93-09

# Environment Canada
## Water Science and Technology Directorate

---

## Direction générale des sciences et de la technologie, eau
# Environnement Canada

Subaqueous Capping of Very Soft Contaminated Sediments

By:
Alex J. Zeman

NWRI Contribution # 93-09

93-09

# SUBAQUEOUS CAPPING OF VERY SOFT CONTAMINATED SEDIMENTS

Alex J. Zeman
Lakes Research Branch
National Water Research Institute
Burlington, Ontario L7R 4A6

## ABSTRACT

A proposed 100-m x 100-m site for a subaqueous capping pilot-scale project in Hamilton Harbour is located in the water depth of about 15 m where the capping material will be in a relatively low-energy environment with little potential for erosion of the cap. The cap will consist of a 0.5-mm dia. clean sand and it will be placed on the bottom with a tremie pipe discharge system mounted on a spudded barge. The design thickness of 0.5 m will provide an effective isolation of contaminants from the overlying water and biota. Consolidation following the placement of the cap is estimated to occur within the period of about 10 to 50 days. The settlement of the cap surface will range from about 14 to 21 cm. Release of significant concentrations of contaminants due to rapid consolidation is unlikely. The results of a laboratory capping test, as well as theoretical results, suggest that the selected placement technique will not disturb very soft contaminated sediments. The effectiveness of the cap will be tested by physical, chemical and biological monitoring to ensure that the cap is placed as intended and that it prevents contaminant migration to the aquatic environment.

## INTRODUCTION

Subaqueous capping has become an important concept for isolating contaminated fine-grained sediments from the aquatic environment. Cost comparisons indicate that capping is the least-cost alternative when compared to other forms of handling contaminated sediments, e.g., incineration, land fill and upland confined disposal. Capping is considered an appropriate technology for effective chemical and biological isolation of contaminants in the U.S. Army Corps of Engineers dredging regulations (Palermo, 1991) and it is further recognized by the London Dumping Convention (Edgar and Engler, 1984) as a management technique to rapidly render harmless contaminated in-situ sediments and dredged material. Capping projects began in the late 1970s and experience has been gained under a variety of site conditions. Both granular and cohesive sediments have been found to be suitable capping materials. Most capping projects described in the U.S. literature have been concerned with in-water capped disposal of contaminated dredged material either as a level-bottom capping (LBC) project or a contained aquatic disposal (CAD) project. In Japan, the term "capping" usually refers to the placement of clean sand-sized material over contaminated marine or lacustrine in-situ sediments (Kikegawa, 1983; Togashi, 1983; Toa Construction, 1990).

Arguments against the application of capping as a remedial measure for contaminated sediments include the potential instabilty of a cap due to waves and bottom currents, the disturbance of very soft sediments during the placement of a cap, the potential transfer of contaminants through a cap due to consolidation, bioturbation and diffusion, and the impact of capping on aquatic organisms (especially on benthos). Most of these concerns will be addressed in this paper and results will be given on ongoing research at NWRI related to the design and monitoring of capping projects. Voluminous information related to physical, chemical and biological aspects of capping has been recently compiled as an annotated bibliography (Zeman et al., 1992).

## GENERAL OUTLINE OF DEMONSTRATION PROJECT

Subaqueous capping is considered as one of several sediment remediation measures in Areas of Concern (AOCs) on the Great Lakes identified by the International Joint Commission as major sources of pollution in the basin. This paper describes the preparation of a field demonstration project for one AOC, Hamilton Harbour, Lake Ontario, where most recent harbour sediments show various degrees of toxicity. In addition, these sediments exceed acceptable limits for open water disposal of dredgeate under current Provincial Guidelines (Hamilton Harbour RAP Team, 1989).

