SETTLEMENT PREDICTION OF FINE-GRAINED DREDGED MATERIAL

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By: Timothy D. Stark[1], Ivan Contreras[2], and Jack Fowler[3]

Abstract

Non-linear finite strain consolidation theory is used to predict the settlement of fine-grained dredged material due to self weight and surcharge-induced consolidation. The finite strain consolidation theory provides for the effects of (a) self weight consolidation, (b) changes in hydraulic conductivity with consolidation, (c) a non-linear void ratio-effective stress relationship, and (d) large strains. An empirical desiccation model is used to describe the removal of water from the dredged material by surface drying. The combined model has been coded into the microcomputer program PCDDF89 (Primary Consolidation, and Desiccation of Dredged Fill), which is also described. The Craney Island Dredged Material Management Area near Norfolk, Virginia is used to illustrate the use and accuracy of the model.

Introduction

U.S. Army Corps of Engineer District Offices are continually addressing the placement problem of fine-grained dredged material from navigable waterways throughout this country. Increasing environmental concerns together with a general decrease in the number of available placement areas have created the need for maximum utilization of existing and planned dredged material containment areas. In order to maximize the long-term benefits derived from dredged material placement areas, the design and operation of the areas must accurately account for the increase in storage capacity resulting from settlement of previously deposited dredged material. The height of the dredged fill is reduced by sedimentation, consolidation, and desiccation.

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The two most important natural processes affecting the long-term height of confined dredged material are consolidation and desiccation. Fine-grained dredged materials may undergo axial strains greater than 50 percent during self-weight consolidation. Greater strains are possible, if the disposal site is managed so that surface water is removed and desiccation can occur. The resulting problem is to determine the time rate of settlement for dredged material subjected to the effects of a) self-weight consolidation, b) crust formation due to desiccation, and c) additional consolidation due to the surcharge created by the crust and additional dredged material.

This paper provides a brief description of the mathematical model used in the microcomputer program PCDDF89 (Primary Consolidation and Desiccation of Dredged Fill). A field case history is used to illustrate the use and accuracy of the model in estimating the long-term storage capacity of confined dredged material management facilities.

PCDDF89

PCDDF89 simulates the consolidation and desiccation processes in fine-grained soils using the one-dimensional finite strain theory of consolidation (Gibson et al., 1967) and an empirical desiccation model. PCDDF89 calculates the total settlement of a dredged fill layer based on consolidation characteristics of the soils below the layer, the consolidation characteristics of the dredged fill layer, local climatological data, and the effectiveness of surface water management within the containment area. This settlement is then accumulated for each dredged fill and compressible foundation layer within the one-dimensional profile to estimate a cumulative settlement.

The major input required by PCDDF89 is the void-ratio effective stress and void ratio-hydraulic conductivity relationships obtained from laboratory consolidation tests on dredged fill and compressible foundation materials. In addition, specific gravity, initial void ratio, and desiccation characteristics of the dredged fill material are required. Climatological data, anticipated dredging schedules and quantities, water surface elevation, and drainage characteristics of the containment site are also required.

The original version of PCDDF was developed by Cargill (1985). This version could analyze one dredged fill and one compressible foundation material type. PCDDF was modified by Stark (1991) to account for twenty-five different dredged fill and foundation material types, accelerate interpolation of the void ratio relationships, allow the restart of a previous simulation, and facilitate usage of PCDDF89 by providing data files containing climatological, void ratio relationships, and desiccation parameters for various parts of the country. An interactive interface for PCDDF was also developed and the program was incorporated into the Corps of Engineers Automated Dredging and Disposal Alternatives Management System (ADDAMS) software package (Schroeder and Palermo, 1990)

Consolidation and Desiccation Models. In PCDDF89 the consolidation and desiccation processes are solved separately to a certain point in time and then the solutions are combined to determine the net settlement of the dredged material. This reconciliation occurs monthly to conform with the availability of average evaporation and rainfall data.

