Figure 12. Strip drain design theory presented by Lo (1991)

Vertical Strip Drain Design Parameters

Since Craney Island is divided into three compartments, each compartment is utilized approximately every 2 to 4 years depending on the dredging schedule. For design purposes, the preliminary strip drain spacing was designed such that a degree of consolidation of 90 percent will occur within 4 years. Using 4 years instead of 2 reduces the number of strip drains required and the cost. The time period is not critical because consolidation will still occur if additional dredged material is placed in a compartment prior to 4 years. In fact, a time period greater than 4 year could be used to reduce the quantity and cost of the strip drains.

The strip drain spacing is governed by the values of C_v and C_h . It can be seen from Figure 7 that the strip drains will penetrate the dredged fill and marine clay which have different permeabilities. The soil types are similar but the void ratio of the dredged fill is larger which results in a higher permeability. The values of C_v and C_h are not well defined for either the dredged fill or the marine clay. Therefore, it was decided to treat the dredged fill and marine clay as a single layer and use an average C_v and C_h for preliminary design purposes. A subsurface investigation is proposed in Chapter 5 to better define the values of C_v and C_h of the dredged fill and marine clay. The results of the subsurface investigation will be used to differentiate the two materials and refine the strip drains spacing presented herein. For preliminary design purposes, values of C_v and C_h were obtained from previously published test results and empirical correlations.

The results of permeability tests in the recently installed piezometers were initially used to estimate C_v and C_h . In these tests the water in the piezometers is either pumped down or raised by filling. After the pumping or filling is completed, the time required for the water level to return to the original condition is measured. The flow around the piezometer tip is probably a combination of vertical and horizontal flow. However, for simplicity the flow was assumed to be horizontal, and the permeability tests were assumed to be measuring the horizontal permeability.

The value of horizontal permeability is calculated from the permeability tests using the following equation (British Standards Institution 1981):

$$K_h = \frac{1.45 A}{(t_2 - t_1)} \times \text{Log} \frac{H_1}{H_2} \quad (8)$$

where K_h is horizontal permeability, t is time, A is the cross sectional area of the standpipe, and H is the variable head at times t_2 and t_1 . The values of C_h were calculated for the dredged fill using the horizontal permeability, an initial void ratio, e_o , of 6, and a coefficient of compressibility, a_v , of $2.2\text{E}-03$ (psf)⁻¹. The values of e_o and a_v were obtained from oedometer and self weight consolidation test results (Cargill 1983) in the proper range of effective stress. The average horizontal permeability from three permeability tests in

the dredged fill was estimated to be $7.9E-03$ ft/day which corresponds to an average C_h of 0.40 sq ft/day.

The values of C_h were calculated for the marine clay using the average horizontal permeability from the field permeability tests, an initial void ratio of 3, and a coefficient of compressibility of $1.2E-03$ (psf)⁻¹. The average horizontal permeability from three permeability tests in the marine clay was estimated to be $2.4E-03$ ft/day which corresponds to an average C_h of 0.13 sq ft/day. As expected, the marine clay exhibited a lower horizontal permeability and C_h due to the lower void ratio.

The installation of vertical strip drains decreases the permeability of the soil such that the ratio of the horizontal permeability to the vertical permeability ranges from 1.0 to 1.5 in marine clays (Mesri and Lo 1991). In undisturbed soil this ratio can range from 3 to 10. Based on the data presented by Mesri and Lo (1991), a value of C_v was estimated by dividing C_h by an average ratio of 1.25. The values of C_v for the dredged fill and marine clay were calculated to be 0.32 and 0.10 sq ft/day, respectively (Table 1).

Source of Data	C_v (sq ft/day)	C_h (sq ft/day)
Dredge Fill Data		
Field Piezometers (1991)	0.320	0.400
Cargill (1983)	0.095	0.119
Marine Clay Data		
Field Piezometers (1991)	0.101	0.130
Design Memorandums (1949 and 1986)	0.016	0.020
Empirical Correlations (U.S. Navy, 1982)	0.085	0.106
Preliminary Design Parameters	0.100	0.120

Oedometer test results from General Design Memorandums (U.S. Army Engineer District, Norfolk 1949 and 1986) were also used to estimate C_v . Thirty-two time curves corresponding to the average effective stress at Craney Island (approximately 1,250 psf) were used to estimate an average value of C_v for the marine clay. The average value of C_v is 0.016 sq ft/day, and the average value of C_h was estimated to be 0.02 sq ft/day by multiplying C_v by 1.25.

It can be seen from Table 1 that the oedometer test results from the General Design Memorandums (U.S. Army Engineer District, Norfolk 1949 and 1986) yielded values of C_v and C_h that are lower than the field permeability test values. The difference is attributed to sample disturbance, the lack of a representative sample, the accuracy of measuring permeability in oedometer tests, and the combined vertical and horizontal flow that probably occurred around the piezometers during the field permeability tests.

Laboratory consolidation data on the dredged fill reported by Cargill (1983) were also used to obtain values of C_v and C_h equal to 0.018 and 0.023 sq ft/day, respectively, for a void ratio of 6. Since these values of C_v and C_h were obtained from consolidation tests on the dredged fill at void ratios greater than or equal to 6 (Cargill 1983), these values should be greater than the field permeability tests. This discrepancy may be due to differences in soil type and the presence of thin drainage layers around the piezometers.

Empirical correlations of C_v presented in the Navy Design Manual DM-7.1 (U.S. Navy 1982) were also used to estimate a value of C_v equal to 0.085 sq ft/day for the normally consolidated marine clay. This C_v corresponds to a value of C_h equal to 0.106 sq ft/day. Since the dredged fill is undergoing self-weight consolidation, values of C_v and C_h could not be estimated from this correlation. The values of C_v and C_h reported in this correlation corresponds to effective stresses greater than those present in the dredged fill. Therefore, the dredged fill values of C_v and C_h are probably higher than those reported in the DM-7.1 correlation.

From Table 1 it can be seen that the values of C_v and C_h are uncertain, and the strip drain spacing calculated using these values should only be used for planning-level purposes. The subsurface investigation and field test section described in Chapter 5 of this report should be conducted to determine the design values of C_v and C_h . For preliminary design purposes, it was decided to use a weighted average value of C_v and C_h . The weighted average was based on the thicknesses of the dredged fill (33 ft) and marine clay (90 ft). The average values of C_v and C_h are equal to 0.10 and 0.12 ft/day, respectively, and they were used to estimate the preliminary spacing of the strip drains.

The generalized foundation conditions at Craney Island are depicted in Figure 7. It can be seen that the thickness of the dredged fill and marine clay varies from 45 to 75 ft in the southern compartment. Therefore, the average length of the strip drains in the southern compartment is assumed to be 60 ft. In the center compartment the thickness of the dredged fill and foundation clay varies from 75 to 123 ft (Figure 7). Using a weighted averaging scheme, the average length of the strip drains in the center compartment is assumed to be 100 ft. The strip drains in the northern compartment will have an average length of 123 ft. Based on the dimensions of each compartment shown in Figure 1, the area of the northern, center, and southern compartments were calculated to be 689, 766, and 734 acres, respectively. Therefore, strip drains will be installed over a total area of 2,189 acres.

The other major parameters required to develop a preliminary estimate of the strip drain spacing are the well resistance and the extent of the smear zone. It can be seen in Figure 12 that the well resistance is governed by the ratio of K_h/K_w or K_h/q_w . Using field case histories, Lo (1991) showed that the effect of well resistance can be neglected if G is less than 0.2. Typical values of strip drain discharge capacity, q_w , range from 200 to 400 cu ft/day (Koerner 1990). Since the consolidating clay is doubly drained, the maximum drainage length of the strip drain is equal to 62 ft. Using these parameters

and the average horizontal permeability measured in the field piezometers, the value of G ranges from 0.06 to 0.03. Therefore, well resistance may be neglected if the field discharge capacity of the strip drains is greater than 200 cu ft/day.

The radial extent of the smear zone was studied using laboratory model tests by Onoue et al. (1991) and experience from pile driving and sand drain installations. This study revealed that the ratio of smear zone diameter to strip drain diameter, d_s/d_w , varies from 1.6 to 4. For preliminary design purposes the ratio of d_s/d_w was assumed to be 2. In addition, the horizontal permeability in the smear zone, K_s , was assumed to be one-half of the undisturbed permeability, K_h . This assumption is based on data presented by Onoue et al. (1991) that showed that the ratio of K_s/K_h ranged from 0.2 to 1.0 in the smear zone.

Using the design theory presented by Lo (1991) and the design parameters just described (Table 2), a value of d_e equal to 12.4 is required to obtain a

Parameter	Value
Degree of Consolidation	90 percent
Time	4 years
K_h	2.4E-003 ft/day
C_v	0.10 sq ft/day
C_h	0.12 sq ft/day
H_{dr}	62 ft
q_w	300 cu ft/day
l_m	62 ft
s	2.0
K_s/K_h	0.5

degree of consolidation of 90 percent in the dredged fill and foundation clay within 4 years. The value of d_e is obtained by an iterative process in which values of d_e are selected until Equation 5 yields a degree of consolidation of 90 percent. This iterative procedure is coded into the micro computer program VDRAIN. The area influenced by each vertical strip drain is calculated using the following equation:

$$A = \pi (d_e/2)^2 \quad (9)$$

Therefore, the area influenced by a vertical strip drain is the same for a square or triangular pattern. However, it can be seen from Figure 13 that a triangular pattern provides better drainage for a specified area. It can be seen that the radius of influence does not reach the center of the square area, and thus the square pattern will require a slightly longer time to consolidate. Since the area influenced by a square and triangular pattern is the same, it is recommended that a triangular pattern be used to facilitate drainage. A preliminary strip drain spacing for a triangular pattern was calculated to be 12 ft by dividing d_e by 1.05.

