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Consolidation Settlement of Capped Sediment (I): Centrifuge Simulation by Modeling of Models Technique

캡이 설치된 퇴적층의 압밀 침하 (I): 원심모형시험기를 이용한 모델링 방법

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요 지

모래를 이용한 해안퇴적층 캡핑은 오염원의 이동을 줄일 수 있는 하나의 방법이다. 캡핑 설계시 자중에 의한 캡 자체의 압밀과 새로 추가된 캡층에 의한 퇴적층의 압밀을 반드시 고려해야만 한다. 이를 위해 원심모형시험기를 이용한 모형실험이 실시되었다. 이 연구에서는 실험의 정확성을 알아보기 위해 모델을 다시 모델링 하는 방법이 이용되었다. 즉, 똑 같은 경계 조건에서 서로 다른 중력가속도를 가지고 실험이 실시 되었다. 두 실험의 결과가 잘 일치함을 알 수 있었다. 이것은 캡이 설치된 해안퇴적층의 압밀침하 거동을 원심모형실험을 이용하여 예측이 가능함을 알 수 있다.

Abstract

Marine sediment capping is a technique where clean sand is placed over contaminated sediment to reduce the migration of contaminants to the environment. The design of in-situ caps placed over marine sediment must take into consideration the self-weight consolidation of the cap and the consolidation of the sediment as a result of adding the cap layer. Centrifuge tests were adopted to simulate the effects of consolidation settlement of capped marine sediment caused by the placement of a clean sand layer. The modeling of models technique was utilized to verify the correct modeling procedures used in this study. Two centrifuge tests were conducted with the same boundary conditions at different gravitational accelerations of 100 g and 50 g. There was good agreement between these tests. It can be concluded that the centrifuge experiment is able to model consolidation settlement of capped marine sediment.

Keywords : Capping, Centrifuge, Consolidation, Modeling of models, Sediment, Settlement

1. Introduction

Sediment must be dredged from waterways and ports to maintain the navigation system. However, when materials are unsuitable for ocean disposal, there are four basic options for remediation of contaminated sediment: containment in-place, treatment in-place, removal and containment, and removal and treatment. Economic considerations make decontamination and upland disposal (disposal on land) options unfavorable

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to many port authorities (Wakeman et al., 1997). *In-situ* capping of sediment and disposal of contaminated sediments in sub-aqueous pits are the least expensive alternative. *In situ* capping involves placing a layer of clean sand over contaminated sediment. In sub-aqueous pit disposal, contaminated marine sediment is capped with a layer of clean sand, thus reducing the environmental impact of the sediment from the surrounding ecosystem. Environmental regulations have limited the use of *in-situ* sediment capping due to the concerns about the contaminant migration through the cap (NRC, 1997).

In-situ capping projects have been conducted in 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).

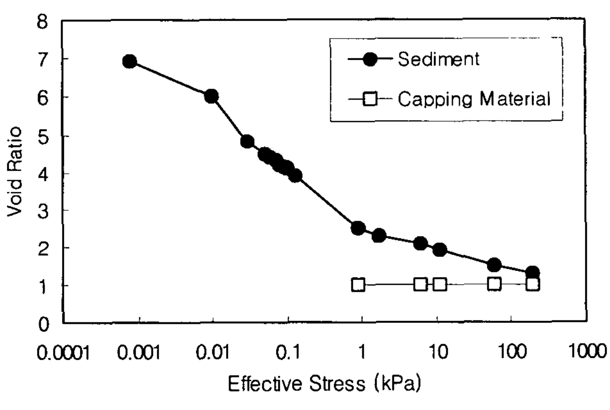
The design of in-situ caps placed over marine sediment must also take into consideration the self-weight consolidation of the cap and the consolidation of the sediment as a result of adding the cap layer. The consolidation characteristics of high water content materials (dredging, mine tailings and sludges) have been studied by numerous researchers (McVay et al., 1986; Townsend et al., 1989; Townsend and McVay, 1990). These studies have primarily focused on the consolidation of an accreting soil layer, which involves both sedimentation and self-weight consolidation. However, *In-situ* caps are typically placed on top of marine sediments that are between 1 to 25 m below sea level where the accumulation rates of sediment are low, thus reducing the effects of soil accretion.

The purpose of this study was to utilize the research centrifuge at Waterways Experiment Station (WES) to simulate the consolidation of marine sediment caused by the placement of an *in-situ* cap with a coarse grained material. Two tests were conducted at different centrifuge acceleration values to verify by means of the modeling of models technique. Based on the obtained data, centrifuge modeling for predicting the consolidation of capped contaminated sediment was evaluated and discussed.