The governing equation of finite strain consolidation theory is:

$$\left(\frac{\gamma_s}{\gamma_w}-1\right)\frac{d}{de}\left[\frac{k(e)}{1+e}\right]\frac{\partial e}{\partial z}+\frac{\partial}{\partial z}\left[\frac{k(e)}{\gamma_w(1+e)}\frac{d\sigma'}{de}\frac{de}{dz}\right]+\frac{\partial e}{\partial t}=0 \qquad (1),$$

where

γ_s = unit weight of solids,
γ_w = unit weight of water,
e = void ratio,
$k(e)$ = hydraulic conductivity as a function of void ratio,
z = vertical material coordinate measured against gravity,
σ' = effective stress, and
t = time.

This equation is suited for prediction of consolidation in thick deposits of soft fine-grained soils, such as dredged material, because it provides for the effects of a) self-weight consolidation, b) hydraulic conductivity varying with void ratio, c) a non-linear void ratio-effective stress relationship, and d) large strains. The model has application to other projects, including mine tailings ponds, under-water disposal of fine-grained material, construction of artificial islands on soft marine clay, and structures and embankments constructed on soft clay.

An implicit finite difference scheme is used to solve Equation 1. After the initial and boundary conditions are defined and appropriate relationships between void ratio and effective stress, and void ratio and hydraulic conductivity are specified, the void ratio in the consolidating layer is calculated using an implicit finite difference technique for any future time. The void ratio distribution in the saturated dredged fill layer is used to calculate the corresponding stresses and pore pressures.

At each monthly interval during times when the desiccation process is active, the thickness of the consolidating dredged material will decrease due to evaporation. After desiccation the layer acts as a surcharge on the consolidating layer and is assumed to be free draining. The empirical desiccation process is divided into two major stages. During the first stage, sufficient free water is available at the surface of the material so that evaporation takes place at the full potential rate. The water lost from a dredged material layer during first-stage drying can be expressed by the following equation and is assumed equal to the vertical settlement:

$$\Delta W' = CS - C_E' - EP + (1 - C_D)\,RF \qquad (2)$$

where

$\Delta W'$ = water lost during first-stage drying,
CS = water supplied from lower consolidating soil,
C_E' = maximum evaporation efficiency for soil type,
EP = class A pan evaporation,
C_D = drainage efficiency of containment area, and
RF = rainfall.

Water lost during second-stage drying can be defined as:

$$\Delta W'' = CS - C_E\left[1-\frac{h_{wt}}{h_{2nd}}\right]EP + (1-C_D)\,RF \qquad (3)$$

where

$\Delta W''$ = water lost during second-stage drying,

h_{wt} = depth of water table below surface, and

h_{2nd} = maximum depth of second-stage drying.

The appearance of an extensive cracking and the probable loss of saturation within the dried material prevent a direct correspondence between water loss and settlement during second stage drying. Therefore, the desiccation settlement during second-stage drying is estimated using the following equation:

$$\delta_D'' = -\Delta W'' - \left[1 - \frac{PS}{100}\right] h_{wt} \tag{4}$$

where

δ_D'' = settlement due to second-stage drying, and

PS = gross percent saturation of dried crust which includes cracks.

Determining the second-stage drying settlement involves an iterative process. Additional details of the solution technique for the consolidation and desiccation processes are described by Stark (1991).

Craney Island Dredged Material Management Area

Since 1956 the Craney Island Dredged Material Management Area (CIDMMA) has been used for containment of dredged material from navigable channels and harbors near Hampton Roads, Virginia. The 2200 acre area annually receives 4 to 5 million cubic yards of fine-grained maintenance and new work dredged material (Figure 1). As a result, a 35 to 40 foot thick layer of dredged material currently overlies a 100 to 120 foot thick deposit of soft foundation clay. The foundation clay is underlain by a freely draining dense sand.

With current practices, the CIDMMA is expected to reach ultimate capacity around the year 2000 (Palermo and Schaefer, 1990). However, if suitable material is placed in the ocean and the unsuitable material is placed in the CIDMMA, the useful life may be extended. An analysis of the service life of the CIDMMA under the proposed Restricted Use Program (RUP) was conducted to evaluate the benefits of the RUP. A simulation of the filling history from 1956 to 1984 was compared to field settlement data to calibrate the input parameters for conditions existing prior to subdivision of the area and implementation of dewatering operations. Simulations of filling history from 1984 (the time of cross dike closure) to 1992 were conducted for each of the three compartments (Figure 1). Finally, simulations of projected filling rates from 1992 were used to determine the service life of the CIDMMA under the proposed RUP. Two dredging scenarios, Baseline Maintenance Dredging and Worst Case Dredging were considered for the proposed RUP.