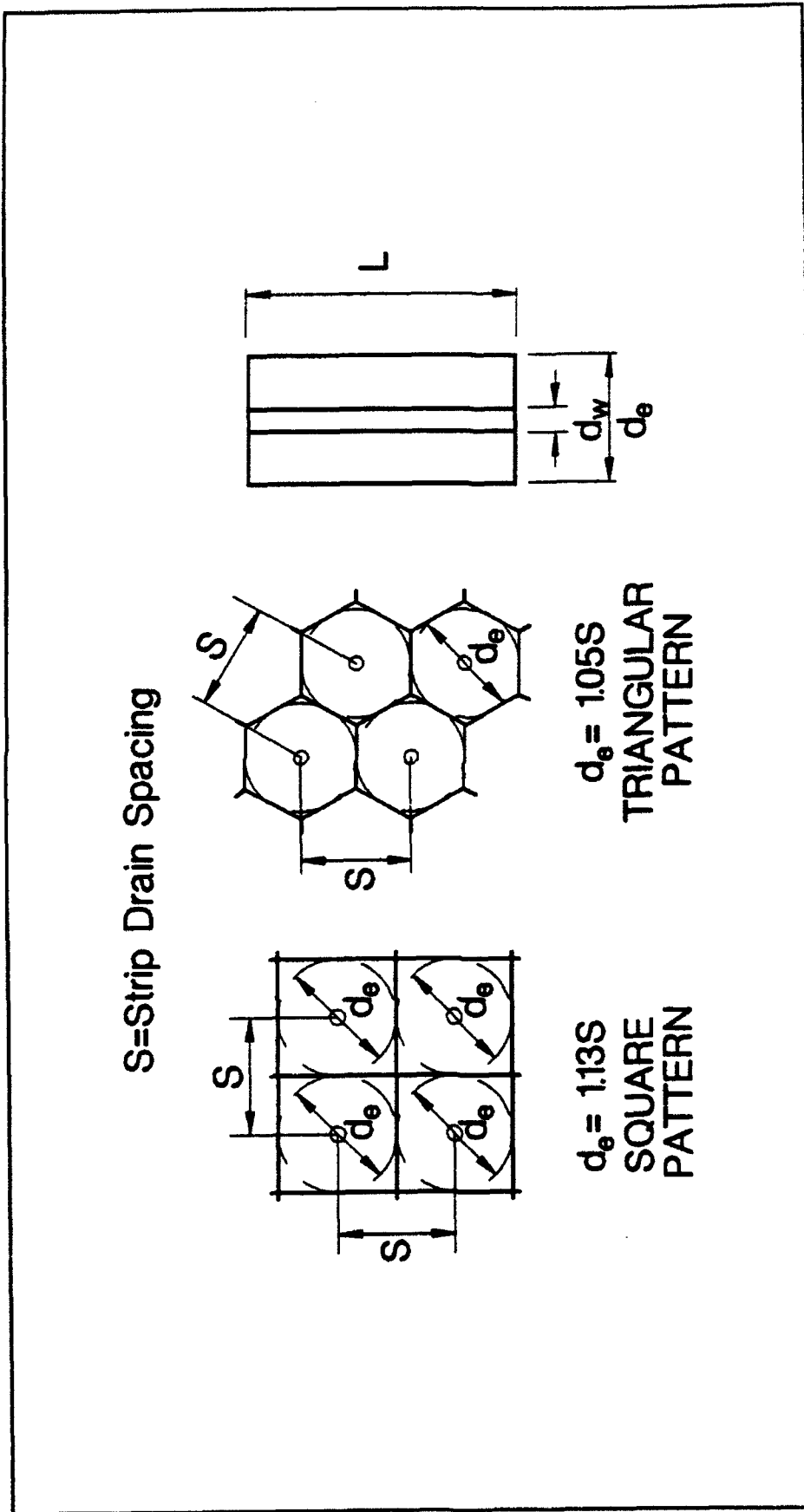


Figure 13. Plan of square and triangular strip drain patterns

Using Equation 9, the area influenced by a 12 ft triangular spacing was calculated to be approximately 121 sq ft or 2.8E-03 acres. Therefore, the number of strip drains required in each compartment were calculated and are shown in Table 3. The lineal footage of strip drain required in each compartment is also shown in Table 3 and was calculated by multiplying the average drain length by the number of drains. Several strip drain contractors were contacted during this study and the cost of installing strip drains ranged from \$0.40 to \$0.70/ft. Due to the large lineal footage required in each compartment, a unit price of \$0.40/ft was used to calculate the cost of installing strip drains at Craney Island. This unit price includes the mobilization and demobilization costs. It should be noted that the total cost of the 12 ft triangular pattern shown in Table 3 does not include the cost of a horizontal drainage system.

Table 3 Estimated Cost of Vertical Strip Drains at Craney Island				
Compartment	Number of Strip Drains	Average Length of Strip Drain (ft)	Lineal Footage of Drains	Total Cost of Strip¹
South	262,140	60	15,728,400	\$6,291,000
Center	273,570	100	27,357,000	\$10,943,000
North	246,100	123	30,270,300	\$12,108,000
Total Cost of 12 ft Triangular Pattern: \$29,342,000				
¹ Total cost does not include horizontal drainage system				

Design of Horizontal Drainage System

Since large amounts of water will be expelled from the consolidating dredged fill and marine clay, a horizontal drainage system may be required to promote drainage from each compartment. Drainage will help preserve the desiccated crust and facilitate installation of strip drains in the remainder of the compartment. It is anticipated that the use of a pontoon mounted crane will preclude the use of a drainage system, and thus reduce the cost of the project. However, if a drainage system is required, it should be installed before or simultaneously with the strip drains to increase drainage between the horizontal drainage system and the strip drains. Figure 14 presents several alternatives for the horizontal drainage system. An investigation to determine the optimal horizontal drainage system for Craney Island should be conducted during the general design phase. The cost and performance of each drainage system should be evaluated to aid the decision. The investigation may reveal that a combination of the alternatives may provide the best overall drainage system. Since the design of the horizontal drainage system is beyond the scope of this report and it may not be required due to the use of pontoon mounted equipment, the cost of the horizontal drainage system is not included in the following cost analysis.

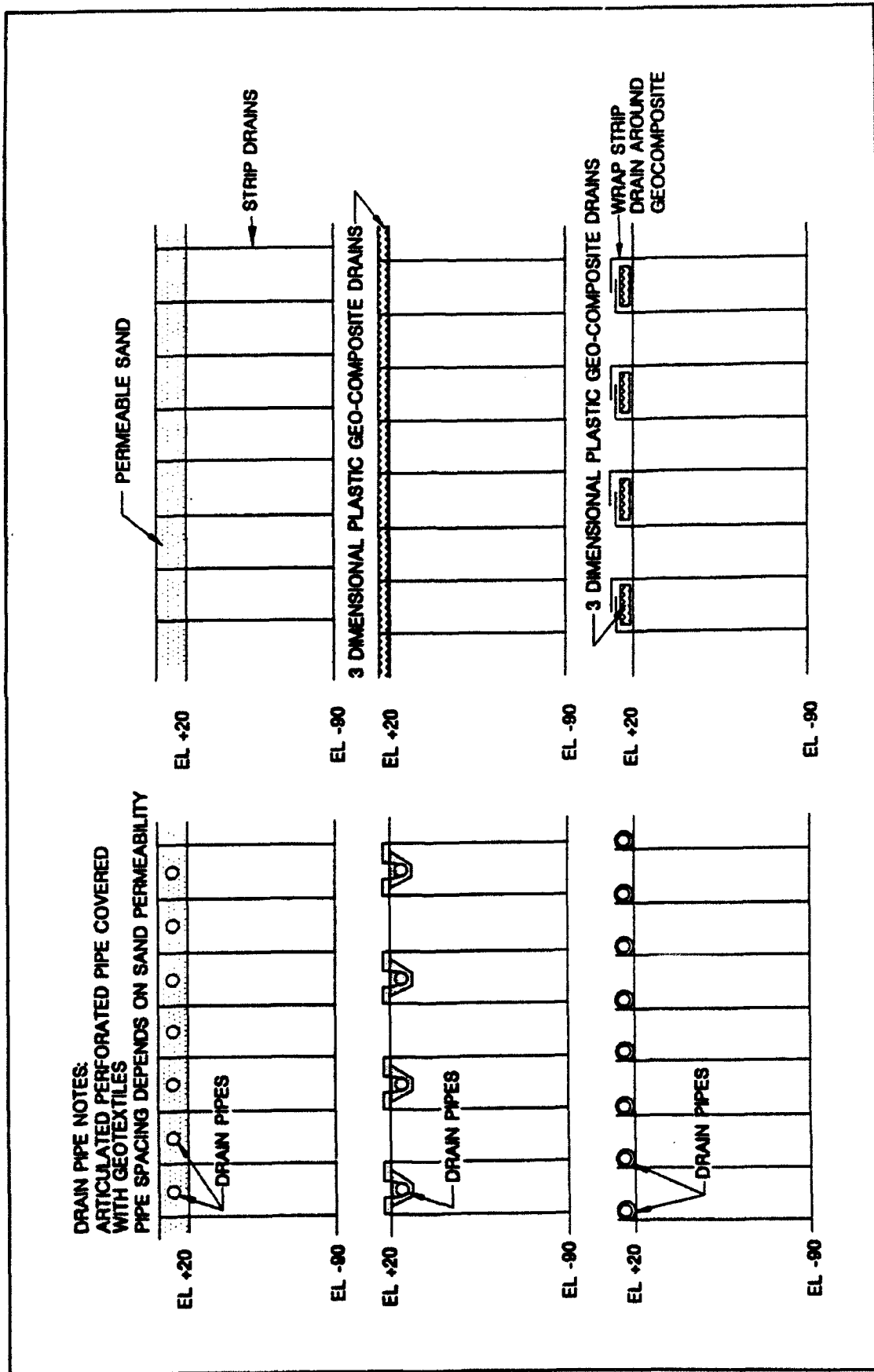


Figure 14. Alternative horizontal drainage systems for vertical strip drains

4 Estimated Cost of Vertical Strip Drains at Craney Island

Background

Previously reported case histories, for example, Ska Edeby test fills, Hong Kong Airport, Changi Airport in Singapore (Lo, 1991), show that the consolidation settlement of marine clays is approximately 10 to 30 percent of the initial layer thickness. Previous analyses of the settlement of dredged fill, for example, Palermo and Schaefer (1990), showed that consolidation settlement can be 50 percent of the initial thickness of the dredged fill. Since some consolidation has already taken place at Craney Island, it is anticipated that the range of consolidation settlement will probably be 5 to 10 percent of the initial thickness of the dredged fill and marine clay. Therefore, the consolidation settlement that will take place after strip drains are installed is probably 3 to 6 ft in the southern compartment, 5 to 10 ft in the center compartment, and 6 to 12 ft for the northern compartment. It should be pointed out that these consolidation settlements are preliminary estimates based on current pore-water pressure data at Craney Island and field case histories. Settlements and piezometric data obtained from the field test section and the subsurface investigation described in Chapter 5 of this report should be used in the design phase to quantify the magnitude of settlement and refine the following cost analysis.

Cost per Increased Storage Volume

If the southern compartment consolidates 3 to 6 ft and the area of the compartment is 734 acres, the increase in storage capacity will range from 3,553,000 to 7,105,000 cu yd. Table 4 presents the estimated consolidation settlement and the resulting increase in storage capacity for each compartment. Table 4 also presents the cost of the strip drains per increased storage capacity for each compartment. It can be seen that the cost of installing vertical strip drains ranges from \$0.45 to \$1.80/cu yd of increased storage capacity. The areas used for the center and northern compartments were 766 and 689 acres,

Compartment	Estimated Percentage and Magnitude of Settlement	Increased Storage Capacity (cu yd)	Cost of Strip Drains¹	Cost of Strip Drains Per Increased Capacity (\$/cu yd)
South	5% (3 ft)	3,553,000	\$6,291,000	\$1.80
South	10% (6 ft)	7,105,000	\$6,291,000	\$0.90
South	20% (12 ft)	14,210,000	\$6,291,000	\$0.45
Center	5% (f ft)	6,179,000	\$10,943,000	\$1.80
Center	10% (10 ft)	12,358,000	\$10,943,000	\$0.45
Center	20% (20 ft)	24,716,000	\$10,943,000	\$0.45
North	5% (6 ft)	6,670,00	\$12,108,000	\$1.80
North	10% (12 ft)	13,339,000	\$12,108,000	\$0.45
North	20% (24 ft)	26,678,000	\$12,108,000	\$0.45

¹ Total cost does not include horizontal drainage system.
Note: 1 acre = 4,840 sq yd

respectively. Figure 15 presents a relationship between the estimated cost of the vertical strip drains per increased storage capacity and the percentage of consolidation settlement. This relationship was extended to a consolidation settlement of 20 percent of the initial thickness of the dredged fill and marine clay (Table 4). Therefore, this relationship can be used to estimate the cost per increased storage capacity for percentages of consolidation settlement ranging from 5 to 20 percent. It should be noted that the costs shown in Figure 15 correspond to a 12 ft triangular spacing of strip drains that will yield a degree of consolidation equal to 90 percent in 4 years.