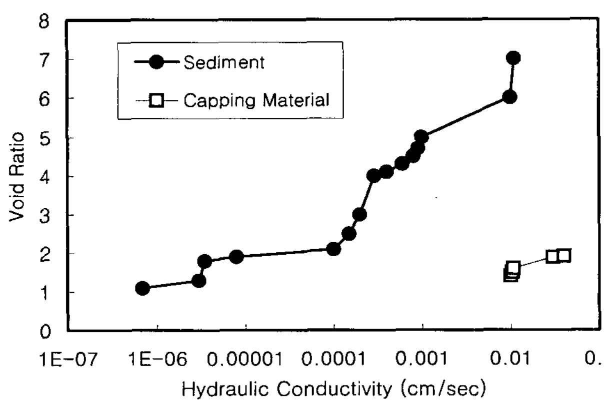
2. Centrifuge Experiments

2.1 Material

The sediment utilized in this study was a composite of 11 sites in the New York/New Jersey Harbor area collected for the New York Dredged Material Management Plan (NYDMMP). The NYDMMP sediment was analyzed for the geotechnical properties. Consolidation tests were performed on the sediment according to ASTM procedure D-2435 Method A. Consolidation test results show that



(a) Consolidation curve for sediment and capping material



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

Fig. 1

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

the sediment is compressible as shown in Fig. 1.

A silty-sand capping material collected from the Ambrose channel was used in this study. According to ASTM designation D-2487, the sediment is classified as silty sand (SP - SM). Consolidation tests were also performed on the capping material, and the void ratio and effective stress relationship is also shown in Fig. 1. The material properties for the sediment and capping materials are summarized in Table 1.

2.2 Test Equipments

The research centrifuge at WES was utilized. The centrifuge has a radius of 6.5 m, and an acceleration range from 10 to 350 g. The maximum payload for the WES centrifuge is 8000 kg at an acceleration of 143 g, and 2000 kg at an acceleration of 350 g.

A leak-proof modeling box was specially designed and fabricated by the acrylic plastic panel with thickness of 1.27 cm. The modeling box was 30.5 cm in length, 30.5 cm in width, and 45.7 cm in height. The modeling box was constructed with holes in each side that served as outlets for collecting water samples during the centrifuge tests. Figure 2 is a schematic diagram of modeling box with the sediment, capping layers, and instrumentation.

An overlying water sampling system was fabricated to collect pore water samples at specified time intervals during the centrifuge tests. Four sampling port connectors were made from threaded metal plugs and stainless steel tubing (0.64 cm in diameter, 15.24 cm in length, and

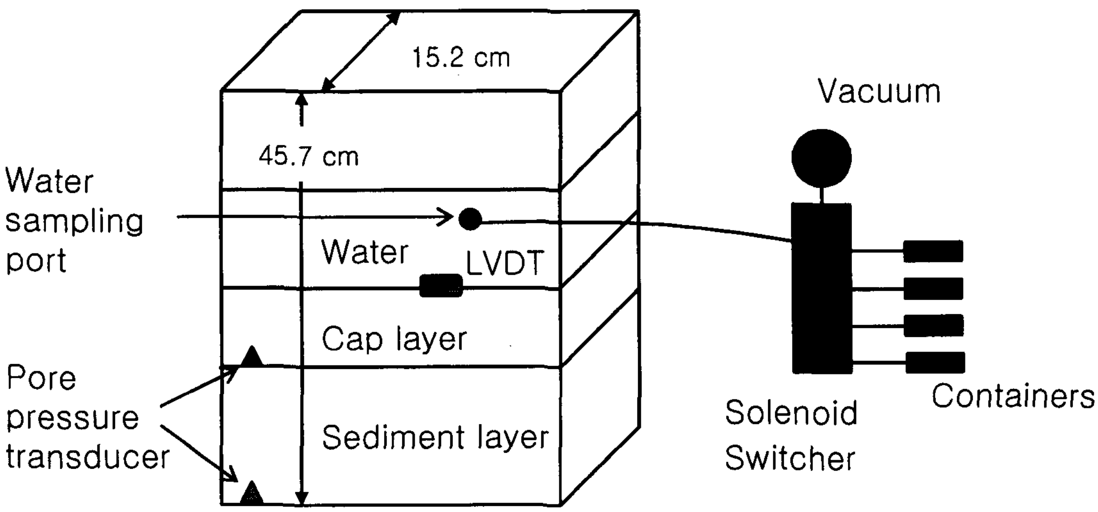


Fig. 2. Diagram of modeling box and instrumentation equipment

curved to 120°(; on one end). One end of the polyethylene tubing was attached to the polyethylene caps of the sampling bottle, and the opposite end of the tubing was inserted in each sampling port about mid-depth below the surface of the overlying water.

