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Experimental Investigation of Consolidation Induced Contaminant Transport Using a Centrifuge

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요 지

캡이 설치된 준설퇴적토층에서 확산에 의한 오염물질이동을 측정할 수 있는 실내 실험방법들이 있지만, 확산에 의한 오염물질이동은 캡핑효과에 큰 영향을 미치지 않는다. 반면, 캡이 설치되는 동안이나 후에 퇴적층의 압밀에 의해 오염물질이 훨씬 더 많이 이동한다. 이것을 증명하기 위해, 원심모형시험기를 이용한 모형실험이 실시되었다. 본 연구에서 22.5시간 100 g에 대해 축소모형실험을 실시하였는데, 이것은 실제로 25년의 오염원이동시간과 축소모형의 100배 규모에 해당되는 모델링이라고 할 수 있다. 원심모형 실험결과 압밀에 의한 이류와 분산이 오염원 이동의 주 원인임을 알 수 있었다.

주제어 : 원심모형, 압밀, 퇴적물, 오염물질이동, 이류

ABSTRACT

Laboratory procedures are available for estimating contaminant migration from sediment into caps by diffusion, but diffusion may not be the major process affecting capping effectiveness. Movement of contaminated pore water from sediment into caps due to sediment consolidation during and after cap placement may be much more significant than contaminant diffusion into caps. To verify this phenomenon, model tests were conducted by utilizing a research centrifuge. In this study, test was modeled for 22.5 hours at 100 g, which modeled a contaminant migration time of 25 years for a prototype that was 100 times larger than the centrifuge model. Centrifuge test results illustrate that advection and dispersion due to consolidation are dominating the migration of contaminants.

Keywords : centrifuge; consolidation; sediment; contaminant transport; advection

I. Introduction

Sediment must be dredged from waterways and ports each year to maintain the navigation system. There are three alternatives for the disposal of marine sediment: open water disposal (e.g. sub-aqueous pits), confined disposal facilities, and beneficial use applications. Economics, technical feasibility, and environmental acceptability must be evaluated to determine the most appropriate option. Open water disposal refers to the placement of marine sediment into a water body by a pipeline or release from a barge. Confined disposal involves the placement of marine sediment into large dike region, constructed adjacent to land, in protected waters, harbors, or in open water. Examples of beneficial use applications include wetland creation, beach nourishment, mine reclamation, and land applications[5,6]. The remainder of materials is either placed into landfills or handled as hazardous waste.

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 options unfavorable to many port authorities[5]. In-situ capping of sediment and disposal of contaminated sediments in sub-aqueous pits are the least expensive alternatives. In-situ

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capping involves placing a layer of clean sand over contaminated sediment (i.e. in-situ) and with a recommended minimum design thickness of 1 foot[6]. 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[4].

Dredged material capping and in situ sediment capping alternatives, however, are not widely used because regulatory agencies are concerned about the potential for contaminant migration through the caps. Laboratory procedures are available for estimating contaminant migration from sediment into caps by diffusion[6-8], but diffusion may not be the major process affecting capping effectiveness. Movement of contaminated pore water from sediment into caps due to sediment consolidation during and after cap placement may be much more significant than contaminant diffusion into caps. Consolidation of sediment is a material and time dependent process where granular soils compress in a short period of time and fine grained sediments gradually compress over time[2].

There is a basic lack of information on the significance of consolidation induced advective transport of contaminants from contaminated sediment into caps. Estimating the amount of advective contaminant transport due to consolidation is usually not performed when designing a capping layer. Analysis of consolidation induced advective transport of contaminants into caps could provide major economic and environmental benefits. Economic benefits accrue from avoiding more costly alternatives for dredged material disposal and sediment remediation. Environmental benefits may also be accrued from more environmentally protective cap design.

The objective of this research was to evaluate the significance of consolidation induced advective transport of radio-labeled organic contaminants from sediment into caps using a research centrifuge. To accomplish this objective, model tests were conducted using a research centrifuge.