The current cost of disposing of dredged material in Craney Island consists of an Operation and Maintenance fee of \$0.90/cu yd (Szelest 1991). Therefore, the total cost of disposal would range from \$1.35 to \$2.70/cu yd if the cost of the vertical strip drains is added to the Operation and Maintenance cost. This cost is still significantly less than ocean dumping, which is estimated to be \$7/cu yd (Szelest 1991). In addition, the use of Craney Island allows dredging to be performed by hydraulic dredges instead of excavation type dredges. This should reduce the time required for dredging and the ship traffic in Norfolk Harbor and Channels. More importantly, the use of strip drains will significantly prolong the life of Craney Island. Consolidation of the dredged fill and underlying marine clay will allow the perimeter dikes to be raised to higher elevations without setbacks or berms. This will provide additional storage capacity at a small cost and may allow future development of the site. An undrained strength stability analysis described in Chapter 6 of this report should be performed to determine the height and geometry of the new perimeter dikes.

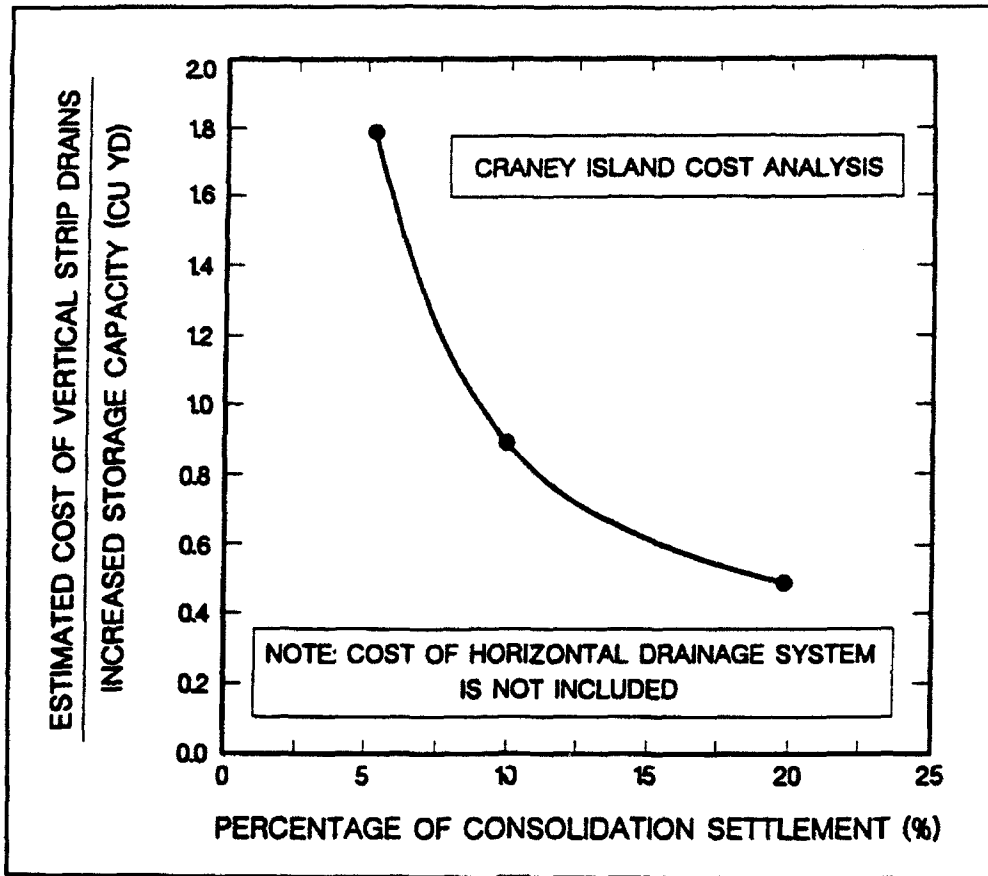


Figure 15. Effect of consolidation settlement on cost per increased storage capacity at Craney Island

5 Field Test Section and Instrumentation

Field Test Section

A field test section should be constructed, instrumented, and monitored to verify the assumptions of the preliminary design. Since the Northern compartment currently has a well-developed desiccated crust, it is recommended that this compartment be used for the test section. The northern compartment will also require the longest drains, which will provide a good comparison between measured and predicted effects of smear zone and well resistance. A site for the test section has been identified near the cross dike at the southern end of this compartment. It is anticipated that the test section will be 400 ft by 500 ft. Due to the small area of the test section, a blanket of dredged sand will be used for the horizontal drainage system. The vertical strip drains will be pushed through the sand blanket into the foundation sands. It is imperative that the elevation of the dredged fill be surveyed before and after the placement of the sand blanket. The top of the sand blanket should be monitored periodically until the strip drains are installed. After the strip drains are installed, the elevation of the sand blanket should be surveyed at least once a day. The changes in elevation with time will provide an insight into the effectiveness of the strip drains.

Subsurface Investigation and Field Monitoring

It is also recommended that an extensive subsurface investigation be conducted in the area of the test section to aid interpreting the effectiveness of the drains. The subsurface investigation should be conducted before the strip drains are installed in the test section. A similar investigation should be conducted before strip drains are installed throughout the remaining portion of the northern compartment. The following is a preliminary list of the tests that should be performed to investigate the subsurface conditions:

- a. Extensive cone and piezocone penetration tests should be conducted to characterize the soil stratigraphy in the test section and northern compartment and to estimate the magnitude and variability of the undrained

shear strength, S_u , and the coefficient of consolidation. The pore-water pressure versus depth profile obtained using the piezocone tests will help delineate irregular layering, due to permeable seams and lenses, in the dredged fill and foundation materials. Pore-water pressure dissipation tests should be conducted every 10 to 20 ft in the piezocone tests to estimate the coefficient of consolidation.

- b. Install 12 piezometers throughout the northern compartment. Five of the piezometers should be installed in the test section area. If the test section is square, the piezometers should create an "X" with one piezometer in the middle of the section and the other four midway between the corners and middle of the square section. The remaining seven should be spaced throughout the remainder of the northern compartment to quantify the excess pore-water pressures in the other portions of the compartment. Five piezometers should be installed at different depths at each location to determine the variation of pore-water pressure with depth. The following depths are suggested, assuming that the surface of the dredged fill is at elevation +20 ft MLW: +10, -20, -40, -60, -75 MLW ft. Field vane shear tests should be conducted every 10 to 20 ft in half of the borings used to install the piezometers. Water content samples should be taken every 10 ft in all of the borings. The field vane shear and moisture content tests will be used with the cone penetration test results to estimate the magnitude and variability of S_u and the coefficient of consolidation.
- c. After equilibrium conditions have been established in the piezometers, permeability tests should be performed in most, if not all, of the piezometers. One possible test procedure to accomplish this might be to pump the water out of the piezometer and measure the rate at which the water level returns to its original condition. These tests will provide important information on the in situ permeability and coefficient of consolidation.
- d. Settlement plates should be installed throughout the test section and the northern compartment to monitor the effectiveness of the strip drains. It is important that these settlement plates be placed before the horizontal drainage system is installed so that accurate settlement measurements can be obtained as the dredged fill and foundation clay consolidate. The settlement plates should be surveyed periodically until the strip drains are installed. After installation of the strip drains, the plates should be surveyed at least once a week or as needed so the rate of settlement can be determined.
- e. If the test section is located near a perimeter dike or an interior dike, one to three slope inclinometers should be installed at the outboard toe of the dike. The inclinometers should be keyed into the dense sand foundation at approximately el -100 ft. The slope inclinometers will help determine if the dike and foundation material are consolidating vertically or spreading laterally. The slope inclinometers may also provide a warning of slope instability if they are monitored regularly.

- f.* After consolidation has been completed, piezocone penetration tests should be conducted within 20 ft of the previous cone penetration test locations. In addition, several borings should be drilled within 20 ft of the previous boreholes to measure the new water content profile. The change in water content and penetration resistance will be related to the increase in S_u and the magnitude of settlement. Quantifying the magnitude of settlement and the increase in S_u will aid in determining whether installing strip drains in the other two compartments is economically feasible.

6 Undrained Strength Stability Analysis

Background

Previous stability analyses of the perimeter dikes at Craney Island, for example, Fowler et al. (1987), utilized a total stress analysis procedure. The undrained shear strength, S_u , used in a total stress analysis is measured before loading, and thus does not reflect any strength gain due to subsequent consolidation. The values of S_u used in the previous analyses were obtained from field vane shear and undrained triaxial tests from 1981 to 1986. Since the effective stress is constantly increasing due to consolidation, the use of previously measured values of S_u will underestimate the strength of the confined dredged material and the foundation clay. Therefore, the values of S_u and the calculated factor of safety were only accurate for the conditions in 1981 to 1986. The use of a total stress analysis is only satisfactory if new values of S_u are continuously measured to reflect the strength increase due to consolidation. This would involve extensive testing and cost to continuously update the undrained shear strength. Therefore, it is recommended that an undrained strength stability analysis be used to update the undrained shear strength and estimate the current stability of the perimeter dikes.

Application to Perimeter Dikes at Craney Island

The undrained strength stability analysis (USSA) was first described by Mesri (1983) and re-introduced by Ladd (1991) as the undrained strength analysis (USA). USSA is a total stress analysis except that a relationship between S_u and effective stress is developed that allows S_u to be updated as the effective stress changes. The technique used to determine the variation of S_u with effective stress depends on the magnitude of the project and the level of the investigation. For preliminary design studies, it is recommended that S_u be determined from existing correlations, such as $S_u = 0.22 \times P_p'$, where P_p' is the maximum preconsolidation pressure (Mesri 1975, 1989). Mesri's correlation has been verified using field case histories, in situ tests, and laboratory shear tests. As a result, it provides a simple but reliable means for estimating the variation in S_u with changes in effective stress. It should be

noted that other S_u versus effective stress correlations have been presented by other researchers, such as, Jamiolkowski et al. (1985) and Ladd (1991), and will be considered during this analysis. Since the dredged fill and the underlying marine clay are under-consolidated, the preconsolidation pressure is assumed to be equal to the vertical effective overburden pressure. The effective overburden pressure will be estimated using piezometric data and stress distribution theory.