Selection of Model Parameters. The consolidation parameters shown in Table 1 were used to evaluate the service life of the CIDMMA under the proposed RUP. The void ratio-effective stress and void ratio-hydraulic conductivity relationships were obtained from the results of self weight and large strain, controlled rate of strain (LSCRS) consolidation tests (Cargill, 1986). The self weight test yields void ratio relationships from an effective stress of approximately

0.02 psf to 20 psf and the LSCRS test provides data for the effective stress range of 20 psf to 20,000 psf. Conventional oedometer tests were also conducted on samples of dredged material (Cargil, 1986) to verify the self weight and LSCRS test results. The results of the self weight and LSCRS tests are combined to define the void ratio relationships over the range of effective stresses encountered in a confined management area.

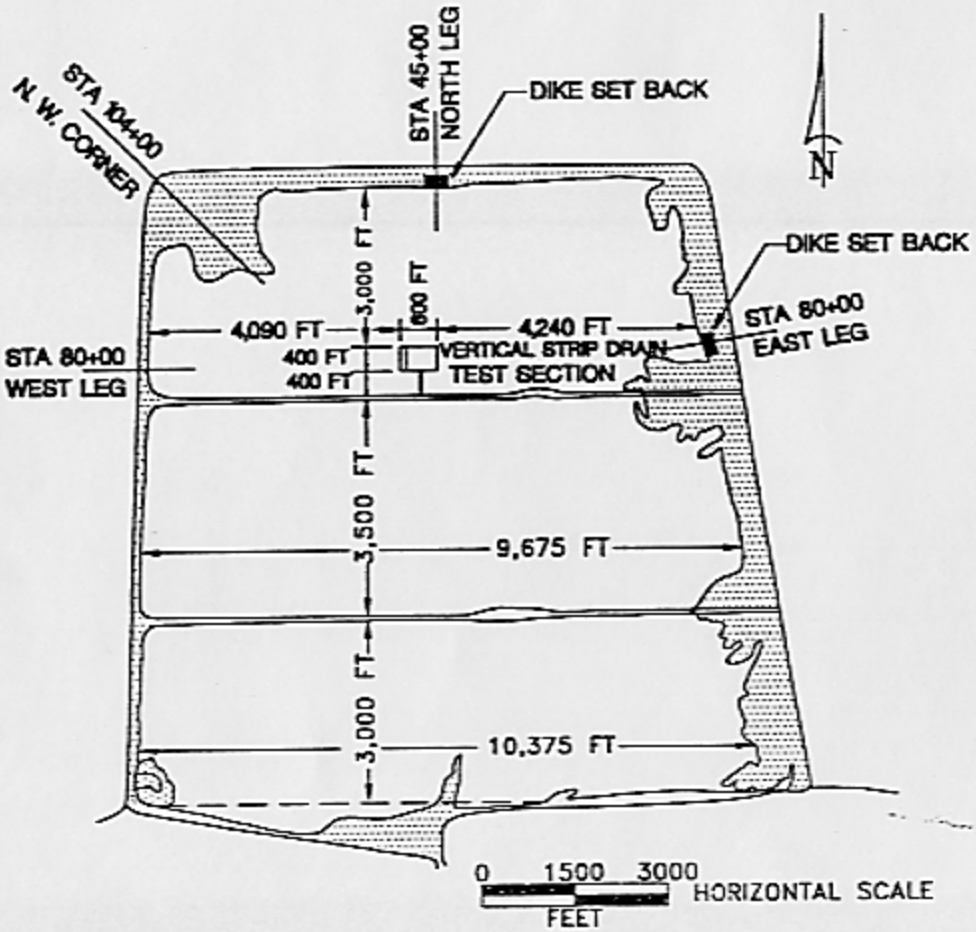

Figure 1. Plan View of Craney Island and Location of Vertical Strip Drain Test Section

The desiccation parameters used in PCDDF89 include rate of precipitation, a pan evaporation efficiency, a maximum crust thickness, and a surface drainage efficiency. The desiccation parameters used in the simulations are shown in Table 2 and represent an active dewatering condition. The precipitation and evaporation rates used for the simulations are shown in Table 3 and were obtained from National Climatic Center (1980) and Brown and Thompson (1977), respectively.