2. Centrifuge experiments

2.1. Material characterization

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). A silty-sand capping material collected from the Ambrose channel located in the New York Harbor was used in this study. Physical properties of the sediment and cap are summarized in Table 1. The sediment and capping material are classified as organic clay (OH) and silty sands (SP-SM) according to the American Society for Testing and Materials procedures. Grain size distributions for the sediment and capping materials are shown in Fig. 1. Laboratory consolidation tests were conducted on the materials in accordance with the Corp of Engineers procedure in EM 110-2-5027, Confined Disposal of Dredged Material, for the purpose of estimating long term volume changes for a confined aquatic disposal (CAD) pit. Fig. 2 shows the laboratory consolidation test results for the

Table 1. Physical Characteristics of Sediment and Cap

Parameter	ASTM method	Sediment	Cap
% Sand	D-422	33	94
% Fines	D-422	66	6
Water content (%)	D-2216	113	29
Organic content (%)	D-2974	2.6	0.2
Density g/cm^3 (pcf)	--	1.4 (88)	1.95 (121)
Specific gravity	D-845	2.64	2.68
Void ratio	--	2.98	0.77
Porosity	--	0.75	0.44
Soil classification	D-2487	CH	SP-SM
Effective size, D10 (mm)		0.004	0.17
Mean particle diameter (mm)		.06	0.35
Hydraulic conductivity (cm/sec)		4×10^{-5}	1×10^{-3}
Plasticity index (%)	D-4318	9	--
Liquid limit (%)	D-4318	76	--

Note: water content was measured as the weight of water/weight of solids

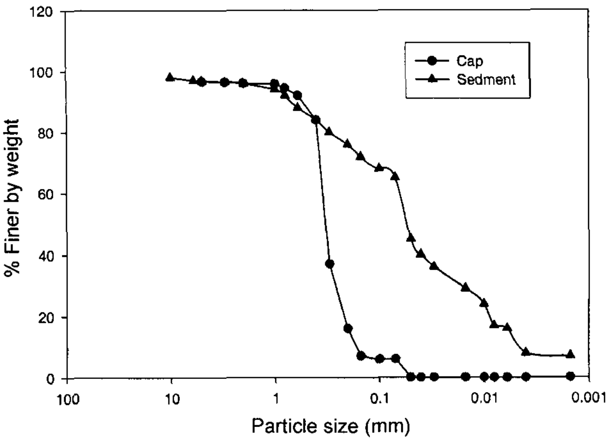


Fig. 1. Grain size distribution curve for sediment and cap.

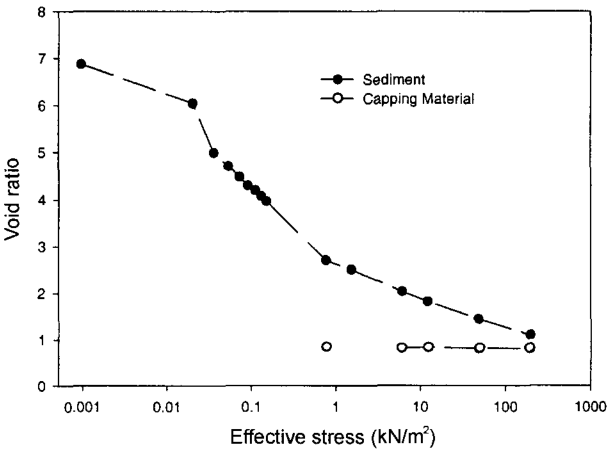


Fig. 2. Consolidation curve for NYDMMP sediment and capping material.

sediment and capping material and clearly indicates that the sediment is very compressible while the cap material is incompressible.

A carbon-14 radio-labeled compound, 2,3,7,8-tetrachloro [U-14]dibenzo-p-dioxin ([14C]TCDD) (referred to as TCDD throughout the rest of the document) purchased from Chemsyn Science Laboratories was used to study the transport of dioxin through the cap material during the centrifuge tests. TCDD was used in order to quantify the dioxin concentrations in thin sections (200 μm) of sediment and cap materials and in small quantities of water. TCDD is a beta emitter that has a half-life of 5730 years and emits 0.156 MeV. Calculations were based on the minimum carbon-14 activity required to obtain reproducible liquid scintillation counts (LSC) on a 200-micron slice. The NYDMMP sediment was spiked at a concentration of 24 μg/kg of TCDD. TCDD was measured using a liquid scintillation counter.