Utilizing existing field and laboratory shear strength data from Craney Island, for example, Fowler et al. (1987), General Design Memorandums (1949, 1986) and the results of the proposed subsurface investigation described in Chapter 5 of this report, it is anticipated that a relationship between S_u and effective stress can be established for Craney Island. This relationship will be used to estimate the current values of S_u and the maximum height of the perimeter dikes after the strip drains have been installed. The four dike cross sections shown in Figures 2 through 5 will initially be used in the proposed undrained strength stability analysis to determine the maximum height of the perimeter dikes. However, different dike geometries, construction materials, and dike realignments will also be considered. Due to consolidation, it is anticipated that the proposed undrained strength stability analysis will result in factors of safety that are higher than those presented by Fowler et al. (1987). This should allow the perimeter dikes to be raised significantly above the current elevations of +34 and +40 ft MLW. Raising the perimeter dikes will provide additional storage capacity and surcharge to the existing dredged fill and marine clay. It is anticipated that the micro computer program, UTEXAS2 (CAGE 1987), will be used to calculate the factor of safety for each cross section.

7 Plan of Action for Installing Vertical Strip Drains in Craney Island

Detailed Plan of Action for Installing Vertical Strip

The research, design, installation engineering and cost management of utilizing vertical strip drains to increase the storage capacity of Craney Island will be a formidable challenge. A detailed preliminary plan of action which describes, assigns, and schedules the specific tasks required to design, install, and monitor vertical strip drains at Craney Island has been developed. It is anticipated that a strip drain test section will be installed in the northern compartment to illustrate the effectiveness of strip drains on accelerating the consolidation of the dredged fill and foundation clay. Upon successful completion of the test section, strip drains will first be installed in the northern compartment at Craney Island to take advantage of the well developed crust in this compartment. Upon successful installation of vertical strip drains in the northern compartment, vertical strip drains will be installed in the center and southern compartments following a similar plan of action.

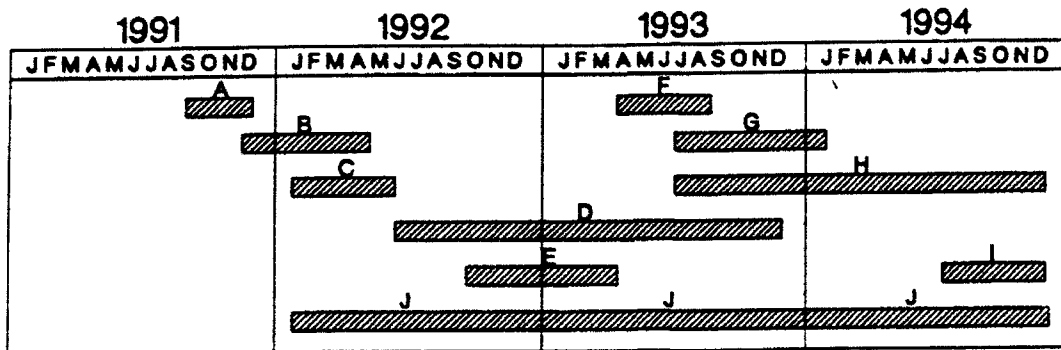
Where possible, task details and suggested assignments are presented in the following detailed plan of action. The tasks assigned to WES will be completed by the Geotechnical Laboratory at WES unless otherwise noted. Figure 16 presents a preliminary time table for the completion of the major tasks, A through J, required to install vertical strip drains in the northern compartment of Craney Island.

Assignment of Specific Tasks

A. PROJECT MANAGEMENT PLAN PHASE - September to December 1991

A.1. Develop Work Scope and Other PMP Components (WES, NAO): This report presents the work scope and a preliminary design of the vertical strip drains for planning-level discussions. This design will be refined in Item B.3.

PLAN OF ACTION:



<u>TASK</u>	<u>DESCRIPTION</u>
A	PROJECT MANAGEMENT PLAN PHASE
B	FEASIBILITY PHASE
C	TEST SECTION DESIGN PHASE
D	GENERAL DESIGN PHASE
E	PLANS AND SPECIFICATIONS PHASE
F	ACQUISITION PHASE
G	CONSTRUCTION PHASE
H	MONITORING PHASE
I	PERIMETER DIKE DESIGN PHASE
J	OTHER WORK

Figure 16. Schedule of major tasks for installing vertical strip drains in the northern compartment of Craney Island

A.2. Develop Study and Design Cost Estimates (NAO, WES): NAO will develop a cost estimate for the tasks assigned to NAO and NAD, and combine them with the WES cost estimate to develop a total project cost.

A.3. Hold Issue Conference (NAO, WES, NAD):

A.4. Prepare Final Project Management Plan (NAO):

A.5. Conduct Command Briefings (NAO, WES):

B. FEASIBILITY PHASE - December 1991 to May 1992

B.1. Literature/Technical Data Review (WES, NAO): WES will conduct an extensive literature review on the design, specification, and installation of vertical strip drains. A database of previous projects in which vertical strip drains were used to consolidate marine clays will also be assembled to investigate previous strip drain spacing, pattern, and the resulting consolidation settlements. This information will be used to estimate the settlement that may occur at Craney Island. In addition, WES will compile data on the permeability, compressibility, and shear strength of marine sediments. NAO will assemble all field and laboratory data on the dredged fill and foundation clay. NAO will use this information to develop design cross-sections for the three disposal compartments at Craney Island and the strip drain design parameters, such as permeability, vertical coefficient of consolidation and horizontal coefficient of consolidation. These parameters will be used by WES to develop concept designs.

B.2. Feasibility Level Field Investigation (WES, NAO): NAO should carry out the feasibility level field investigation. NAO will reduce and plot the resulting data and provide it to WES. WES will oversee part, if not all, of the field investigation and use the data to develop concept designs.

B.3. Concept Designs (WES, NAO): WES will use the data from the literature review and the feasibility level field investigation to develop concept designs. The designs will be reviewed by NAO.

B.4. Cost Engineering/Economic Analysis (NAO, WES): NAO will develop a cost engineering/economic analysis for the concept designs. WES will provide considerable input concerning the cost of various items or tasks that will be used in the design concepts.

B.5. Technical Feasibility Report (WES): WES will write a technical feasibility report describing the literature review, the design parameters and cross-sections, design concepts, and cost analysis.

B.6. Review Process (NAO, NAD, WES): NAO and NAD will conduct an extensive review of the technical feasibility report.

C. TEST SECTION DESIGN PHASE - January 1992 to June 1992

C.1. Select Test Section Location (WES, NAO): WES and NAO will select a location and size for test section based on the design parameters and cross-sections developed by WES and NAO.

C.2. Design Phase Field Investigation (NAO, WES): If necessary, NAO will carry out a field investigation to refine the design parameters and cross-section in the test section area. WES will provide technical advice as necessary.

C.3. Design of Vertical Strip Drains and Horizontal Drainage System (WES, NAO): WES will use the design parameters and cross-sections to design the spacing, length, and pattern of the strip drains in the test section. In addition, a horizontal drainage system will be designed to promote drainage of the expelled water.

C.4. Design Memoranda (NAO, WES): NAO will write the design memoranda for the test section using the design developed by WES. WES will conduct an extensive review of the design memoranda.

C.5. Draft Plans and Specifications (NAO, WES): NAO will draft the plans and specifications to construct the vertical strip drain test section. WES will provide considerable input to the plans and specifications and conduct an extensive review.

C.6. Review Process (NAO, NAD, WES): NAO and NAD will conduct an extensive review of the design memoranda and the plans and specifications for constructing the vertical strip drain test section.

C.7. Final Plans and Specifications (NAO, WES): NAO will incorporate WES and NAD review comments and NAO will write the final plans and specifications to construct the vertical strip drain test section.

C.8. Monitoring Plan (NAO, WES): NAO will install and monitor the field instrumentation that will consist of slope inclinometers, piezometers, and settlement plates. NAO will reduce and plot the resulting data and provide it to WES. WES will oversee part, if not all, of the instrumentation installation and use the data to verify the design procedure and the effectiveness of vertical strip drains.

C.9. Installation of Horizontal Drainage System and Vertical Strip Drains (NAO): NAO will supervise installation of the horizontal drainage blanket and the vertical strip drains in the test section. WES will periodically inspect the installation of the drainage blanket and the vertical strip drains and assist NAO as necessary.

C.10. Monitor Instrumentation (NAO, WES): NAO will monitor the instrumentation in the test section, reduce and plot the resulting data, and provide the results to WES.

C.11. Analysis of Field Instrumentation Data (WES): WES will use the field data to verify the design procedure and effectiveness of installing strip drains on the consolidation of the dredged fill and underlying foundation soil.

C.12. Reevaluation of Design Procedures (WES): WES will use the data from the test section to reevaluate the strip drain design for the remaining portion of the northern compartment. If necessary, the spacing and pattern of the vertical strip drains will be redesigned.

C.13. Monitoring/Performance Report (WES): WES will write a comprehensive report describing the performance of the vertical strip drain test section. The report will include an evaluation of the effectiveness of strip drains in consolidating the dredged fill and foundation clay and a revised cost engineering/economic analysis of installing strip drains throughout Craney Island.

C.14. Follow-Up Monitoring and Analysis (NAO, WES): NAO will continue to monitor the field instrumentation that was installed in the test section and the northern compartment. NAO will reduce and plot the resulting data and provide it to WES. WES will use the data to reevaluate the design procedure and effectiveness of installing strip drains on the storage capacity.

D. GENERAL DESIGN PHASE - June 1992 to December 1993

D.1. Design Phase Field Investigation (WES, NAO): If necessary, NAO will carry out an additional field investigation to refine the design parameters and cross-sections in the northern, middle and southern compartments. The refinement may also require laboratory permeability, self-weight consolidation, and oedometer tests to finalize the design values of permeability and coefficient of consolidation. NAO will make recommendations for final geotechnical soil properties and soil profiles to WES.

D.2. Sand Source Investigation (NAO, WES): NAO will locate and characterize a sand source for possible use as a horizontal drainage system. The characterization should include extensive grain size analyses and permeability tests to ensure adequate drainage. WES will review the findings and assist as necessary.

D.3. Permeability of Vertical Strip Drains (WES): WES will conduct fundamental research on the permeability of the proposed strip drains. In particular, the long-term (20 to 40 years) permeability and clogging of the filter fabric, the effect of drain folding due to excessive settlement, and the effect of creep of the filter fabric into the core on the permeability of the strip drains will be investigated. This research is essential since this is the first project in which vertical strip drains will be required to function for more than 1 to 5 years. It is planned that the strip drains will continue to dissipate excess pore-water pressures that are generated as additional dredged fill is placed in Craney Island for many years. The research will involve long term permeability tests on various strip drains. The strip drains will be inserted in a slurry of Craney Island dredged material and the flow rate will be monitored periodically. After a period of time the drains will be exhumed to investigate the longevity and permeability of the drains. It is anticipated that a new strip drain suited for long-term drainage applications will be developed from this study.

D.4. Durability of Vertical Strip Drains (WES): WES will also conduct fundamental research on the durability of the proposed strip drains. In particular, the long-term (20 to 40 years) biological, chemical, and creep effects

on the well resistance or flow capacity of the strip drain core will be investigated using experiments similar to those just described.