Five solenoid valves controlled vacuum to the sample collection system. Four sampling bottles were connected to separate solenoid valves using polyethylene tubing (0.64 cm)) and the fifth valve vented the system. The sampling bottles were connected to the inlet side of the solenoid switching box with polyethylene tubing.

Because of the high g-levels attained during the experiments, placement of a conventional laboratory vacuum on the centrifuge was not recommended. Thus, the vacuum used to obtain samples of the overlying water was located in the mechanical room below the centrifuge. Polyethylene tubing (0.64 cm) connected the vacuum to a solenoid switching box that was located on the centrifuge. The vacuum was connected to the solenoid switching box by placing the vacuum tubing line through the centrifuge's slip ring, which connected instrumentation on the centrifuge basket to the control and mechanical rooms.

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.

2.3 Experimental Procedures

The centrifuge modeling box was coated with a thin layer of a high viscosity silicone oil (Dow Corning 510) in order to minimize wall effects in the model. The sediment and capping materials were placed in separate large polyethylene bags. The sediment was placed into the modeling box at a water content ranging from 110 - 180 % which agree favorably to field data of similar sediments, where in-situ capping was applied (Palermo et al., 1998). Loading of the modeling box to the desired sediment height and placement of the cap layer 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.

3. Experimental Results

3.1 Centrifuge Test 1

During centrifuge test 1, approximately 2000 g of New York sediment was poured into the modeling box to a height of 45 mm at an initial water content of 180 %. The sediment (layer 1) was consolidated for approximately 26.3 minutes (6 prototype months). Upon completing the pre-consolidation phase of layer 1, the modeling box was removed from the centrifuge basket, and the overlying water was removed. Layer 1 was consolidated to a height of 40 mm. Next, approximately 2000 g of New York sediment was placed above layer 1. Layer 2 was consolidated for 26.3 minutes on the centrifuge. Upon completing the consolidation phase of the layer 2, the modeling box was removed from the centrifuge basket, and the overlying water was removed. Layers 1 and 2 in the model were consolidated by 7 mm to a prototype height of 8.3 m. Table 2 summarizes the boundary conditions for test 1.

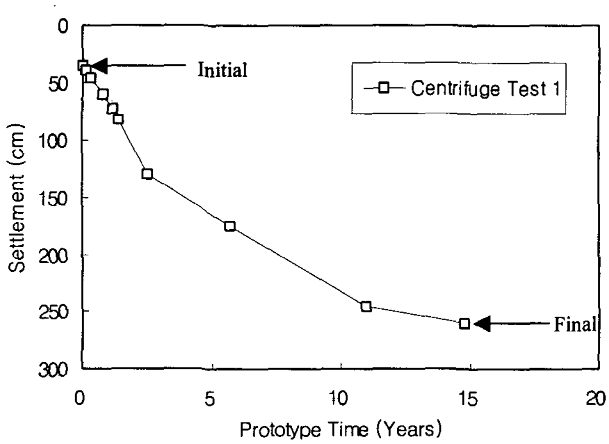


Fig. 3. Settlement curve for centrifuge test 1

A 3 cm (prototype = 300 cm) capping layer was placed on top of the layer 2. The three layers were then consolidated at 100 g for approximately 14.8 years in the prototype (13 hours in the centrifuge). Figure 3 shows the prototype settlement data for test 1 after the cap was placed. From Fig. 3, the total settlement of the sediment and capping layer at the end of test 1 was 260 cm.

3.2 Centrifuge Test 2

Centrifuge test 2 was conducted with the same boundary conditions as test 1 at a gravitational acceleration of 50 g. The purpose of this test was to assure that test 1 was appropriately modeled. This technique is called the modeling of models technique. Table 2 summarizes the boundary conditions for test 2. Figure 4 shows the results from test 2. The total settlement of the sediment and capping layer at the end of test 2 was 168 cm. Figure 5 shows experimental data obtained from tests 1 and 2 for comparison. As seen in Fig. 5, test 2 had less initial settlement in comparison to test 1. However, as time increased, consolidation behavior in the tests 1 and 2 began to converge. The convergence of the data occurred around 40,000 prototype hours or 4.6 years. Since there was good agreement between tests 1 and 2, it can be concluded that the experiment has been correctly modeled using the modeling of models technique.