Table 2. Centrifuge Scaling Relationships

Quantity	Prototype	Model
Length	N	1
Area	N^2	1
Volume	N^3	1
Velocity	1	N
Acceleration	1	N
Mass	N^3	1
Force	N^2	1
Stress	1	1
Strain	1	1
Time (Advection)	N^2	1

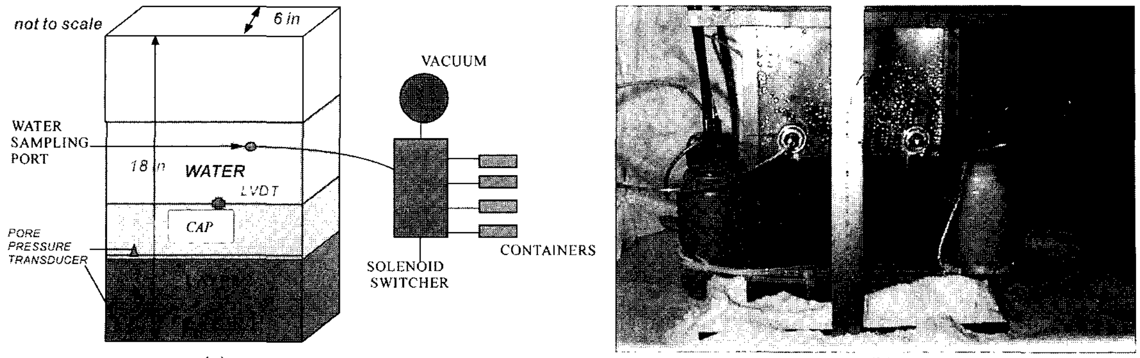
Rhodamine WT, a water-soluble, fluorescent dye was also used in this study to monitor the movement of pore water through the cap layer. The sediment was spiked with 4-ml of 1000-ppm dye per 1000 g of sediment. The sediment was stirred on a mechanical mixer for at least 24 hours. The sediment was stirred on a mechanical mixer for at least 24 hours. Dye was not added to the capping material.

2.2. Centrifuge apparatus and test procedure

The research centrifuge at Waterways Experiment Station (WES) is the largest research centrifuge in North America. The research 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. Table 2 displays the scaling relationships for centrifuge experiments[1,3].

The 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. The modeling box was constructed with holes in each side that served as outlets for collecting water samples during the centrifuge tests. Fig. 3a is a schematic diagram of modeling box with the sediment, capping layers, and instrumentation. To test the effectiveness of the acrylic-modeling box, the box was filled with water, pressurized, tested for leaks and no failures occurred. The environmental modeling box used in this test is shown in Fig. 3b.

LVDTs (Liner Variable Differential Transducers) were utilized in the centrifuge consolidation studies to measure the vertical settlement of the sediment. An LVDT is an electromechanical transducer that produces an electrical



(a) (b)

Fig. 3. (a) Schematic diagram of modeling box. (b) Environmental modeling box with sediment, cap layer and LVDT's.

output proportional to the displacement of a separate movable core. A special footing was fabricated to allow the LVDT to remain on each surface layer before consolidation was induced. Construction of the footing was accomplished by placing a washer at the tip of each LVDT, and gluing the washer to a piece (6.1 cm^2) of polyethylene mesh using the dental adhesive. Each LVDT was mounted near the center of the modeling box with its foot placed on the surface of each layer of material.