D.5. Effect of Installation on Strip Drains (WES): WES will conduct fundamental research on the effect of installation procedures on soil disturbance. The installation method will influence the degree of disturbance, extent of the disturbed zone, and the effects of the mandrel and base plate on soil disturbance. Excess pore-water pressures are generated by insertion of the base plate and mandrel into the ground. This causes consolidation of the soil near the drain and a reduction in permeability of the soil near the strip drain. The size and shape of the base plate and mandrel need to be carefully studied and specified to reduce the extent of disturbance and maximize drainage. In addition, the insertion technique, static or dynamic, needs to be carefully studied and specified. The research will involve laboratory model tests to investigate the amount of disturbance induced by various insertion techniques, mandrels, and base plates. A slurry of Craney Island dredged material will be placed in a large container and various base plates, including reinforcing bars, and mandrels will be used to insert strip drains into the slurry. The slurry will be consolidated periodically and the consolidation time rates will be compared to determine the effect of disturbance on the effectiveness of the strip drains. The test section settlement rates will be used to verify the laboratory test results.

D.6. Design of Vertical Strip Drains (WES): WES will use the research results from Tasks D.3. through D.5., the final geotechnical soil properties, and final soil profiles to design the spacing, length, and pattern of the strip drains in the northern, middle, and southern compartments. During this task, the microcomputer program PSDDF, i.e., Primary Consolidation, Secondary Compression, and Desiccation in Dredged Fill, developed by Stark (1991) will be modified to analyze consolidation due to radial flow to simulate the installation of vertical strip drains. The use of PSDDF will also allow the variation of the coefficient of consolidation with effective stress to be accurately modeled. At the present time, a constant value of coefficient of consolidation is assumed for an average effective stress in the soil profile in the northern compartment. Upon completion, PSDDF will be able to incorporate the decrease in the coefficient of consolidation with depth, and provide a better methodology for designing the spacing, length, and pattern for vertical strip drains at Craney Island.

D.7. Design of Horizontal Drainage System (WES, NAO): WES will design the horizontal drainage system which will promote drainage of the expelled water. The drainage system may consist of perforated pipes, a geo-composite drain, and/or dredged sand depending on the cost and availability of each alternative. If pipes or prefabricated drains are used, the design will require a substantial investigation to determine the size, spacing, location, collapse potential of the pipes and/or drains under future dredged fill, clogging potential of the pipes and/or drains, and the design of a collection system. WES will develop a design for the horizontal drainage system and NAO will provide technical information and review comments as necessary.

D.8. Cost Engineering/Economic Analysis (NAO, WES): NAO will develop a cost engineering/economic analysis for the concept designs. WES will provide considerable input concerning the cost of various items or tasks that will be used in the design concepts. WES will review and modify the cost analysis as needed.

D.9. Monitoring Plan (NAO, WES): NAO will install and monitor the field instrumentation described in C.8. NAO will reduce and plot the resulting data and provide it to WES. WES will oversee part, if not all, of the field investigation and use the data to verify the design procedure and effectiveness of installing vertical strip drains on the storage capacity.

D.10. Environmental Documents (NAO, WES): NAO will develop the necessary environmental documents to construct the horizontal drainage system and install vertical strip drains at Craney Island. It is recommended that Dr. Mike Palermo of the Environmental Laboratory at WES help develop the documents and provide extensive review.

D.11. Construction Plan (NAO, WES): NAO will develop the construction plan with input from WES.

D.12. Acquisition Plan (NAO): NAO will develop the necessary acquisition plan. If needed, WES will provide input in the development of the acquisition plan.

D.13. Design Memoranda (NAO): NAO will write the design memoranda for the construction of the horizontal drainage system and the installation of vertical strip drains in the northern, middle, and southern compartments. WES will conduct an extensive review of the design memoranda.

D.14. Value Engineering Review (NAO): NAO will perform a value engineering review.

D.15. Review Process (NAO, WES, NAD): NAO, WES, and NAD will conduct an extensive review of the design memoranda for the construction of the drainage blanket and the installation of vertical strip drain test section.

E. PLANS AND SPECIFICATIONS PHASE - October 1992 to April 1993

E.1. Draft Plans and Specifications (NAO, WES): NAO will draft the plans and specifications for construction of the horizontal drainage system and the installation of vertical strip drains. WES will provide considerable input to the specifications.

E.2. Review Process (NAO, WES, NAD): NAO, WES, and NAD will conduct an extensive review of the plans and specifications for constructing the drainage system and vertical strip drain installation.

E.3. Final Plans and Specifications (WES, NAO): WES and NAO will incorporate the review comments and write the final plans and specifications for the drainage system and the vertical strip drains.

F. ACQUISITION PHASE - April 1993 to September 1993

F.1. CBD/Pre-solicitation Notice (NAO):

F.2. Advertising (NAO):

F.3. Government Cost Estimate (NAO):

F.4. Bid Opening (NAO):

F.5. Award (NAO):

G. CONSTRUCTION PHASE - July 1993 to January 1994

G.1. Install Monitoring Instrumentation (NAO, WES): NAO will install and monitor the field instrumentation that was described in C.8. NAO will reduce and plot the resulting data and provide it to WES. WES will oversee part, if not all, of the field investigation and use the data to verify the design procedure and effectiveness of installing vertical strip drains on the storage capacity.

G.2. Construction of Horizontal Drainage System (NAO, WES): NAO will oversee construction of the horizontal drainage system. If pipes and/or drains are used, the construction supervision will require careful monitoring of placement and sealing of pipe and/or drain joints. WES will periodically oversee part of the drainage blanket construction.

G.3. Installation of Vertical Strip Drains (NAO, WES): NAO will oversee the installation of the vertical strip drains. This will include the proper spacing, pattern, and storage of the drains to resist ultraviolet deterioration. WES will oversee part, if not all, of the vertical strip drain installation.

H. MONITORING PHASE - July 1993 to January 1995

H.1. Monitor Instrumentation (NAO, WES): NAO will monitor the instrumentation in the northern compartment, reduce and plot the resulting data, and provide the results to WES.

H.2. Analysis of Field Instrumentation Data (WES): WES will use the field data to verify the design procedure and effectiveness of installing strip drains on the consolidation of the dredged fill and underlying foundation soil. WES will use the data from the northern compartment to reevaluate the strip drain

design for the center and southern compartments. If necessary, the spacing and pattern of the vertical strip drains will be modified.

H.3. Cost Engineering/Economic Analysis (NAO, WES): NAO will develop a revised cost engineering/economic analysis based on the settlements observed in the northern compartment. WES will provide considerable input concerning the cost of various items or tasks that will be revised. WES will review and modify the cost analysis as needed.

H.4. Monitoring/Performance Report (WES): WES will write a comprehensive report describing the performance of the vertical strip drain in the northern compartment of Craney Island. The report will include an evaluation of the effectiveness of strip drains in consolidating the dredged fill and foundation clay and a revised cost engineering/economic analysis for installing vertical strip drains in the center and southern compartments.

H.5. Follow-Up Monitoring and Analysis (NAO, WES): NAO will continue to monitor the field instrumentation that was installed in the test section and northern compartment. NAO will reduce and plot the resulting data and provide it to WES. WES will use the data to reevaluate the design procedure and effectiveness of installing strip drains on the storage capacity.

I. PERIMETER DIKE DESIGN PHASE - July 1994 to January 1995

I.1. Measure Shear Strength of Dredged Fill and Foundation Clay (NAO, WES): The magnitude and variability of the undrained shear strength, S_u , after consolidation using vertical strip drains should be measured using piezocone penetration tests. Field vane shear tests could also be conducted to verify the results of the piezocone penetration tests. NAO will contract and monitor the piezocone penetration tests in the northern compartment, reduce and plot the resulting data, and provide the results to WES. WES will oversee part, if not all, of the piezocone penetration tests.

I.2. Undrained Strength Stability Analysis (WES): WES will use the values of S_u obtained from the piezocone penetration tests in an undrained strength stability analysis of the perimeter dikes. The use of an undrained strength stability analysis will allow the variation of undrained shear strength with effective stress to be modeled, and thus provide a better estimate of the maximum dike heights that may be achieved.

I.3. Design of New Perimeter Dikes (WES): The undrained strength stability analysis will be used to develop a new cross-section for the perimeter dikes at Craney Island. It is anticipated that the new dikes will be constructed to elevations greater than +40 ft.

I.4. Design New Weir and Outlet Structures (NAO, WES): If necessary, NAO will design a new weir and outlet structures for the northern compartment. A new structure might be required if the significant differential

settlements occur. WES will provide input during the design process. WES will review and modify the design as needed.

J. OTHER WORK - January 1992 to January 1995

J.1. Project Management (NAO-OP):

J.2. Technical Management (NAO):

J.3. Engineering Management (NAO-EN):

J.4. Operations Management (NAO-OP):

J.5. Program Development and Budget (NAO-PD):

J.6. Construction Management (NAO-OP):

8 Conclusions and Recommendations

It was concluded that it is technically feasible to consolidate the dredged fill and foundation clay at Craney Island using vertical strip drains. The use of vertical strip drains will significantly reduce the time required for consolidation. This consolidation will result in a rapid increase in storage capacity and soil shear strength. This strength gain will allow perimeter dikes to be constructed to higher elevations without setbacks or stability berms. The installed strip drains and horizontal drainage system will also accelerate consolidation of the existing dredged fill and foundation clay as new dredged material is placed in Craney Island.

A preliminary triangular strip drain spacing of 12 ft is recommended for Craney Island. This spacing will result in 90 percent consolidation in 4 years based on values of coefficient of consolidation obtained from existing laboratory test results and preliminary permeability tests in existing piezometers. It is recommended that a subsurface investigation be conducted before the strip drains are installed to clarify the subsurface stratigraphy and the consolidation properties of the dredged fill and foundation clay. In addition, a field test section should be constructed to demonstrate the effectiveness of the vertical strip drains. The elevation of the dredged fill should be carefully surveyed before and after the strip drains are installed to aid in evaluating the strip drains. A subsurface investigation should be conducted after consolidation to quantify the increase in undrained shear strength in the dredged fill and foundation clay.

A detailed plan of action is presented herein which describes, assigns, and schedules the specific tasks required to design, install, and monitor vertical strip drains at Craney Island. The details of each task and the responsibility of WES and NAO in executing each task is presented. In addition, a preliminary time table for the completion of the major tasks for installing vertical strip drains in the northern compartment of Craney Island is presented.