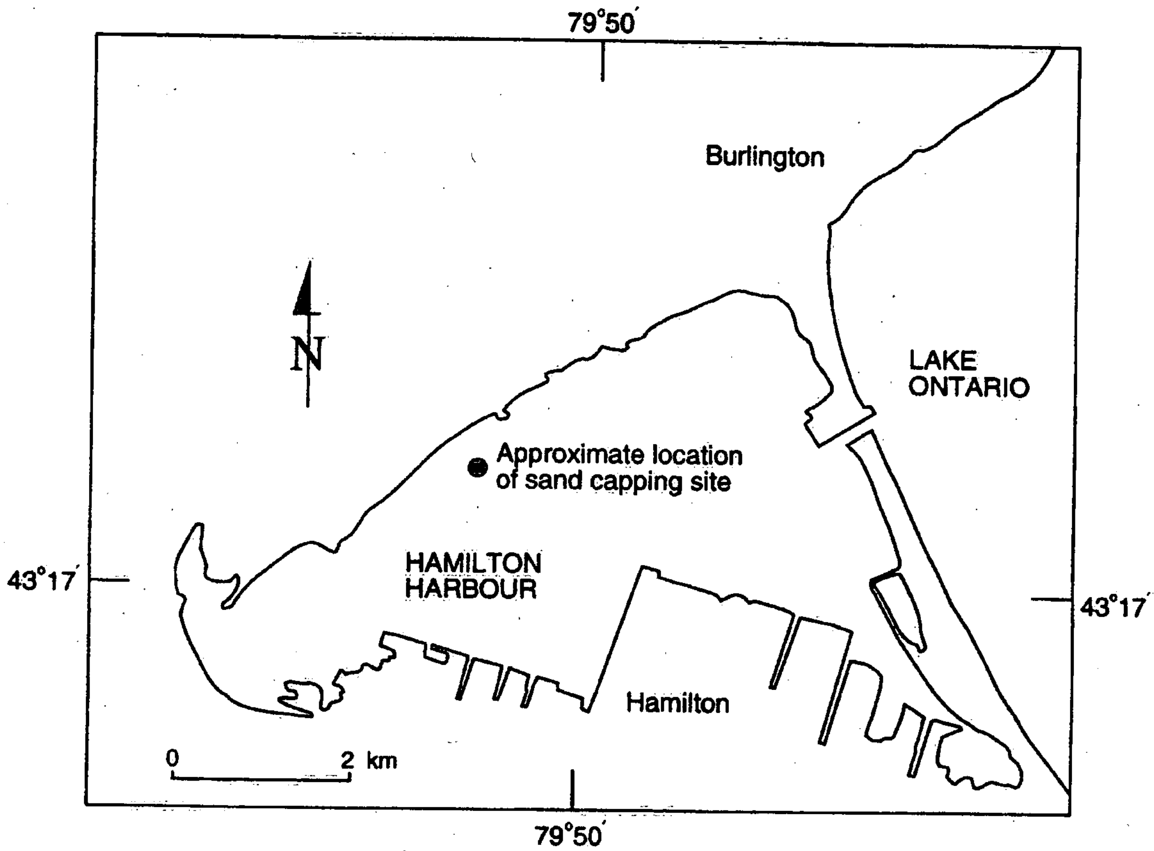


Figure 1. Location of the proposed capping demonstration project in Hamilton Harbour.

It is proposed to demonstrate the feasibility and effectiveness of subaqueous capping at a site in the Harbour (Figure 1) where bottom sediments are of intermediate to high acute toxicity. Bottom sediments at the site consist of about 30 cm of very soft black silty clay (industrial contaminated sediment) underlain by very soft greyish brown silt and clay (natural harbour sediment). The cap layer will consist of clean medium to coarse sand spread evenly over bottom sediments to a thickness of 0.5 m. This thickness has been found sufficient in providing an effective chemical and biological seal in laboratory capping experiments (Brannon et al., 1985, Gunnison et al., 1987). The bottom area of the site will be 1 ha (100 m x 100 m). The average water depth at the site is about 15 m.

## SITE SELECTION CRITERIA

### Stability of Capping Material

General guidelines for capping (Palermo, 1991) recommend that a capping site be located within a relatively low-energy environment. In the case of the Hamilton Harbour site (Figure 1), the stability of capping sand has been evaluated for a range of depth from 8 to 12 m and two sand sizes. The critical and maximum wave induced shear stresses were determined following the procedure described in Krishnappan and Skafel (1976). The results are presented in Table 1 below.