Each centrifuge modeling box was coated with a thin layer of a high viscosity silicone spray (Dow Corning 510) in order to minimize wall effects in the model and to prevent adhesion of the TCDD contaminant to the surface of the acrylic modeling box. The two sediment mixtures and the capping material were placed in separate large polyethylene bags. 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 material out of the bag into the modeling box. After placement of the cap material, deionized

Table 3. Testing Protocol for Consolidation Study

Procedure	Description	Test protocol
Step 1	Bulk consolidation of sediment (1st layer)	1. Add a 4.5 cm premixed dye and sediment to test cell as 1st layer of sediment 2. Consolidate on centrifuge for 26 minutes at 100 g 3. Monitor surface settlement and pore water pressure 4. Obtain an overlying water sample and measure dye concentration in overlying water 5. Test dye concentration in overlying water 6. Visually measure the magnitude of sediment consolidation
Step 2	Bulk consolidation of sediment (2nd layer)	1. Add 4.5 cm layer of premixed dye and sediment as 2nd layer of sediment 2. Consolidate sediment for 26 minutes at 100 g 3. Monitor surface settlement and pore water pressure 4. Visually observe dye breakthrough 5. Remove overlying water 6. Test dye concentration in overlying water 7. Measure the magnitude of sediment consolidation
Step 3	Cap/sediment consolidation	1. Add a 3-cm layer of capping material, saturate the capping layer with deionized water, and add 0.3 cm of overlying water 2. Centrifuge material for 22.5 hours (25 prototype years) 3. Monitor surface settling and pore water pressure in cap 4. Visually observe dye breakthrough 5. Collect overlying water samples 6. Test dye concentration in laboratory 7. Measure magnitude of sediment and cap consolidation 8. Core sediment, test sediment profile (moisture content) 9. Core sediment slices on microtome, determine dye concentration on a fluorometer (dye test)

water was sprayed on the cap in order to minimize void areas in the cap layer, and 0.3 cm of overlying water was placed above the capping layer.

Table 3 lists the testing protocols for the centrifuge consolidation test, and Table 4 shows the protocols followed in conducting the radiochemical contaminant transport study. Overlying water samples were collected during the radioactive transport study 5,10, 15, and 20 prototype years (4.5, 9, 13.5 and 18 hours) to monitor concentration changes. Note that two sediment layers were placed into the modeling box where layer 2 contained the contaminant of interest. Table 5 summaries the test conditions for the prototype and the two centrifuge models, I and II.

Utilizing the core sampler described in the equipment section, sediment cores from the modeling box were obtained. The sediment cores were then sectioned on a Carl Zeiss, Inc., Model HM 440E microtome into thin sediment slices. The microtome was equipped with an automatic sample feed mechanism and an electronic monitoring system with the capability of measuring sample thickness in microns and sequentially counting and summing individual sediment slices. The sediment slices were tested for water content, dye concentration, and for TCDD radioactivity. At the completion of the TCDD study, a radioisotope wipe test was conducted on the side wall of the centrifuge to determine if TCDD adhered to the side wall. The wipe test revealed that no TCDD adhered to the side wall.

Table 5. Test Conditions for Model and Prototype

Test Conditions	Test I	Test II
Centrifuge Acceleration (g)	100	100
Model Cap Thickness (cm)	3	3
Prototype Cap Thickness (cm)	300	300
Model Sediment Thickness (cm)	9	9
Prototype Sediment Thickness (cm)	900	900
Prototype Area (m^2)	1385	248.3
Test Duration (hr)	22.5	22.5
Prototype Time (years)	25	25

3. Results and analysis

3.1. Centrifuge test I

Centrifuge test I was conducted to determine the consolidation characteristics of the sediment and cap material. The sediment layers were placed into the modeling box at an initial water content of 110% and were pre-consolidated prior to the placement of the capping layer. Fig. 4 shows the centrifuge prototype settlement curve for test I after the placement of the cap. The data were obtained from

