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Consolidation Settlement of Capped Sediment (II): Advective Transport of Pore Water and Analytical Prediction of Settlement

캡이 설치된 퇴적층의 압밀 침하 (II): 간극수의 이동 및 침하의 해석적 예측

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요 지

캡이 설치된 오염된 해성 퇴적층의 압밀침하를 연구하기 위해 원심모형 실험이 실시 되었다. 간극수의 이동을 관측하기위해 형광색 염료가 사용되었다. 염료이동을 추적한 결과 압밀에 의한 오염원의 이류이동이 확실히 나타났다. 그러므로 압밀에 의한 오염원의 이류이동을 감소시키기 위해 캡핑을 적절하게 설계해야만 한다. 그리고, 원심모형실험 결과와 캡이 설치된 해성 퇴적층의 압밀침하를 예측할 수 있는 PSDDF프로그램으로 예측된 값이 비교되었다. 원심모형실험결과와 PSDDF예측치 비교에서 원형시간이 18년 이후에는 원심모형실험 결과와 PSDDF예측치가 대체로 잘 일치하지만, 원형시간 6년에서 두 결과 사이에 최대 20% 가까운 격차가 나타났다. 그러므로 설계자는 PSDDF 프로그램에 의해 얻은 압밀침하 결과를 사용 시 주의가 요구된다.

Abstract

Centrifuge test was conducted to simulate the effects of consolidation settlement of capped contaminated marine sediment. A fluorescent dye was used to monitor the movement of pore water through the cap layer. Dye tracer study clearly showed the consolidation induced advective transport of contaminants. Thus, the capping layer must be appropriately designed to reduce the effects of consolidation induced advective transport. The results from the centrifuge test were compared to predictions made by the Primary consolidation, Secondary compression, and Desiccation of Dredged Fill (PSDDF) computer program, which can qualitatively estimate the consolidation settlement of capped marine sediment. Although PSDDF approximated closely the secondary compression in the centrifuge test (i.e., compare data points from 18 to 25 prototype years), the maximum deviation between centrifuge test result and PSDDF prediction was 20 % about prototype time 6 years. Thus, designers should utilize PSDDF consolidation settlement results with caution.

Keywords : Advection, Capping, Consolidation, PSDDF, Sediment, Settlement

1. Introduction

In situ capping involves placing a layer of clean sand over contaminated sediment, thus reducing the environmental impact of the sediment from the surrounding ecosystem. This technique has been conducted in

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rivers, near shore, and estuarine settings in the U.S., Japan, and Europe containing nutrients, PAHs, PCBs, dioxins, or metals, and these projects have been summarized by Palermo et al. (1998). Previous research has shown that both fine and coarse grained materials can be used effectively as capping material (Klapper, 1991; 1992; Suszkowski, 1983). The primary advantage of coarse grained capping material is that it is easier to place, and more stable along steep slopes (Palermo et al., 1998). The design of *in-situ* caps placed over marine sediment must also take into consideration the self-weight consolidation of the cap and the consolidation of the sediment as a result of adding the capping layer.

To simulate the consolidation of marine sediment caused by the placement of an *in-situ* cap with a coarse grained material, centrifuge test was firstly conducted by using a research centrifuge at Waterways Experiment Station (WES). Movement of contaminated pore water from sediment into caps due to sediment consolidation during and after cap placement was also studied by using a dye tracer. In addition, the settlement data obtained from the centrifuge test was compared to predictions from the Primary consolidation, Secondary compression, and Desiccation of Dredged Fill (PSDDF) module of Automated Dredging and Disposal Alternatives Modeling System (ADDAMS) (Stark, 1997). Although there are numerous consolidation programs that can be utilized such as CS4, SOA, and CON2D (Fox, 2000; Duncan et al., 1981; Townsend and McVay, 1990), PSDDF is currently used by the Corp of Engineers to design and simulate the placement of fine-grained sediment in both underwater applications and confined disposal facilities. The mathematical model for one-dimensional primary consolidation used in PSDDF is based on the finite strain theory of consolidation described by Cargill (1982) and Gibson et al. (1967)