Simulation of Dredged Material Disposal. Thicknesses of dredged material for each disposal operation were determined from the actual dredging volumes and the surface areas available for placement in the management area. Since PCDDF89 applies an entire lift instantaneously, the disposal history had to be subdivided and applied at the mid-point time of each subdivision.

Table 1. Consolidation Parameters of the Marine Clay Foundation and Dredged Material at the CIDMMA

Marine Clay Foundation			Dredged Material		
Void Ratio	Effective Stress (psf)	Hydraulic Conductivity (ft/day)	Void Ratio	Effective Stress (psf)	Hydraulic Conductivity (ft/day)
3.00	0.00	8.60E-04	10.50	0.00	9.36E-01
2.90	8.80	1.03E-03	10.40	0.08	8.21E-01
2.80	19.60	8.85E-04	10.20	0.15	6.62E-01
2.70	32.00	7.61E-04	10.00	0.22	5.26E-01
2.60	48.00	6.39E-04	9.80	0.30	4.18E-01
2.50	70.00	5.22E-04	9.60	0.40	3.31E-01
2.40	104.00	4.23E-04	9.40	0.50	2.59E-01
2.30	154.00	3.45E-04	9.20	0.62	2.09E-01
2.20	232.00	2.73E-04	9.00	0.76	1.66E-01
2.10	344.00	2.16E-04	8.80	0.92	1.30E-01
2.00	510.00	1.40E-04	8.60	1.10	1.05E-01
1.90	780.00	1.32E-04	8.40	1.30	8.35E-02
1.80	1,160.00	1.03E-04	8.20	1.54	6.48E-02
1.70	1,700.00	7.70E-05	8.00	1.80	5.18E-02
1.60	2,540.00	5.80E-05	7.80	2.10	4.10E-02
1.50	3,750.00	4.30E-05	7.60	2.44	3.24E-02
1.40	5,540.00	3.10E-05	7.40	2.80	2.59E-02
1.30	8,500.00	2.70E-05	7.20	3.20	2.02E-02
1.25	10,400.00	1.90E-05	7.00	3.70	1.61E-02
0.87	50,000.00	1.00E-05	6.80	4.60	1.28E-02
0.80	60,000.00	5.00E-06	6.60	5.80	1.01E-02
			6.40	7.80	7.99E-03
			6.20	10.60	6.31E-03
			6.00	14.60	5.03E-03
			5.80	20.00	3.96E-03
			5.60	28.00	3.15E-03
			5.40	39.00	2.46E-03
			5.20	55.00	1.94E-03
			5.00	75.60	1.56E-03
			4.80	105.00	1.23E-03
			4.60	139.00	9.72E-04
			4.40	183.00	7.63E-04
			4.20	240.00	6.05E-04
			4.00	316.00	4.75E-04
			3.80	618.00	2.46E-04
			3.00	1,240.00	1.11E-04
			2.50	2,420.00	3.80E-05
			2.00	4,740.00	1.00E-05

Table 2. Consolidation and Desiccation Parameters for the CIDMMA

Parameter	Active Dewatering
Surface drainage efficiency, percent	100
Maximum evaporation efficiency, percent	100
Saturation at end of desiccation, percent	80
Maximum crust thickness, ft	1.0
Time to desiccation after filling, days	30
Elevation of fixed water table, ft MLW	1.5
Void ratio at saturation limit	6.5
Void ratio at desiccation limit	3.2
In-channel void ratio	5.93
Void ratio at zero effective stress	10.50
Void ratio of incompressible foundation sand	0.65
Hydraulic conductivity of incompressible foundation sand, ft/day	3.0 E-04