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Appendix A
VDRAIN: Interactive
Microcomputer Program for
Design of Vertical Strip Drains

```

*****
*
* DECEMBER, 1991: VDRAIN.EXE WAS DEVELOPED TO DESIGN VERTICAL
* STRIP DRAINS FOR CONSOLIDATION OF COMPRESSIBLE CLAYS. THE
* SOLUTION INCLUDES RADIAL AND VERTICAL CONSOLIDATION, WELL
* RESISTANCE, AND THE EFFECT OF SMEAR. THE MAIN PROGRAM WAS
* DEVELOPED BY DR. TIMOTHY D. STARK, MR. SUNGHOON CHOI, AND
* IVAN CONTRERAS AT THE UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN
*
*****

```

```

REAL      U(3), T(4)
CHARACTER INFILE*12, TITLE*70, VARC(18)*50, DFILE*12
CHARACTER NEWOLD(1)*18, FLAG*12, OUTFILE*12, ANSW*1
LOGICAL   LAST , TWICE, FILE_OK

```

```

COMMON/VAR0/ INFILE, TITLE, VARC, OUTFILE
COMMON/VAR1/ VARV(13), S, R
COMMON/VAR2/ A0, B0, TOL
COMMON/VAR3/ DE, SSQ, STR(3,4), AVEA, RNDR, RLDR, TOCO(3,4)
COMMON/CHECK/FILE_OK

```

```

LAST = .FALSE.
FLAG(1:) = ' '
INFILE = 'VDRAIN.DAT'
ICHO= 1
A0 = 5.0
B0 = 200.0
TOL = 0.001

```

```

1000 WRITE(*,2001)
2001 FORMAT(

```

```

+ 12X, '*****', //
+ 12X, '* * * * *', //
+ 12X, '          DESIGN OF VERTICAL STRIP DRAINS', //
+ 12X, '          INCLUDING WELL RESISTANCE AND', //
+ 12X, '          SMEAR EFFECTS', //
+ 12X, '* * * * *', //
+ 12X, '          UNIVERSITY OF ILLINOIS', //
+ 12X, '          AT URBANA - CHAMPAIGN', //
+ 12X, '          VERSION 1.1', //
+ 12X, '          JULY 1992', //
+ 12X, '*****', //)

```

```

C
C

```

```

CALL SETMODE(ICHO)
ICHO=2
AKS = VARV(7)
S = 1

```

```

CALL SETNEWV(NEWOLD,NO, LAST,AKS,U,T)
TWICE = .FALSE.
      U(1) = VARV(1) - 5.0
      U(2) = VARV(1)
      U(3) = VARV(1) + 5.0
      DO i = 1,3
        IF ( U(i).GE.100 ) THEN
          U(i) = 99
        END IF
      END DO
      T(1) = VARV(2) / 2.0
      T(2) = VARV(2)
      T(3) = VARV(2) * 1.5
      T(4) = VARV(2) * 2.0
      DO i = 1,3
        VARV(1) = U(i)
        DO j = 1,4
          VARV(2) = T(j)
        END DO
      END DO
1200 CALL BISEC (X0,AKS)
      IF ( X0 .LT. -5000.0 ) THEN
        WRITE(*,*) ' FATAL ERROR : INVALID DATA INPUT ... '
        WRITE(*,*) ' PROGRAM IS TERMINATED ABNORMALLY ... '
        WRITE(*,*) ' PLEASE TRY AGAIN ... '
        GO TO 1500
      ENDIF
      CALL CALVAL(X0,i,j)
      END DO
      END DO
      VARV(1) = U(2)
      VARV(2) = T(2)
      LAST = .TRUE.
      CALL DISPLAY(NEWOLD,NO, LAST,U,T,AKS)
      CALL PRINTF(NEWOLD,NO, LAST,U,T,AKS)
1500 WRITE (*,150)
      READ (*,'(A1)') ANSW
      IF((ANSW.EQ.'Y').OR.(ANSW.EQ.'y')) THEN
        CALL DISPLAY1 (NEWOLD,NO, LAST,U,T,AKS)
      END IF
      WRITE(*,200)
      READ(*,'(A12)') DFILE
      IF((DFILE.EQ.'Y').OR.(DFILE.EQ.'y')) GO TO 1000
      IF((DFILE.EQ.'N').OR.(DFILE.EQ.'n')) STOP

```

```

GO TO 1500
100 FORMAT(5X,'==>',\)
150 FORMAT(5X,'DO YOU WANT TO PRINT INPUT AND OUTPUT (Y/N)? ==>',\)
200 FORMAT(5X,'DO YOU WANT TO ANALYZE ANOTHER PROBLEM(Y/N)? ==>',\)

```

```
END
```

```

*****
*   SUBROUTINE SETMODE:  THIS SUBROUTINE SETS THE DIFFERENT MODES *
*   IN WHICH THE PROGRAM OPERATES.  THESE MODES ARE:  NEW DATA *
*   FILE, EDIT A DATA FILE, OR USE THE CURRENT DATA FILE *
*   *   *   *   *   *   *   *   *   *   *   *   *   *   *   *   *
*****

```

```
SUBROUTINE SETMODE (ICHO)
```

```

CHARACTER INFILE*12,OUTFILE*12,VARC(18)*50,TITLE*70
CHARACTER MODE1*1, ANSWER*1
LOGICAL FILE_OK,EXIST1

```

```
C
C
```

```

COMMON /VARO/ INFILE,TITLE,VARC,OUTFILE
COMMON /VAR1/ VARV(13),S,R
COMMON /CHECK/FILE_OK
5 CONTINUE
IF (ICHO.EQ.1) THEN
WRITE (*,2500)
2500 FORMAT(
+ 18X,'*****',//
+ 18X,'* * * * *',//
+ 18X,'* N = create a New data file *',//
+ 18X,'* E = use an Existing data file *',//
+ 18X,'* * * * *',//
+ 18X,'*****',//
+ 5X,'ENTER YOUR OPTION:',//,
+ 5X,'==>',\)
GOTO 17
END IF
10 WRITE (*,2000)
2000 FORMAT(
+ 18X,'*****',//
+ 18X,'* * * * *',//
+ 18X,'* N = create a New data file *',//
+ 18X,'* E = use an Existing data file *',//
+ 18X,'* C = use Current data file *',//
+ 18X,'* * * * *',//
+ 18X,'* *****',//
+ 5X,'ENTER YOUR OPTION:',//,
+ 5X,'==>',\)

```

```
C
C
```

```

17 CONTINUE
  READ (*,'(A1)') MODEL
  IF ((MODEL.EQ.'N').OR.(MODEL.EQ.'n')) GOTO 40
  IF ((MODEL.EQ.'E').OR.(MODEL.EQ.'e')) GOTO 50
  IF (((MODEL.EQ.'C').OR.(MODEL.EQ.'c')).AND.(ICHO.EQ.2)) GOTO 20
  IF (ICHO.EQ.1) GOTO 5
  GOTO 10
C
C
40 WRITE (*,200)
  READ (*,'(A12)') INFILE
C
C
  INQUIRE (FILE=INFILE,EXIST=EXIST1)
C
  IF (.NOT.EXIST1) THEN
    CALL SETINIV
    GOTO 20
  END IF
  WRITE (*,300)
  GOTO 40
C
50 WRITE (*,400)
  READ (*,'(A12)') INFILE
C
C
  INQUIRE (FILE=INFILE,EXIST=EXIST1)
C
  IF (EXIST1) THEN
    CALL READIN(*1000)
    GOTO 20
  END IF
  WRITE (*,500)
  GOTO 50
C
C
20 WRITE (*,150)
  READ (*,'(A1)') ANSWER
  IF ((ANSWER.EQ.'N').OR.(ANSWER.EQ.'n')) THEN
    FILE_OK=.FALSE.
    GOTO 1000
  END IF
  IF ((ANSWER.EQ.'Y').OR.(ANSWER.EQ.'y')) THEN
    FILE_OK=.TRUE.
    GOTO 30
  END IF
  GOTO 20
30 WRITE (*,600)
  READ (*,'(A12)') OUTFILE
  IF (OUTFILE.EQ.' ') THEN OUTFILE='VDRAIN.OUT'
1000 CONTINUE
  RETURN
150 FORMAT (5X,'DO YOU WANT TO CREATE AN OUTPUT FILE (Y/N)?',/,
+ 5X,'(IF NO, THE OUTPUT WILL BE DISPLAYED ONLY ON THE SCREEN)')

```

```

+      ,/,5X,'==>',\ )
200 FORMAT (5X,'ENTER NAME OF NEW FILE:',/,
+      5X,'==>',\ )
300 FORMAT (5X,'THERE IS A FILE WITH THAT NAME PLEASE')
400 FORMAT (5X,'ENTER NAME OF EXISTING DATA FILE:',/,
+      5X,'==>',\ )
500 FORMAT (5X,'THERE IS NO FILE WITH THAT NAME PLEASE')
600 FORMAT (5X,'ENTER NAME OF OUTPUT FILE:',/,
+      5X,'==>',\ )
END

```

```

*****
*
*   VARV = VARIABLE INPUT DATA
*   VARC = VARIABLE CHARACTER OF INPUT DATA
*   TITLE = THE TITLE OF THIS PROJECT
*
*****

```

SUBROUTINE SETINIV

CHARACTER INFILE*12, TITLE*70, VARC(18)*50, OUTFILE*12

COMMON/VARO/ INFILE, TITLE, VARC , OUTFILE
COMMON/VAR1/ VARV(13),S,R

```

VARC(1) = 'AVERAGE DEGREE OF CONSOLIDATION REQUIRED (*)'
VARC(2) = 'TIME ALLOWED TO REACH DEGREE OF CONSOLIDATION'
VARC(3) = 'HORIZONTAL COEFFICIENT OF CONSOLIDATION'
VARC(4) = 'VERTICAL COEFFICIENT OF CONSOLIDATION'
VARC(5) = 'THICKNESS OF COMPRESSIBLE CLAY LAYER (H)'
VARC(6) = 'MAXIMUM DRAINAGE LENGTH OF CLAY LAYER (H OR H/2)'
VARC(7) = 'HORIZONTAL PERMEABILITY OF UNDISTURBED SOIL'
VARC(8) = 'PERMEABILITY OF THE STRIP DRAIN'
VARC(9) = 'WIDTH OF STRIP DRAIN'
VARC(10) = 'THICKNESS OF STRIP DRAIN'
VARC(11) = 'MAXIMUM LENGTH OF STRIP DRAIN'
VARC(12) = 'AREA TO BE CONSOLIDATED WITH STRIP DRAINS'
VARC(13) = 'COST PER LENGTH OF INSTALLED STRIP DRAIN'
VARC(14) = 'SMEAR ZONE EFFECTS'

VARC(15) = 'SAVE DATA FILE AND REMAIN IN VDRAIN'
VARC(16) = 'SAVE DATA FILE AND EXIT TO DOS'
VARC(17) = 'SAVE DATA FILE AND EXECUTE VDRAIN'
VARC(18) = 'EXIT TO DOS'