2. Centrifuge Experiment

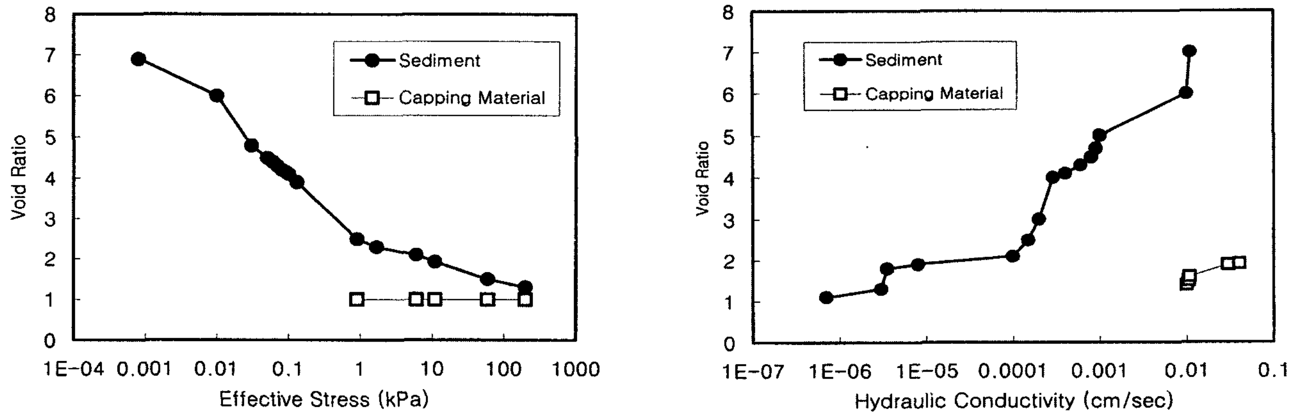
2.1 Materials

A composite of 11 sites in the New York/New Jersey Harbor collected for the New York Dredged Material Management Plan (NYDMMP) was utilized as sediment.

Table 1. Material properties of sediment and capping materials

Property	Symbol	Sediment	Capping Material
Specific Gravity	G_s	2.64	2.68
Water Content (%)	w	110	29
Plasticity Index (%)	PI	39	--
Liquid Limit (%)	LL	76	--
% Fines	--	66	6.2
Organic Content (%)	O_c	2.6	0.2
Void Ratio	e	2.9	0.78
Compression Index	C_c	0.66	0.02
Secondary Compression Index	C_α	0.05	--
Recompression Index	C_s	0.09	--
USCS	--	CH	SP-SM

USCS: Unified Soil Classification System



(a) Consolidation curve for sediment and capping material

(b) Void ratio and hydraulic conductivity relationship for sediment and cap

Fig. 1

A silty-sand capping material (SP-SM) collected from the Ambrose channel was used in this study. Table 1 shows the material properties for the sediment and the capping material. Figures 1(a) and 1(b) show the void ratio and effective stress relationship, and void ratio and hydraulic conductivity relationship, respectively.

2.2 Rhodamine Fluorescent Dye

Rhodamine WT, a water-soluble, fluorescent dye was used to monitor the movement of pore water through the cap layer. The sediment was spiked with 4 ml of 1000 ppm dye per 1000 g of sediment. The final concentration of dye in the sediment was 140 ppb. The sediment was stirred on a mechanical mixer in air for at least 24 hours. It should be noted that the dye was not added to the capping material.

2.3 Equipment

The research centrifuge at Waterways Experiment Station was utilized (Fig. 2). A leak-proof modeling box was designed and fabricated from 1.27 cm acrylic plastic. The modeling box was 30.5 cm in length, 30.5 cm in width, and 45.7 cm in height.

Movement of each soil layer was monitored by Linear Variable Differential Transducers (LVDTs) with their core resting on a small plates glued to flat rubber washer. Pore pressure transducers were placed in the sediment before the consolidation test and were located on the bottom of the box and at the interface between the two sediment layers.