Table 3. Precipitation and Evaporation Rates at the CIDMMA

Month	Precipitation inches	Pan Evaporation inches	Excess Evaporation (inches) 100-Percent Infiltration	75-Percent Infiltration
January	3.4	0.0	—	—
February	3.3	0.6	—	—
March	3.4	1.0	—	—
April	2.7	4.5	1.8	2.4
May	3.3	7.0	3.7	4.5
June	3.6	7.7	4.1	5.0
July	5.7	7.7	2.0	3.4
August	5.9	6.6	0.7	2.2
September	4.2	4.9	0.7	2.2
October	3.1	3.6	0.5	1.3
November	2.9	1.2	—	—
December	3.1	0.0	—	—
Total	44.6	44.8	13.5	21.0

The height of each lift was obtained by dividing the in-channel disposal volume by the surface area of the entire site prior to subdivision. Dredged material was placed using two different filling criteria. In the Baseline Maintenance Dredging Case, dredged material was placed in a compartment until a thickness of approximately one foot was obtained. After reaching approximately one foot, placement in that compartment was discontinued and dredged material was placed in the next compartment. A one foot lift was used to investigate the consolidation and

desiccation characteristics of thin lifts. In previous years, the filling schedule involved an annual rotation of the compartments. As a result, a large amount of dredged material was usually placed in a compartment causing lift thicknesses of 3 to 6 ft, which may have slowed the rate of consolidation and desiccation. For comparison purposes, an annual rotation of the compartments was used for the Worst Case Dredging Scenario. This was due to the large quantity of material that was to be placed under the Worst Case Scenario.

Craney Island Filling Simulation, 1956 to 1984. Simulations of the filling history from 1956 to 1984 are shown in Figure 2. The main objective of this simulation was to calculate the void ratio and effective stress profiles in the dredged fill and compressible foundation in October, 1983 (the time of cross dike closure). For discussion purposes, the time of cross dike closure is referred to as 1984 even though the analysis used October, 1983 (Figure 2). The simulation incorporated the affects of desiccation and the results are in excellent agreement with field surface elevations. The calculated void ratio and effective stress profiles reflect the consolidation and desiccation that occurred between 1956 and 1984 and were used as a starting point for subsequent simulations using the restart option in PCDDF89. The excellent agreement with field surface elevations indicates that the input parameters are representative of field conditions and can be used to estimate the service life of the CIDMMA under the proposed RUP.