Table 2. Boundary conditions for centrifuge model and prototype

	Centrifuge Test 1	Centrifuge Test 2
g-level	100	50
Model Time, hours	13	20
Initial Void Ratio of Sediment	4.8	4.8
Model Properties		
Height of Layer 1, cm	4.5	9
Height of Layer 2, cm	4.5	9
Height of Cap, cm	3	6
Prototype Properties		
Prototype Time, years	14.8	5.7
Height of Layer 1, cm	450	450
Height of Layer 2, cm	450	450
Height of Cap, cm	300	300
Void Ratio of Incompressible Foundation	0.5	0.5
Permeability of Incompressible Foundation, cm/sec	1×10^{-9}	1×10^{-9}
Length of Drainage Path in Incompressible Foundation, m	30	30
Elevation at Top of Incompressible Foundation, m	0	0
Elevation of External Water Table, cm	1524	1524
Excess Pore Water Pressure Where Secondary Compression Starts, kN/m^2	4.8	4.8

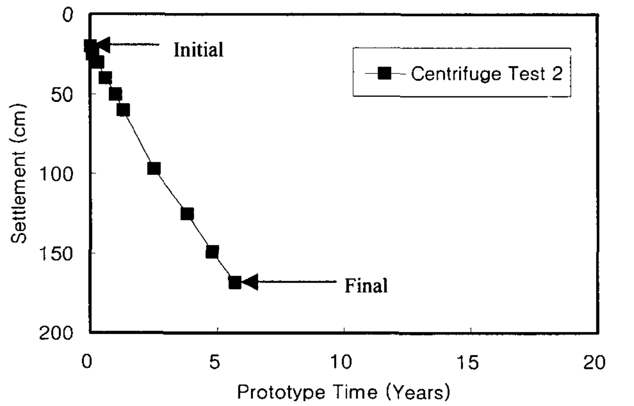


Fig. 4. Settlement curve for centrifuge test 2

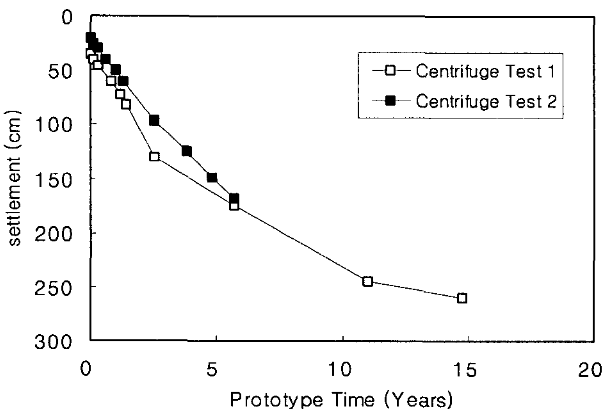


Fig. 5. Comparison settlement curve for centrifuge tests 1 and 2

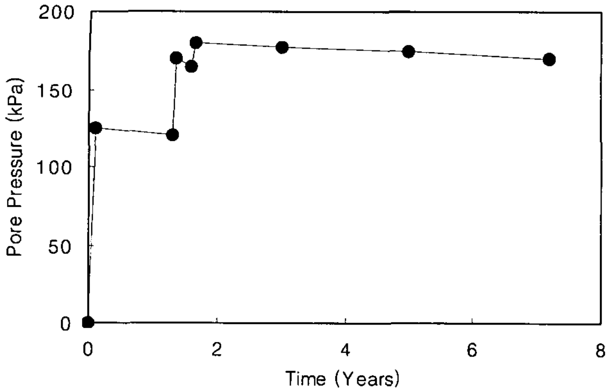


Fig. 6. Pore pressure transducer measurements at lower boundary

Pore pressure readings were obtained during centrifuge tests 1 and 2. Figure 6 shows the pore pressure transducer measurements at the lower boundary of the modeling box. Increases in the pore pressure indicate either the addition of another layer or an increase in gravity. The high initial pore water pressures were expected in centrifuge testing and resulted from the build up of pore water pressure caused by the increase in gravity.

4. Conclusions

Centrifuge tests were utilized to predict the consolidation of marine contaminated sediment caused by the placement of a capping layer. The centrifuge tests used the modeling of models technique to verify that correct modeling procedures were utilized. Initial settlements in tests 1 and 2 were different, but, as time increased, consolidation behavior in the tests began to converge. The convergence of the data occurred around 40,000 prototype hours or 4.6 years. Since there was good agreement between tests 1 and 2, it can be concluded that the centrifuge experiment can model the behavior of consolidation of marine contaminated sediment caused by the placement of a capping layer.

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