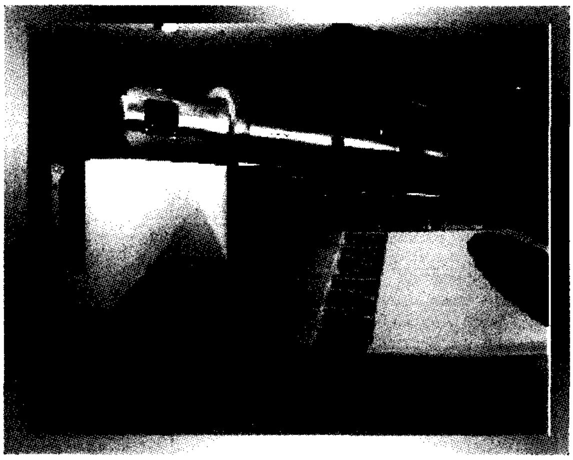


Fig. 2. Waterways Experiment Station (WES) centrifuge

Fabrication of a sediment core sampler from 1.9 cm diameter acrylic plastic tubing was accomplished by machining one end of the tubing to a thin edge and using a piston-driven attachment to supply the force needed to push the core sampler through the consolidated sediment and cap layers. Application of a vacuum to the sampling device created a negative pressure on the sample in a manner similar to a piston sampler.

The sediment cores were then sectioned on a Carl Zeiss, Inc., Model HM 440E microtome into thin sediment slices. The sediment slices were tested for water content and dye concentration at the end of the tests.

2.4 Experimental Procedures

The sediment materials were placed in large polyethylene bags. The sediment layers were then placed into the modeling box at an initial water content of 110 % and were pre-consolidated prior to the placement of the capping layer. Loading of the modeling box to the desired sediment height and placement of the cap layer

Table 2. Boundary conditions for centrifuge model and prototype

Items	Centrifuge Test
g-level	100
Model Time, hours	22.5
Initial Void Ratio of Sediment	3.1
Model Properties	
Height of Layer 1, cm	4.5
Height of Layer 2, cm	4.5
Height of Cap, cm	3
Prototype Properties	
Prototype Time, years	25.6
Height of Layer 1, cm	450
Height of Layer 2, cm	450
Height of Cap, cm	300
Void Ratio of Incompressible Foundation	0.5
Permeability of Incompressible Foundation, cm/sec	1×10^{-9}
Length of Drainage Path in Incompressible Foundation, m	30
Elevation at Top of Incompressible Foundation, m	0
Elevation of External Water Table, cm	1524
Excess Pore Water Pressure Where Secondary Compression Starts, kN/m^2	4.8

were accomplished by cutting open one corner of the polyethylene bags and slowly squeezing the material out of the bag into the modeling box. After placement of the cap material, deionized water was sprayed on the cap in order to saturate the cap layer effectively minimizing any voids within which air could be entrained, and 0.3 cm of overlying water was placed above the capping layer. Table 2 shows the boundary conditions for centrifuge test.

The overlying water sampling system was tested during test to determine the required vacuum pressure needed to obtain samples. Through trial and error, the appropriate vacuum pressure was determined to be 102 kN/m^2. Samples were obtained at 5, 10, 15, and 20 prototype years (4.5, 9, 13.5 and 18 hours) during the test.

2.5 PSDDF Program

This program uses finite strain consolidation theory, the ratio of the secondary compression index, C_α, to the compression index, C_c, concept for secondary compression (Mesri and Godlewski, 1977), and an empirical desiccation model to estimate the changes in dredged material surface elevation with time. PSDDF computes the total settlement of a dredged fill layer based on the consolidation characteristics of the soils above and below the layer, the consolidation of the dredged fill, local climate data, and surface water management techniques within the containment area. Total settlement is obtained by cumulating the settlement for each dredged fill and compressible foundation layer. The primary input parameters are the specific gravity of solids, initial void ratio, the ratio of C_α/C_c, the ratio of C_r/C_c where C_r is the recompression index, and the desiccation characteristics. The mathematical model for one-dimensional primary consolidation used in PSDDF is based on the finite strain theory of consolidation described by Cargill (1982) and Gibson et al. (1967)

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

where γ_s = unit weight of solids

γ_w = unit weight of water

e = void ratio

$k(e)$ = coefficient of soil permeability as a function of void ratio

z = vertical material coordinate measured against gravity

σ' = effective stress

t = time.