Table 4. Testing Protocol Radiochemical Advective Transport Test

Procedure	Description	Test protocol
Step 1	Bulk consolidation of sediment (1^{st} layer)	1. Add premixed dye and sediment to test cell as 1^{st} layer of sediment 2. Consolidate on centrifuge 3. Monitor surface settling and pore water pressure 4. Remove overlying water 5. Measure magnitude of sediment consolidation 6. Test dye concentration in overlying water
Step 2	Bulk consolidation of sediment (2^{nd} layer)	1. Add premix dye, sediment and C-14 (TCDD) labeled dioxin as 2^{nd} layer of dredged sediment 2. Reconsolidate sediment for 26 minutes at 100 g 3. Monitor surface settling and pore water pressure 4. Remove overlying water 5. Measure magnitude of sediment consolidation. 6. Test dye concentration in overlying water
Step 3	Cap/sediment And centrifuge for specified time	1. Add capping material 2. Centrifuge material for 22.5 hours at 100 g 3. Monitor surface settling and pore water pressure in cap 4. Obtain overlying water samples at (4.5, 9, 13.5, and 18 hours) 5. Remove overlying water remaining at end of test 6. Measure magnitude of sediment and cap consolidation 7. Analyze dye and C-14 (TCDD) dioxin in overlying water samples. 8. Core sediment, slice cores on microtome, test slices on liquid scintillation counting (LSC).

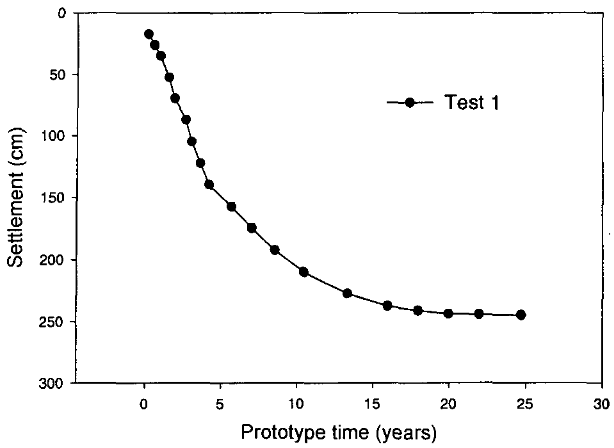


Fig. 4. Prototype settlement curve (centrifuge test I).

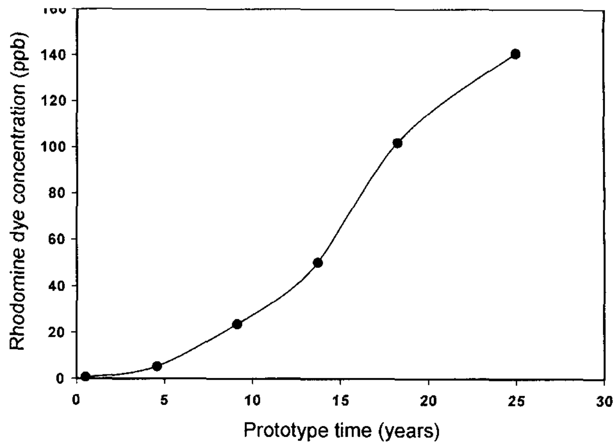


Fig. 6. Rhodamine dye concentration in advected pore water (centrifuge test I).

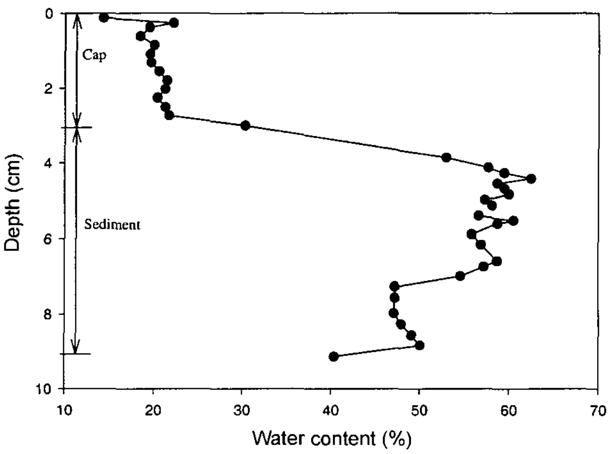


Fig. 5. Water content profile for the sediment and cap (centrifuge test I).