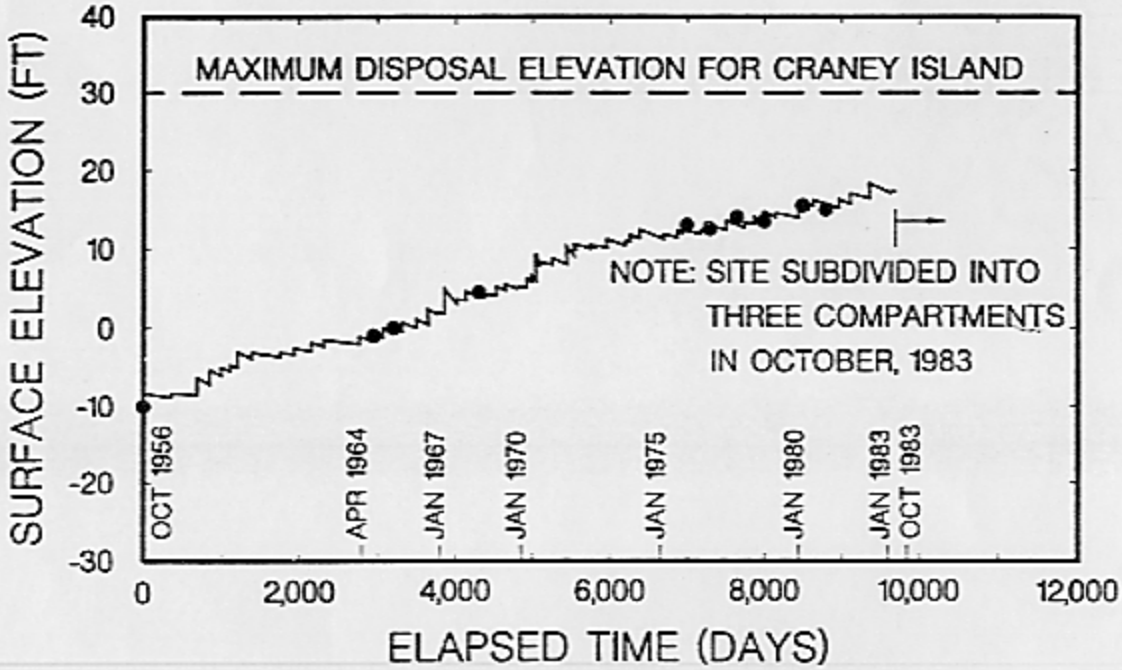

Figure 2. Fill Rates for Craney Island from 1956 to 1984

Craney Island Filling Simulations, 1984 to 1992. Simulation of the filling history from 1984 to 1992 in the north compartment is shown in Figure 3. The void ratio and effective stress profiles calculated in the previous simulation were input using the restart option and the surface elevation shown in Figure 2 at October, 1983 was the starting elevation in each compartment. It can be seen from Figure 3 that the calculated surface elevations are in excellent agreement with field data.

Baseline Maintenance Dredging Simulations, 1992 to 2135. The Baseline Maintenance Dredging simulation from 1992 to 2135 under the proposed RUP is also shown in Figure 3 for the north compartment. Dredged material was initially placed in the center compartment. After approximately one foot of material was placed in the center compartment, dredged material was placed in the south compartment. Placement was moved to the north compartment after a one foot lift was placed in the south cell and this cycle was repeated until an elevation of +30 ft MLW was obtained in all three compartments. It can be seen from Figure 3 that the north compartment reached capacity in January, 2069. After January, 2069, all of the dredged material was alternately placed in the center and south compartments using one foot lifts. Analysis showed that the center compartment reached capacity in May, 2131. After May, 2131, all of the Baseline Maintenance dredged material was placed in the south compartment. As a result, this compartment reached capacity in May, 2132. In summary, the service life of the CIDMMA would be extended to approximately the year 2130 under the proposed Baseline Maintenance Dredging Case of the proposed RUP.

This analysis predicts that the CIDMMA has a service life of approximately 140 years under the Baseline Maintenance Dredging Case of the RUP. Clearly, this prediction is a planning level estimate and is only being used to determine if the RUP deserves further consideration. This prediction involves many assumptions that may not pertain to the CIDMMA around the year 2130. For example, the precipitation and evaporation rates will be different, which may lead to a change in the quantity and character of the dredged material and/or desiccation rate of the confined material. In summary, the results of the Baseline Maintenance Dredging Case clearly show that reducing the amount of dredged material placed in Craney Island under the RUP will significantly extend the service life of this facility.

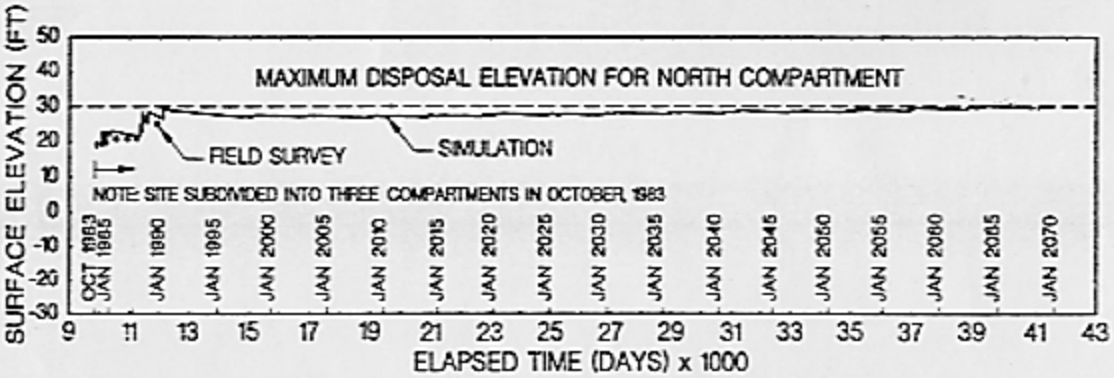

Figure 3. Simulation of Fill Rates for Baseline Maintenance Dredging Case in North Compartment from 1984 to 2069