3. Analysis of Results

3.1 Centrifuge Test Results

Figure 3 plots the settlement and prototype time relationship for centrifuge test. The total settlement for layers 1 and 2 after the placement of the cap were 119 and 126 cm (as measured by the LVDTs), respectively. Upon completing the centrifuge test, physical measurements of the sediment and cap layers were taken. Physical measurements indicated that the average final height of the sediment and cap was 9.4 cm (i.e., average settlement = 2.6 cm), which is comparable to the average final settlement of the sediment and cap of 2.45 cm as measured by the LVDTs.

Sediment cores were taken from the modeling box. Cored samples were sectioned utilizing a microtome to conduct water content analysis. Figure 4 shows the water content and sediment depth relationship for the cored samples. The capping layer is represented from 0 to

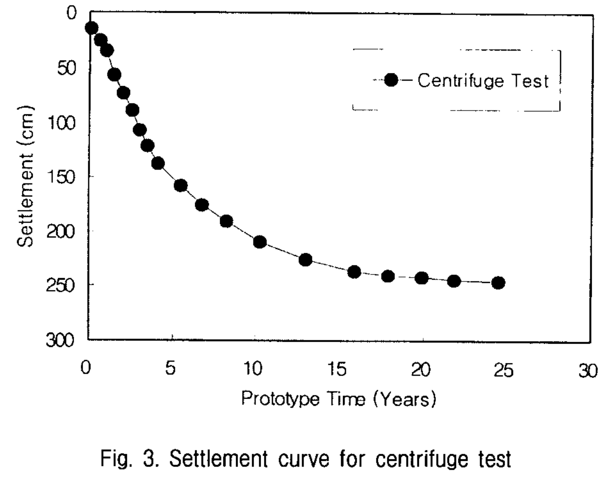


Fig. 3. Settlement curve for centrifuge test

3-cm, and the sediment layers are represented from 3 to 9.4 cm. Figure 4 indicates that pore water was advected from the sediment layer through the cap since there was a decrease in the water content.

Figure 5 shows the Rhodamine dye concentration in the overlying water in centrifuge test. The increase in the dye concentration as time increases indicates that pore water is moving from the sediment layer through the capping material. Furthermore, the instantaneous breakthrough of the dye illustrates that there was no retardation and that advection is the dominant transport process. Figure 6 shows the Rhodamine dye concentration in a cored sample from the centrifuge test. As expected, the dye concentration was much greater in the sediment (i.e., layer 2) than in the cap.