Table 1. The critical and maximum induced shear stresses for the central north shore of Hamilton Harbour.

| d,m | A,m | U,m/s | D = 0.1 mm | | | D = 0.5 mm | | |
|---|---|---|---|---|---|---|---|---|
| | | | $\tau_c$, Pa | $\tau_s$, Pa | $\tau_r$, Pa | $\tau_c$, Pa | $\tau_s$, Pa | $\tau_r$, Pa |
| 8 | 0.153 | 0.241 | 0.14 | 0.29 | 1.16 | 0.40 | 0.26 | 1.16 |
| 10 | 0.095 | 0.149 | 0.14 | 0.17 | 0.33 | 0.40 | 0.11 | 0.33 |
| 12 | 0.058 | 0.091 | 0.14 | 0.10 | 0.17 | 0.40 | 0.12 | 0.17 |

The symbols in Table 1 are: D is the sand diameter, d is the water depth, U is the amplitude of the horizontal bottom velocity due to the waves just above the bottom boundary layer, A is the amplitude of the horizontal water displacement just above the bottom boundary layer, $\tau_c$ is the critical shear stress of the sand, $\tau_s$ is the stress on the sand with no bed forms and $\tau_r$ is the stress on the sand in the presence of ripples due to the ambient waves.

For the three water depths and both sand sizes, ripples are formed so that only the shear in the presence of ripples need be considered. The ripples for the two sand sizes are of similar height under the same conditions so that the resultant shear stress on the bed is the same. The 0.1-mm dia. (fine to very fine) sand is expected to be unstable at all of the depths under the most severe conditions observed in a recent ten year wind climate. The 0.5-mm dia. (medium to coarse) sand, to be used in the capping demonstration project, would be stable at the water depth larger than 10 m. These estimates are applicable only to the vicinity of the site considered in Figure 1 and cannot be simply extended to other sites.

The influence of currents is assumed to play only a relatively minor role in the deeper water of the Harbour. Currents in windy periods are strongest along the shore and they are stronger in surface layers than in depth. For the 0.5-mm dia. sand, mean velocity measured 15 cm above the bottom would have to be in the order of 30 cm/s for movement of sand to occur (Postma, 1967). Particle movement predictions using the Ackers-White method (Pankow and Trawle, 1987) suggest that the 0.5-mm dia. sand at the water depth larger than 10 m will resist natural bottom velocities of about 45 cm/s. Such strong near-bottom currents are highly unlikely for deeper portions of the Harbour.

**Ship Traffic**

The effects of shipping are especially important in design considerations for capping projects because bottom stresses due to propeller wash and/or direct hull contact are typically of a greater magnitude than the combined effects of waves and currents (Truitt et al., 1989). Capping should not be considered in turning basins and other harbour areas where vessels' propeller wash strongly resuspends bottom sediments. The results of analysis by Pankow and Trawle (1987) suggest that armour stone with size of about 0.6 m would be required for long-term bottom protection in ship channels. They further point out that dropping of an anchor or dragging anchor across the cap would have a major adverse impact on the integrity of the cap. For these reasons, areas where the clearance between the propeller and the bottom is small should be avoided. In a feasibility study for capping in Indiana Harbour, Clausner and Abel (1987) have concluded that the minimum depth for capping should be 9.1 m (30 ft) to allow for squat, pitch, roll and heave of the 7.9-m (26-ft) draft vessels that use the harbour. Another of their conclusions was that, in depths larger than about 12 m, the maximum bottom stresses are due to waves rather than due to high propeller velocities.

In Hamilton Harbour, research to date has shown large and unsystematic variations in physical properties of modern bottom sediments (Rukavina, 1991). This appears to be the result of extensive and largely undocumented sediment dredging and dumping, and may also be related to disturbance of bottom sediments by ship traffic and anchorage. The proposed capping site will be surveyed by side-scan mapping prior to capping in order to detect possible areas of sediment disturbance.