Worst Case Dredging Simulations, 1992 to 2085. The Worst Case Dredging simulation from 1992 to 2085 under the proposed RUP is shown in Figure 4 for the north compartment. Dredged material was placed using an annual rotation starting with the center compartment and ending with the north compartment. The north compartment reached capacity by September, 2031. After September, 2031 dredged material was placed only in the center and south compartments using an annual

rotation schedule. The analysis showed that the south compartment reached capacity in May, 2079. After May, 2079 all dredged material was placed in the center compartment, causing this compartment to reach capacity in September, 2080. Therefore, even under the worst case dredging scenario, the service life of the CIDMMA will be extended to approximately the year 2080 under the proposed RUP. It should be noted that similar simulations were conducted for the center and south compartments.

Comparison of the Baseline and Worst Case Dredging simulation revealed that the use of a one foot lift exhibited better consolidation and desiccation characteristics than thicker lifts. It is anticipated that one foot lifts will also enhance trenching and crust farming operations in a management area.

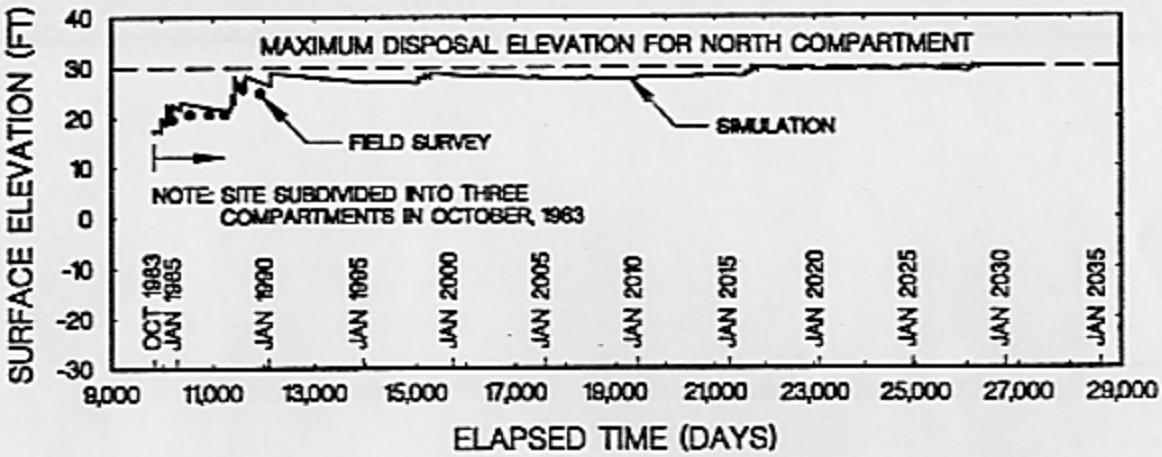

Figure 4. Simulation of Fill Rates for Worst Case Dredging Scenario in North Compartment from 1984 to 2031

Vertical Strip Drains

Review of the calculated void ratio and effective stress profiles in 1992 revealed that the majority of the calculated consolidation occurred in the dredged fill. As a result, large excess pore-water pressures were calculated in the compressible clay foundation. This suggests that the compressible foundation is under-consolidated due to the large drainage path. This is in good agreement with large excess pore-water pressures that were measured in the clay foundation using piezometers in the perimeter dikes. These piezometers showed excess pore-water pressure levels in February 1991 that exceeded the ground surface elevation by 25 feet in some locations. The installation of vertical strip drains would significantly reduce the drainage path and thus the time required to consolidate the dredged fill and foundation clay. Consolidation of the dredged fill and foundation clay would cause a significant increase in storage capacity and undrained shear strength of these materials. This strength gain would allow the perimeter dikes to be constructed to higher elevations without setbacks or stability berms.