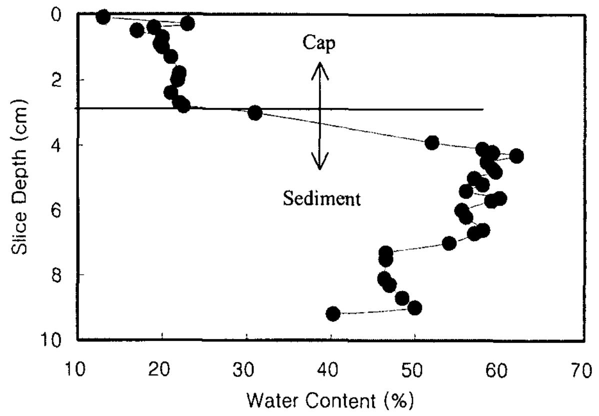


Fig. 4. Water content profile of soil cores from centrifuge test

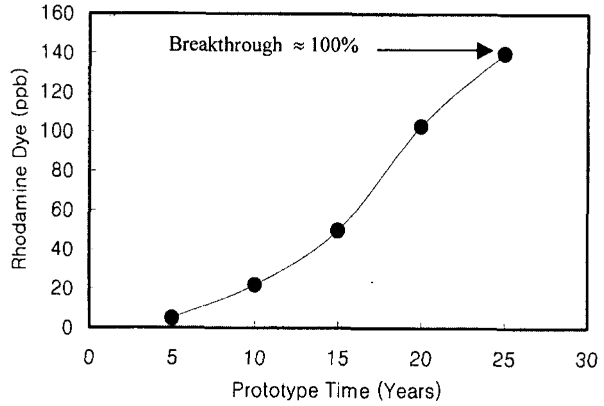


Fig. 5. Rhodamine dye concentration in advected pore water centrifuge test

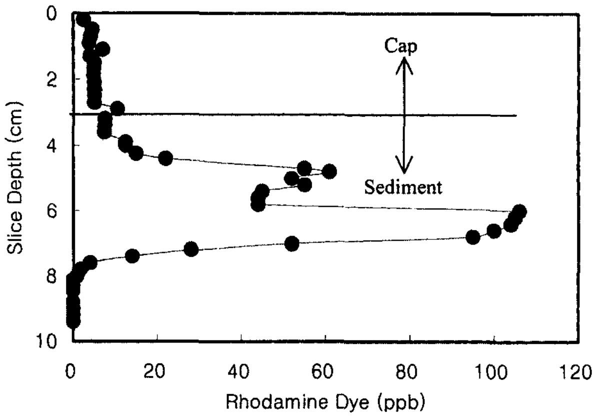


Fig. 6. Rhodamine dye concentration in sediment and cap

3.2 Comparison Between Centrifuge Test Results and PSDDF Predictions

The settlement data obtained from centrifuge test were compared to predictions from the Primary consolidation, Secondary compression, and Desiccation of Dredged Fill (PSDDF). In the centrifuge experiments, the water table was above the surface of the cap, and desiccation was considered negligible in conducting the PSDDF simulations. The same boundary conditions listed in Table 2 were adopted for the PSDDF simulation. The consolidation curves for the sediment and capping material in Fig. 1(a) provided the void ratio and effective stress relationship for the PSDDF model, and the permeability and void ratio relationship shown in Fig. 1(b) was also utilized in the model. The material properties shown in Table 1 were also utilized in the PSDDF simulations. For the capping material, the default values for a sand cover in the program were used. In the PSDDF simulation, layers 1 and 2 of the sediment were consolidated under self-weight for six months.

Figure 7 compares the PSDDF model to centrifuge

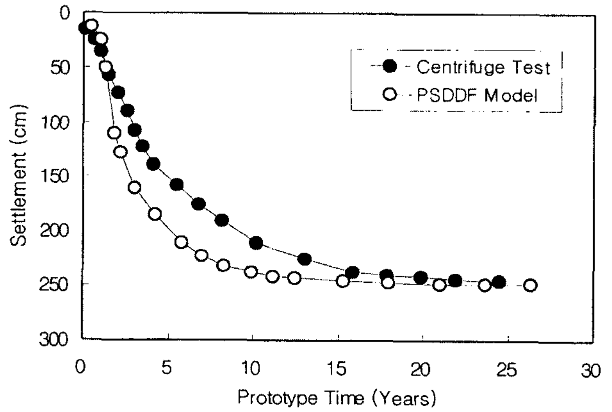


Fig. 7. Comparison of PSDDF model to centrifuge test

test. PSDDF predicted that the settlement of the sediment due to self-weight consolidation after six and twelve months was 0.12 m and 0.24 m, respectively. These values are lower than the centrifuge results. However, after 2 to 18 years during primary consolidation, the PSDDF model overpredicts the settlement. Similarly, Mitchell and Liang (1986) found that the computer program, CON2D, overestimated the immediate settlement beneath the central portion of the embankment. The maximum deviation between the PSDDF prediction and centrifuge test reaches up to about 20 %. PSDDF approximates closely the secondary compression in the centrifuge test (i.e., compare data points from 18 to 25 years).

4. Conclusions

Dye tracer studies clearly showed the consolidation induced advective transport of contaminants in centrifuge test. The increase in dye concentration in the overlying water as well as the decrease in the water content of the sediment illustrated the importance of this advective transport induced by consolidation. For soluble contaminants and contaminants with a low partitioning coefficient, advection may dominate the transport phenomena through the cap. Thus, the capping layer must be appropriately designed to reduce the effects of consolidation induced advective transport. This may be accomplished by adding a reactive barrier or geosynthetic barrier layer to the cap design.

PSDDF program was utilized to predict the consolidation of marine sediment caused by the placement of a capping layer. The PSDDF predictions were compared to the centrifuge test results. PSDDF overpredicted primary consolidation settlement throughout the test (i.e. 2- 18 years). PSDDF approximated closely secondary settlement. It can be concluded that although PSDDF can be used to qualitatively estimate the consolidation settlement of capped marine sediment, designers should utilize PSDDF consolidation settlement results with caution, because the deviation between the centrifuge test results and PSDDF prediction is found as shown in Fig. 7.

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