**EQUIPMENT AND PLACEMENT TECHNIQUE**

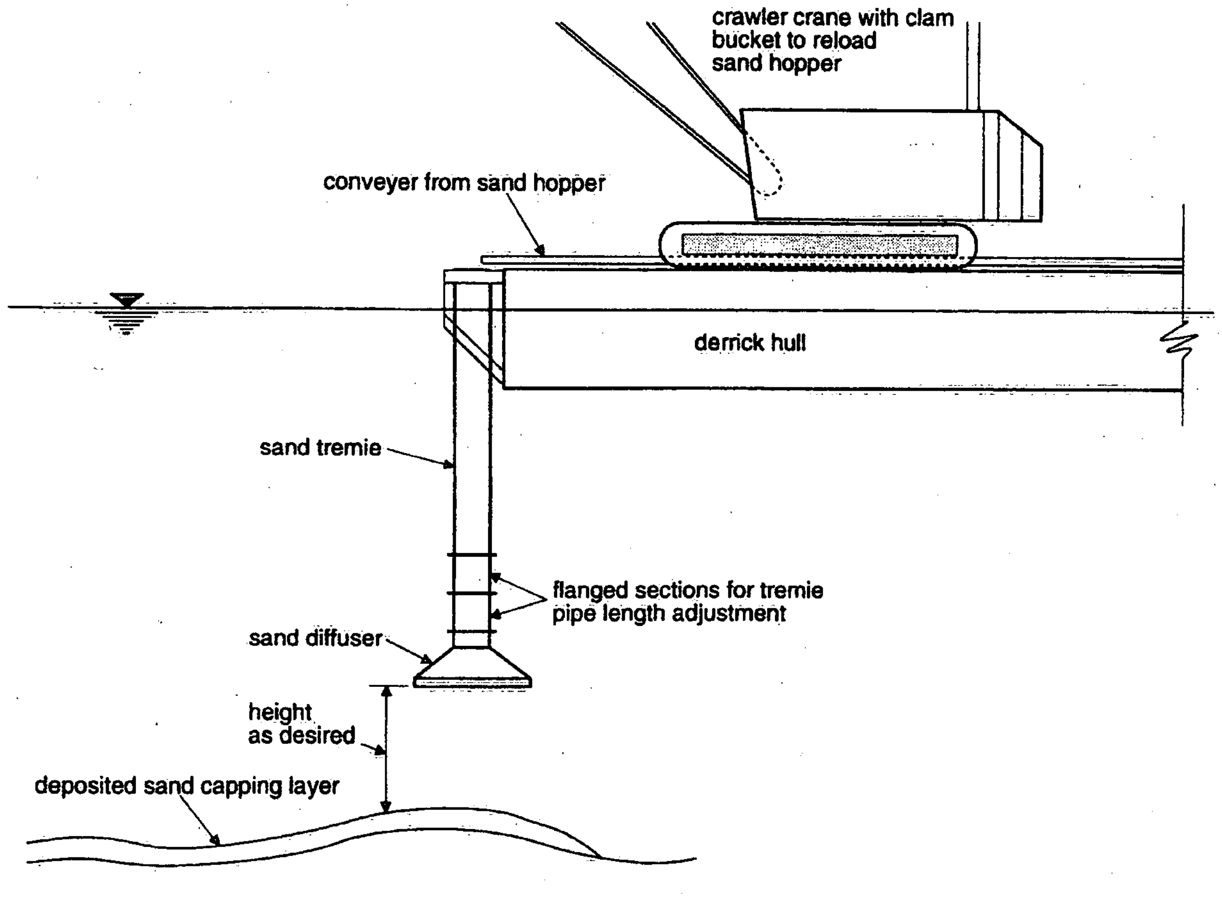


Figure 2. A tremie pipe discharge system considered for sand placement (after Cartier Construction Inc.).

Capping projects require precise placement of capping material over contaminated sediments with minimum sediment disturbance and mixing. Conventional dredging equipment with minor modifications is typically used in capping projects (Truitt et al., 1989).