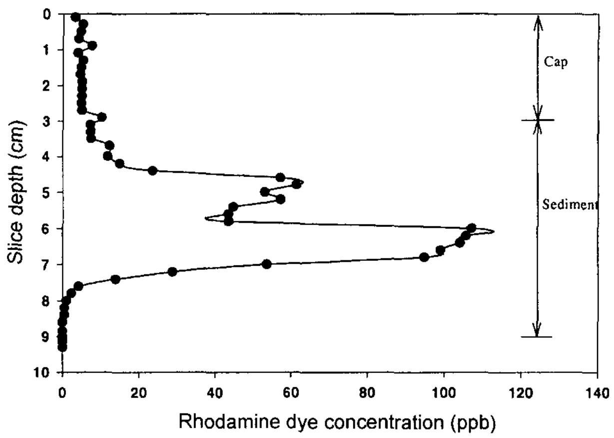


Fig. 7. Rhodamine dye concentration in sediment and cap (centrifuge test I).

the LVDT at the interface of the sediment and cap. The total settlement in the model was 2.65 cm (i.e. 2.65 m in the prototype). Sediment cores were taken from the modeling box. Cored samples were sectioned utilizing a microtome to conduct water content analysis. Fig. 5 shows the water content and sediment depth relationship for the cored samples. The capping layer is represented from 0 to 3 cm, and the sediment layers are represented from 3 to 9.4 cm. Fig. 5 indicates that pore water was advected from the sediment layer through the cap since there was a decrease in the water content.

Fig. 6 shows the Rhodamine dye concentration in the overlying water in centrifuge test I. The increase in the dye concentration with time indicates that pore water is moving from the sediment layer through the capping material. Furthermore, the breakthrough of the dye illustrates that there was no retardation and that advection is the dominant transport process. Fig. 7 shows the Rhodamine dye concentration in a cored sample from the centrifuge test. As expected, the dye concentration was much greater in the sediment than in the cap.

3.2. Centrifuge test II

Centrifuge test II was conducted to monitor the consolidation induced advective transport of TCDD. Because of safety concerns involved, Centrifuge test II was conducted as a semi-sealed source test with no instrumentation for measuring sediment settlement. Fig. 8 plots the TCDD concentration (in μg/l) versus the prototype time for the overlying water samples obtained during the centrifuge tests and shows that the maximum concentration of TCDD advected from the sediment was 0.024 μg/l.

Fig. 9 shows the vertical profile of TCDD concentration for three sediment cores taken at the end of the test. An

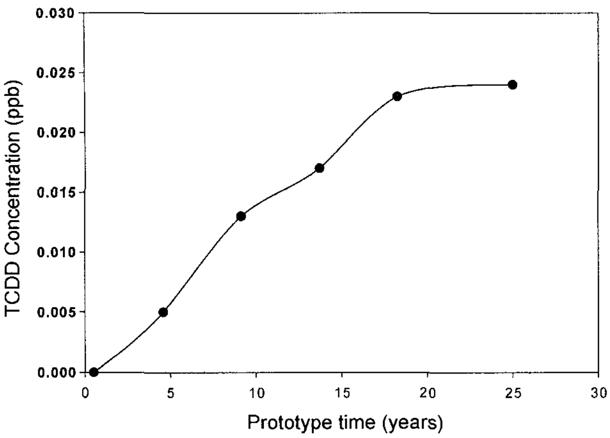


Fig. 8. TCDD concentration in overlying water (centrifuge test II).