```

```

DO 1111 I = 1, 13
  VARV(I) = 0.0

```

1111 CONTINUE

```

WRITE(*,'(A31)') ' ENTER A TITLE FOR THIS PROJECT?'
READ(*,'(A70)') TITLE

```

```
RETURN
END
```

```
*****
*
* SUBROUTINE READIN: READS EXISTING DATAFILE AND CREATES A NEW *
* DATAFILE. THE VARIABLE INFILE IS THE EXISTING DATAFILE NAME, *
* A0 REPRESENTS THE LOWER LIMIT FOR SOLVING EQUATION (5), AND *
* B0 REPRESENTS THE UPPER LIMIT FOR SOLVING EQUATION (200) *
*
*****
```

```
      SUBROUTINE READIN(*)
      CHARACTER INFILE*12, TITLE*70, VARC(18)*50, DUMC*1 ,OUTFILE*12
      COMMON/VAR0/ INFILE, TITLE, VARC, OUTFILE
      COMMON/VAR1/ VARV(13),S,R
      COMMON/VAR2/ A0, B0, TOL
      OPEN(UNIT=11,FILE=INFILE,STATUS='OLD',ERR=9010)
      N=0
      READ(11,'(/,28X,A70,/)', ERR=9020, END=9030) TITLE
      DO 1110 N=1,13
      READ(11,'(I3,2X,A50,E13.2)', ERR=9020, END=9030) IN,
+
1110 CONTINUE
      N = 14
      READ(11,'(I3,2X,A50)', ERR=9020, END=9030) IN,VARC(N)
      READ(11,*)
      DO IROW = 15, 18
      READ(11,'(I3,2X,A50)',ERR=9020, END=9030) IN,VARC(IROW)
      ENDDO
      CLOSE(11)
1200 RETURN
9010 WRITE(*,2000) INFILE
      WRITE(*,2010)
      READ(*,'(A1)') DUMC
      RETURN 1
9020 WRITE(*,2020) INFILE,N
      WRITE(*,2010)
      READ(*,'(A1)') DUMC
      CLOSE(11)
      RETURN 1
9030 WRITE(*,2030) INFILE, N
```

```

WRITE(*,2010)

READ(*,'(A1)') DUMC
CLOSE(11)

RETURN 1

2000 FORMAT(' ERROR OPENING DATAFILE',1X,A12)
2010 FORMAT(' PLEASE TYPE [ENTER] TO CONTINUE.')
2020 FORMAT(' ERROR LOADING DATAFILE',1X,A12,'LINE',1X,I2)
2030 FORMAT(' END OF FILE ENCOUNTERED READING DATAFILE',1X,A12,'LINE',
+         1X,I2)
END

*****
*
*   NEWOLD(1) = CURRENT INPUT DATA
*   NEWOLD(2) = NEW INPUT DATA
*
*****

SUBROUTINE SETNEWV (NEWOLD, NO, LAST,AKS,U,T)

REAL      U(1), T(1)
CHARACTER INFILE*12, TITLE*70, VARC(18)*50, NEWOLD(2)*(*)
CHARACTER OUTFILE*12, DUMMY*12
LOGICAL   LAST,ERROR

COMMON / VAR0 / INFILE, TITLE, VARC , OUTFILE
COMMON / VAR1 / VARV(13),S,R
COMMON / VAR2 / A0, B0, TOL
COMMON / VAR3 / DE,SSQ,STR(3,4),AVEA,RNDR,RLDR,TOCO(3,4)

NEWOLD(1) = 'CURRENT INPUT DATA'

NO      = 1
ERROR = .FALSE.

1000 WRITE(*,2000)
WRITE(*,2010) NEWOLD(1),TITLE,
+           (N,VARC(N),VARV(N),N=1,13),(N,VARC(N), N=14,18)
WRITE(*,*)
N =1
NO =2
DO WHILE (N.LE.15)
WRITE(*,2015)
READ(*,'(I2)') N
IF (N.LE.13) THEN
9000 WRITE(*,2020) VARC(N)
READ(*,*,ERR=9000) VARV(N)
IF ((N.EQ.1)) THEN

```

```

        U(1) = VARV(1) - 5.0
        U(2) = VARV(1)
        U(3) = VARV(1) + 5.0
        DO i = 1,3
            IF( U(i).GE.100 ) THEN
                U(i) = 99
            END IF
        END DO
    END IF
    IF ((N.EQ.2)) THEN
        T(1) = VARV(2) / 2.0
        T(2) = VARV(2)
        T(3) = VARV(2) * 1.5
        T(4) = VARV(2) * 2.0
    END IF
END IF

IF(N.EQ.14) THEN
    WRITE(*,2030)
    READ(*,'(A1)') DUMMY
    IF ((DUMMY.EQ.'Y').OR.(DUMMY.EQ.'y')) THEN
        WRITE(*,2040)
        READ(*,'(A1)') DUMMY
        IF ((DUMMY.EQ.'Y').OR.(DUMMY.EQ.'y')) THEN
            WRITE(*,2050)
            READ(*,*) S
        ELSE IF ((DUMMY.EQ.'N').OR.(DUMMY.EQ.'n')) THEN
            S=2
        END IF
        WRITE(*,2060)
        READ(*,'(A1)') DUMMY
        IF ((DUMMY.EQ.'Y').OR.(DUMMY.EQ.'y')) THEN
            WRITE(*,2070)
            READ(*,*) R
            AKS = VARV(7) * R
        ELSE IF ((DUMMY.EQ.'N').OR.(DUMMY.EQ.'n')) THEN
            R = 0.5
            AKS = VARV(7) * 0.5
        END IF
        ELSE IF ((DUMMY.EQ.'N').OR.(DUMMY.EQ.'n')) THEN
            S = 1
        END IF
    END IF
END IF

IF ( N.LE.14 ) GO TO 1000

IF(N.EQ.15) THEN
    LAST = .FALSE.
    CALL DISPLAY (NEWOLD,NO, LAST,U,T,AKS)
    LAST = .TRUE.
    CALL PRINTF(NEWOLD,NO, LAST,U,T,AKS)
ENDIF
ENDDO

```



```

IF(N.EQ.16) THEN
  CALL PRINTF (NEWOLD,NO, LAST,U,T,AKS)
  STOP
ENDIF

IF(N.EQ.17) THEN
  LAST =.TRUE.
  CALL PRINTF(NEWOLD,NO, LAST,U,T,AKS)
  RETURN
END IF

IF(N.EQ.18) STOP

RETURN

2000 FORMAT(25(/))
2010 FORMAT(5X,A18,' FOR ',A45//,
+      13(1X,I2,2X,A50,E13.2/),1X,I2,2X,A50//,4(1X,I2,2X,A50//))
2015 FORMAT(5X,'ENTER INTEGER OF DESIRED OPTION ==> ',\ )
2020 FORMAT(5X,'ENTER NEW VALUE OF ',A50,/,,' ==> ',\ )
2030 FORMAT(5X,'DO YOU WANT TO INCLUDE SMEAR ZONE EFFECTS(Y/N)?',\ )
2040 FORMAT(/,5X,'CURENTLY THE RATIO OF SMEAR ZONE DIAMETER TO STRIP',
+      ' DRAIN DIAMETER IS 2',/,
+      5X,'DO YOU WANT TO CHANGE THIS RATIO(Y/N)? ==> ',\ )
2050 FORMAT(5X,'ENTER RATIO OF SMEAR ZONE DIAMETER RO STRIP DRAIN',
+      ' DIAMETER',/,5X,'==> ',\ )
2060 FORMAT(/,5X,'CURRENTLY THE RATIO OF SMEAR ZONE PERMEABILITY TO',
+      ' UNDISTURBED SOIL',/,5X,'PERMEABILITY IS 0.5',/,
+      5X,'DO YOU WANT TO CHANGE THIS RATIO(Y/N)? ==> ',\ )
2070 FORMAT(5X,'ENTER RATIO OF SMEAR ZONE PERMEABILITY TO UNDISTURBED'
+      '/,6X,'SOIL PERMEABILITY ==> ',\ )
3000 FORMAT(5X,'PLEASE ENTER A NUMBER')
END

```

```

*****
*
*   SUBROUTINE BISEC:  SOLVES THE NONLINEAR EQUATION FOR
*   VERTICAL DRAIN SPACING USING THE BISECTION METHOD.
*
*
*
*****

```

```

SUBROUTINE BISEC(X0,AKS)
COMMON/VAR1/ VARV(13),S,R

A = 5.0
B = 200.0
TOL = 0.001

FA = FUNC(A,AKS)
FB = FUNC(B,AKS)

```

```

IF (FA*FB.GE.0.0) THEN
  IF (FA*FB.GT.0.0) THEN
    XO=-9999.9
  ELSE IF (FA.EQ.0.0) THEN
    XO=FA
  ELSE IF (FB.EQ.0.0) THEN
    XO=FB
  END IF
  RETURN
END IF

1000 C = (A + B)/2.0
FC = FUNC(C,AKS)

IF (FC.EQ.0.0) THEN
  XO=C
ELSE
  IF (FC*FA.LT.0.0) THEN
    B = C
    FB = FC
  ELSE IF (FC*FB.LT.0.0) THEN
    A = C
    FA = FC
  END IF
END IF

IF (ABS(A-B).GT.TOL) GO TO 1000
XO= C

RETURN
END

```

```

*****
*
*   FUNCTION FUNC IS THE NONLINEAR EQUATION FOR VERTICAL DRAIN
*   SPACING, DEVELOPED BY LO AND MESRI (1991), THAT IS USED TO
*   DESIGN VERTICAL STRIP DRAINS
*
*****

```

```

FUNCTION FUNC(X,AKS)

CHARACTER INFILE*12, TITLE*70, VARC(18)*50, OUTFILE*12

COMMON/VARO/ INFILE, TITLE, VARC, OUTFILE
COMMON/VAR1/ U, T, CH, CV, AH, AMH, AKH, AKW, B, AL, ALM, AR, CO, S, R
COMMON/VAR2/ A0, B0, TOL

DW = (B+AL)*2.0/3.141592
G = AKH/AKW*((AH/DW)**2)
F1 = LOG(X/S) - 0.75 + AKH/AKS*LOG(S)

```

```

F2 = X**2/(X**2 - 1.0)*F1
F3 = S**2/(X**2 - 1.0)*(1.0 - S**2/(4.0*X**2))
F4 = (S**4 - 1.0)/(4.0*X**2) - S**2+1.0
F5 = AKH/AKS*F4/(X**2 -1.0)
FNS = F2 + F3 + F5
EXPO = 8.0*CH / ((X*DW)**2*(FNS+2.5*G))
EXPO = -(EXPO + 4.0*CV/AH**2)*T
FUNC = 1.0 - EXP(EXPO) - U/100.0

```

```

RETURN
END

```

```

*****
*
* SUBROUTINE CALVAL: CALCULATES THE NUMBER OF VERTICAL STRIP
* DRAINS REQUIRED TO CONSOLIDATE THE SPECIFIED AREA, THE TOTAL
* LENGTH OF VERTICAL STRIP DRAINS REQUIRED, AND THE TOTAL COST
* OF THE INSTALLED STRIP DRAINS
*
* DW = DIAMETER OF STRIP DRAIN
* DE = DIAMETER OF INFLUENCED ZONE BY DRAIN
* SSQ = SPACING FOR SQUARE METHOD
* STR = SPACING FOR TRIANGULAR METHOD
* AVEA = THE AREA INFLUENCED BY STRIP DRAIN
* RNDR = REQUIRED NUMBER OF STRIP DRAIN
* RLDR = REQUIRED LENGTH OF STRIP DRAIN
* TOCO = TOTAL COST
*
*****

```

```

SUBROUTINE CALVAL (X,i,j)

```

```

CHARACTER INFILE*12, TITLE*70, VARC(18)*50, OUTFILE*12

```

```

COMMON/VAR0/ INFILE, TITLE, VARC , OUTFILE
COMMON/VAR1/ U,T,CH,CV,AH,AMH,AKH,AKW,B,AL,ALM,AR,CO,S,R
COMMON/VAR3/ DE, SSQ, STR(3,4), AVEA, RNDR, RLDR, TOCO(3,4)