For the demonstration project in Hamilton Harbour, a dredging industry consultant/contractor has been retained to evaluate various placement techniques for the site-specific conditions of the Harbour (Cartier Construction Inc., 1992). A 0.914-m dia. tremie pipe discharge system with a submerged diffuser mounted on a 18.3-m x 45.7-m spudded barge (derrick) will be used for uniform distribution of sand (Figure 2). The lower end of the diffuser flares out to a 3-m x 0.55-m rectangular opening that is covered with a porous plate. The diffuser will be equipped with internal baffles and air-operated bin vibrators.

The procedure to be used to cover the demonstration site with the uniform layer of sand is shown in Figure 3. The site will be subdivided into four strips each 25 m wide and 100 m long. The alignment of the derrick will be controlled by three lasers positioned on shore stations. The placement of sand will be achieved by swinging the derrick on the port spud which will be anchored in the bottom. After each 3-m wide and 0.5-m thick arc of sand is placed across the 25-m strip, the derrick will be moved back and repositioned for the placement of the next 3-m wide arc. By stepping the derrick backwards and by keeping the anchors out of the capping area (Figure 3), the cap will not be disturbed by the placement operation or its equipment. It is expected that about 20 work days will be required to completely cover the demonstration site.

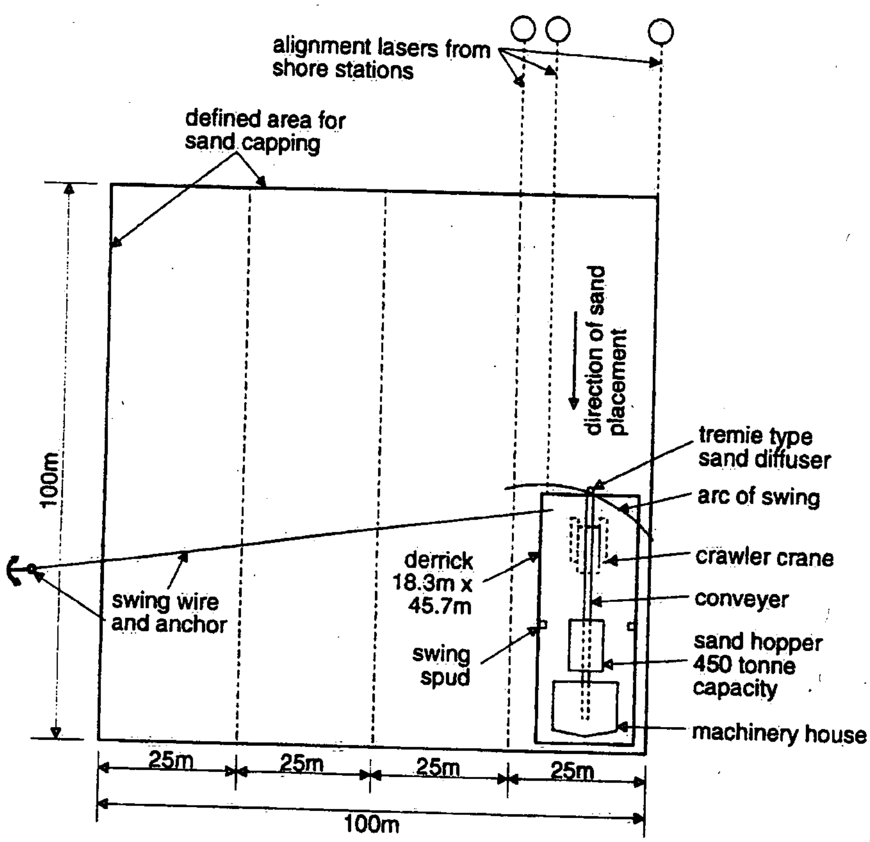


Figure 3. Sand placement method considered for the capping demonstration project (after Cartier Construction Inc.).

## CAP DESIGN CRITERIA

### Contaminant Isolation

The transfer of contaminants from sediments into the overlying water and biota occurs by numerous processes, e.g. by desorption, molecular diffusion, pore water advection and sediment bioturbation. The theoretical evaluation of these processes (Thibodeaux et al., 1990) led to the conclusion that bioturbation is the dominant transport mechanism which is an order-of-magnitude more rapid than molecular diffusion. Consequently, the most significant remediation as a result of capping occurs due to the relocation of the active bioturbation layer from the contaminated sediment to the clean sediment cap.