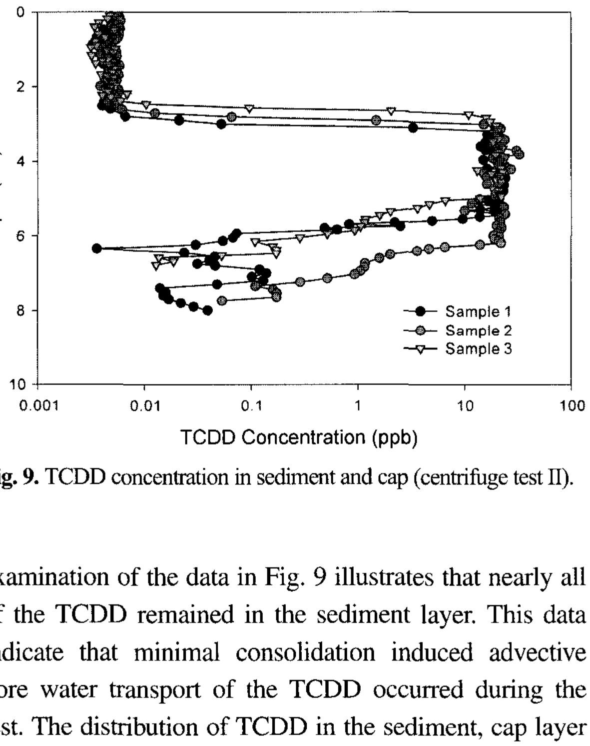


Fig. 9. TCDD concentration in sediment and cap (centrifuge test II).

examination of the data in Fig. 9 illustrates that nearly all of the TCDD remained in the sediment layer. This data indicate that minimal consolidation induced advective pore water transport of the TCDD occurred during the test. The distribution of TCDD in the sediment, cap layer and advected pore water at the end of 25 prototype years is 99.8, 0.03 and 0.12%, respectively.

4. Conclusion

The objective of this research was to evaluate the significance of consolidation induced advective transport of radio-labeled organic contaminants from sediment into caps using a research centrifuge. A centrifuge consolidation test was conducted to estimate the settlement of the sediment and cap. Also, a centrifuge test was conducted to determine the significance of consolidation induced advective transport of radiolabeled organic contaminants through a cap.

Centrifuge test results illustrate that advection and dispersion are the dominant transport processes. The movement of water during the centrifuge test was illustrated by the transport of TCDD and dye from the sediment through the cap and into the overlying water. Core samples taken at the end of the centrifuge test also showed the transport of TCDD and dye from the sediment and into the cap.

References

1. Cargill, K. W., and Ko, H. Y., "Centrifugal Modeling of Transient Water Flow", *Journal of Geotechnical Engineering*, 109, pp. 536-555 (1983).
2. Das, B. M., Principles of Geotechnical Engineering, P.S.W. Kent. New York, NY (2001).
3. Ibrahim, I., Centrifugal Modeling of Water Movement in Unsaturated Soils. Ph.D. Thesis, University of Colorado, Boulder (1990).
4. National Research Council (NRC), Contaminated Sediment in Ports and Waterways: Cleanup strategies and technologies. National Academy Press, Washington, D.C. (1997).
5. Palermo, M. and Wilson, J., Dredging State of the Practice: Corps of Engineers Prospective. Dredging and Management of Dredged Material: Geotechnical Special Publication 65, Meegoda JN, Wakeman TH, Arulmoli A, Librizzi W (Eds.), American Society of Civil Engineers, Reston, pp. 1-11 (1998)
6. Palermo, M., Maynord, S., Miller, J. and Reible, D.D., Guidance for In-situ Subaqueous Capping of Contaminated Sediment. EPA 905-B96-004., Great Lakes National Program Office, U.S. Environmental Protection Agency Chicago, IL (1998)
7. Thoma, G. J., Reible, D. D., Valsaraj, K.T. and Thibodeaux, L. J., "Efficiency of Capping Contaminated Sediments In-Situ: 2. Mathematics of Diffusion-Adsorption in the Capping Layer", *Environmental Science and Technology*, 27, pp. 2412-2419 (1993).
8. Wang, X. Q., Thibodeaux, L. J., Valsaraj, K. and Reible, D. D., "The Efficiency of Capping Contaminated Bed Sediments In-Situ-Lab-Scale Experiments on Diffusion/Adsorption in the Capping Layer", *Environmental Science and Technology*, 25, pp. 1578-1584 (1991).