```

```

DW      = (B+AL)*2.0/3.141592
DE      = X*DW
SSQ     = DE/1.13
STR(i,j) = DE/1.05
AVEA    = 3.141592*(DE/2.0)**2
RNDR    = AR/AVEA
RLDR    = RNDR*ALM
TOCO(i,j) = RLDR*CO

```

```

RETURN
END

```

```

*****
*
*   SUBROUTINE PRINTF:  WRITES THE RESULTS TO THE OUTPUT FILE
*
*
*****

```

```

SUBROUTINE PRINTF(NEWOLD,NO, LAST,U,T,AKS)

```

```

REAL      U(1), T(1)
INTEGER   iU(3), iSTR(3,4), iTOCO(3,4)
CHARACTER INFILE*12, TITLE*70, VARC(18)*50,NFILE*12
CHARACTER FORM_FEED*1, NEWOLD(1)*(*), OUTFILE*12
LOGICAL   LAST, FILE_OK

```

```

COMMON/VAR0/INFILE, TITLE, VARC, OUTFILE
COMMON/VAR1/VARV(13),S,R
COMMON/VAR3/DE, SSQ, STR(3,4), AVEA, RNDR, RLDR, TOCO(3,4)
COMMON/CHECK/FILE_OK

```

```

NFILE = INFILE
DO 500 K=1,2
  IF (K.EQ.2) THEN
    NFILE=OUTFILE
    IF (.NOT.FILE_OK) GOTO 500
  END IF
NO = 1

```

```

IOUT = 6
OPEN (UNIT = IOUT, FILE = NFILE, STATUS = 'UNKNOWN')
FORM_FEED = CHAR(12)
WRITE (IOUT,100) FORM_FEED
WRITE (IOUT,200) NEWOLD(NO),TITLE,
+      (N,VARC(N),VARV(N),N=1 ,13), (N,VARC(N), N=14,18)
WRITE (IOUT,250) S,R

```

```

DO i = 1,3
  iU(i) = INT(U(i))
END DO

```

```

DO j = 1,4
  DO i = 1,3
    iSTR(i,j) = INT(STR(i,j))
    iTOCO(i,j) = INT(TOCO(i,j))
  END DO
END DO

```

```

IF (LAST) THEN
  WRITE(IOUT,300) (iU(i),i=1,3),(T(j),(iSTR(i,j),i=1,3),j=1,4)
  WRITE(IOUT,350) (iU(i),i=1,3),(T(j),(iTOCO(i,j),i=1,3),j=1,4)
ENDIF

```

```

CLOSE(IOUT)

```

```

500 CONTINUE
RETURN

100 FORMAT(A1)
200 FORMAT(5X,A18,' FOR ',A45//,
+      13(1X,I2,2X,A50,E13.2//),1X,I2,2X,A50//,4(1X,I2,2X,A50//))
250 FORMAT(5X,'CURRENTLY THE RATIO OF SMEAR ZONE DIAMETER TO STRIP',
+      //,6X,'DRAIN DIAMETER IS ',F10.5,//,
+      5X,'CURRENTLY THE RATIO OF SMEAR ZONE PERMEABILITY TO ',
+      'UNDISTURBED SOIL',//,6X,'PERMEABILITY IS ',F10.5,//////)
300 FORMAT(' << OUTPUT FOR DESIGN OF VERTICAL STRIP DRAIN >>',////,
+      5X,'* VERTICAL STRIP DRAIN SPACING FOR A TRIANGULAR PATTERN *'
+      //,5X,70('_'),//,7X,'TIME      :',3(7X,' U =',I3,6X),//,
+      5X,70('_'),//,4(6X,F6.1,2X,':',3(8X,I4,8X),//),5X,70('_'),//)
350 FORMAT(5X,'* TOTAL COST OF INSTALLED STRIP DRAINS *'
+      //,5X,70('_'),//,7X,'TIME      :',3(7X,' U =',I3,6X),//,
+      5X,70('_')//,4(6X,F6.1,2X,':',3(5X,I10,5X),//),5X,70('_'))

END

```

```

*****
*
*   SUBROUTINE DISPLAY:  WRITES THE OUTPUT ON THE SCREEN
*
*
*****

```

```

SUBROUTINE DISPLAY (NEWOLD,NO, LAST,U,T,AKS)

```

```

REAL      U(1), T(1)
INTEGER   iU(3), iSTR(3,4), iTOCO(3,4)
CHARACTER INFILE*12, TITLE*70, VARC(18)*50
CHARACTER FORM_FEED, NEWOLD(1)*(*),OUTFILE*12
LOGICAL   LAST

```

```

COMMON/VAR0/INFILE,TITLE,VARC,OUTFILE
COMMON/VAR1/VARV(13),S,R
COMMON/VAR3/DE,SSQ,STR(3,4),AVEA,RNDR,RLDR,TOCO(3,4)

```

```

NO = 1

```

```

FORM_FEED = CHAR(12)
WRITE (*,100) FORM_FEED
WRITE (*,200) NEWOLD(NO),TITLE,
+      (N,VARC(N),VARV(N), N=1,13),(N,VARC(N), N=14,18)
WRITE (*,250) S,R

```

```

DO i = 1,3
  iU(i) = INT(U(i))
END DO

```

```

DO j = 1,4
  DO i = 1,3
    iSTR(i,j) = INT(STR(i,j))
  
```

```

        iTOCO(i,j) = INT(TOCO(i,j))
    END DO
END DO

IF (LAST) THEN
    WRITE(*,300) (iU(i),i=1,3),(T(j),(ISTP(i,j),i=1,3),j=1,4)
    WRITE(*,350) (iU(i),i=1,3),(T(j),(iTOCO(i,j),i=1,3),j=1,4)
ENDIF
RETURN
100 FORMAT(A1)
200 FORMAT(5X,A18,' FOR ',A45//,
+       13(1X,I2,2X,A50,E13.2//),1X,I2,2X,A50//,4(1X,I2,2X,A50//))
250 FORMAT(5X,'CURRENTLY THE RATIO OF SMEAR ZONE DIAMETER TO STRIP',
+       /,6X,'DRAIN DIAMETER IS ',F10.5//,
+       5X,'CURRENTLY THE RATIO OF SMEAR ZONE PERMEABILITY TO',
+       1X,'UNDISTURBED SOIL',/,6X,'PERMEABILITY IS ',F10.5//)
300 FORMAT(' << OUTPUT FOR DESIGN OF VERTICAL STRIP DRAIN >>',//,
+       5X,'* VERTICAL STRIP DRAIN SPACING FOR A TRIANGULAR PATTERN *'
+       /,5X,70(' ')//,7X,'TIME   :',3(7X,' U =',I3,6X)//,
+       5X,70(' ')//,4(6X,F6.1,2X,':',3(8X,I4,8X)//),5X,70(' ')//)
350 FORMAT(5X,'* TOTAL COST OF INSTALLED STRIP DRAINS *'
+       /,5X,70(' ')//,7X,'TIME   :',3(7X,' U =',I3,6X)//,
+       5X,70(' ')//,4(6X,F6.1,2X,':',3(5X,I10,5X)//),5X,70(' '))

END

```

```

*****
*
* SUBROUTINE DISPLAY1:  WRITES THE OUTPUT TO THE PRINTER
*
*****

```

```

SUBROUTINE DISPLAY1 (NEWOLD,NO, LAST,U,T,AKS)

```

```

REAL      U(1), T(1)
INTEGER  iU(3), ISTR(3,4), iTOCO(3,4)
CHARACTER INFILE*12, TITLE*70, VARC(18)*50
CHARACTER FORM_FEED, NEWOLD(1)*(*),OUTFILE*12
LOGICAL  LAST

```

```

COMMON/VAR0/INFILE, TITLE, VARC, OUTFILE
COMMON/VAR1/VARV(13), S, R
COMMON/VAR3/DE, SSQ, STR(3,4), AVEA, RNDR, RLDR, TOCO(3,4)

```

```

NO =1
OPEN (20, FILE='PRN')
FORM FEED = CHAR(12)
WRITE (20,100) FORM FEED
WRITE (20,200) NEWOLD(NO), TITLE,
+       (N, VARC(N), VARV(N), N=1,13), (N, VARC(N), N=14,18)
WRITE (20,250) S, R

```

```

DO i =1,3
    iU(i) = INT(U(i))

```

```

END DO
DO J=1,4
  DO I=1,3
    ISTR(I,J) = INT(STR(I,J))
    ITOCO(I,J) = INT(TOCO(I,J))
  END DO
END DO
IF (LAST) THEN
  WRITE (20,300) (IU(I),I=1,3),(T(J),(ISTR(I,J),I=1,3),J=1,4)
  WRITE (20,350) (IU(I),I=1,3),(T(J),(ITOCO(I,J),I=1,3),J=1,4)
END IF
CLOSE (20)
RETURN
100 FORMAT (A1)
200 FORMAT(5X,A18,' FOR ',A45//,
+      13(1X,I2,2X,A50,E13.2//),1X,I2,2X,A50//,4(1X,I2,2X,A50//))
250 FORMAT(5X,'CURRENTLY THE RATIO OF SMEAR ZONE DIAMETER TO STRIP',
+      //,6X,'DRAIN,DIAMETER IS ',F10.5//,
+      5X,'CURRENTLY THE RATIO OF SMEAR ZONE PERMEABILITY TO',
+      1X,'UNDISTURBED SOIL',//,6X,'PERMEABILITY IS ',F10.5//)
300 FORMAT(' << OUTPUT FOR DESIGN OF VERTICAL STRIP DRAIN >>',//,
+      5X,'* VERTICAL STRIP DRAIN SPACING FOR A TRIANGULAR PATTERN *'
+      //,5X,70(' '),//,7X,'TIME      :',3(7X,' U =',I3,6X)//,
+      5X,70(' ')//,4(6X,F6.1,2X,':',3(8X,I4,8X),/,),5X,70(' ')//)
350 FORMAT(5X,'* TOTAL COST OF INSTALLED STRIP DRAINS *'
+      //,5X,70(' ')//,7X,'TIME      :',3(7X,' U =',I3,6X)//,
+      5X,70(' ')//,4(6X,F6.1,2X,':',3(5X,I10,5X),/,),5X,70(' ')
END

```

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13. ABSTRACT (Maximum 200 words) This study investigates the feasibility of installing vertical strip drains to increase the storage capacity of the Craney Island Dredged Material Management Area. The installation of vertical strip drains in the disposal area is technically feasible and will accelerate consolidation of the dredged fill and underlying marine clay. This consolidation will result in a rapid increase in storage capacity and soil shear strength. The shear strength gain will allow the perimeter dikes to be constructed to higher elevations without setbacks or stability berms. The installed strip drains will also accelerate consolidation of the existing dredged fill and marine clay as new dredged material is placed in Craney Island. A preliminary triangular strip drain spacing and cost of installing vertical strip drains in Craney Island is presented. A detailed plan of action and schedule for installing vertical strip drains in the northern compartment of Craney Island is also presented.			
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