A 600 ft by 400 ft strip drain test section (Figure 1) was completed in February, 1993 in the north compartment of the CIDMMA to evaluate the effectiveness of prefabricated strip drains in increasing storage capacity. Preliminary results show that the dredged fill and foundation clay underlying the test section are

undergoing substantial settlement (2 to 3 ft in four months) as shown in Figure 5. It is anticipated that consolidation, and thus settlement, will continue through January, 1994. Based on these results, the feasibility of installing vertical strip drains throughout the entire management area and/or perimeter dikes is being considered.

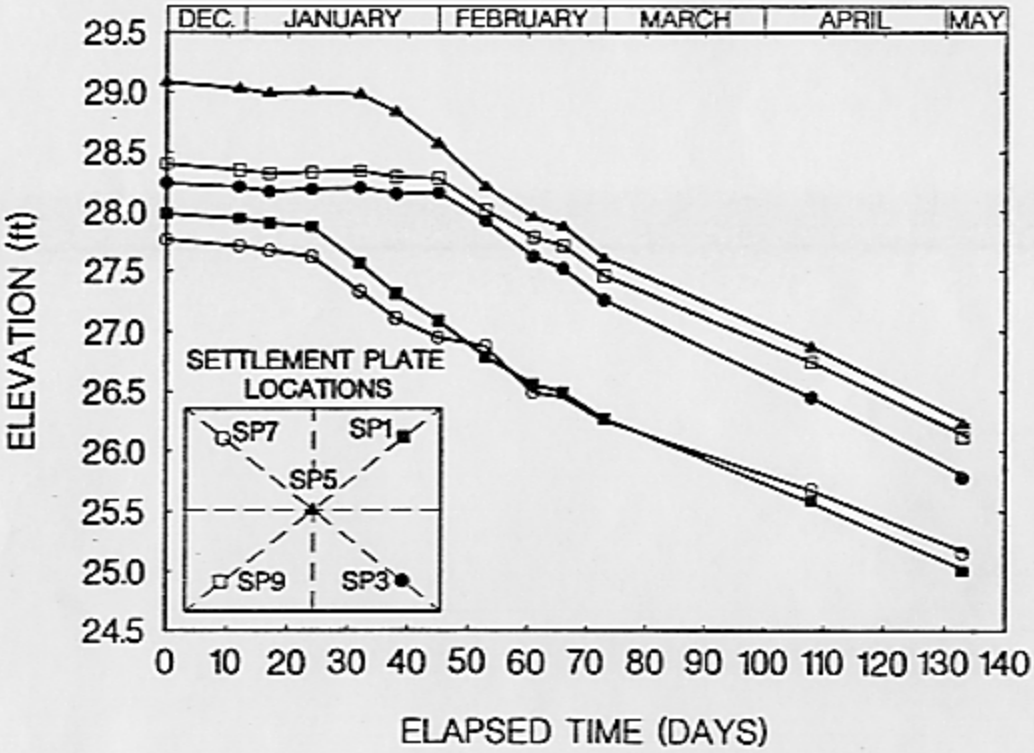

Figure 5. Settlement Data for CIDMMA Strip Drain Test Section

Conclusions

The service life of the Craney Island Dredged Material Management Area under the proposed Restricted Use Program was evaluated using a microcomputer model PCDDF89. Field settlement data from 1956 to 1992 was used to verify PCDDF89 input parameters. Based on projections of fill rates under the RUP, the service life of the Craney Island will be extended significantly by reducing the quantity of dredged material placed. In particular, the CIDMMA will reach capacity around the year 2130 under the Baseline Maintenance Dredging Case and near the year 2080 under the Worst Case Dredging Scenario.

It is also anticipated that the service life of Craney Island can be extended by installing vertical strip drains to consolidate the dredged fill and foundation clay. Early results of a strip drain test section show that the dredged fill and foundation clay are undergoing substantial consolidation settlement (2 to 3 feet in four months). This consolidation will result in increased storage capacity and an increase in undrained shear strength of the dredged fill and foundation clay. An increase in undrained shear strength should allow the perimeter dikes to be constructed to higher elevations without setbacks or stability berms.

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APPENDIX II. SI Unit Conversions

1 psf	= 47.85 kPa
1 foot	= 0.305 m
1 acre	= 4047 m^2
1 cubic yard	= 0.7646 m^3