There are two additional processes that will mitigate the transfer of contaminants through the cap. Firstly, as pore water enters the cap from the underlying consolidating sediment, fresh sorption sites will be available for contaminants, which will be released from the solution and immobilized onto solid surfaces of the cap material. Thus e.g. mass balance analysis performed for PCB-contaminated sediments (Thibodeaux et al., 1990) suggests that PCB penetration into the cap should be of the order of one cm or less. Secondly, new accumulation of clean silts and clays on the surface of the cap will contain natural organic matter that will stimulate the growth of benthos and will provide sites for adsorbing contaminants. These theoretical considerations are supported by

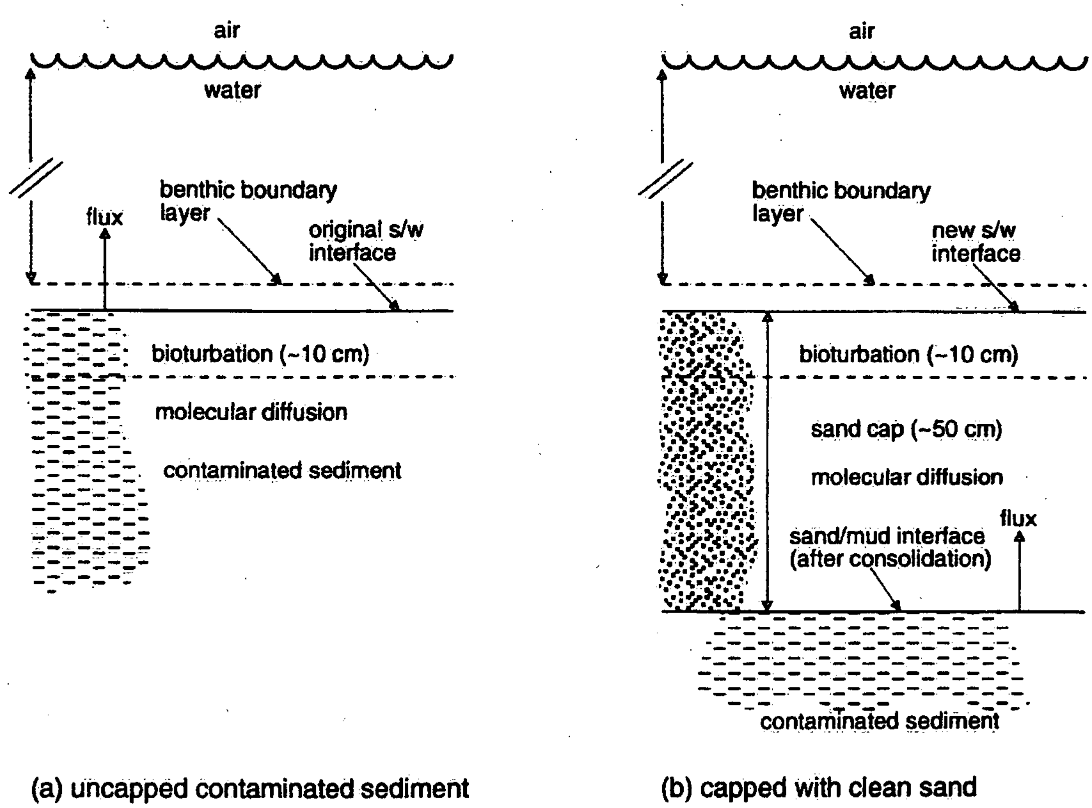


Figure 4. In-situ isolation of contaminated sediment by subaqueous capping (after Thibodeaux et al., 1990).

sediment chemistry profiles from existing capping sites. These sites were monitored from three to 11 years following cap placement and they showed no discernible long-term transport of both heavy metals and organics up into the caps (Sumeri et al., 1991).

As shown in Figure 4, the upper portion of the cap has the function of mitigating the effects of bioturbation by confining this process within the cap. A conservative estimate for this layer is about 20 cm. The remaining 30 cm act as the chemical barrier. Based on the published results of laboratory tests and capping experiments (Brannon et al., 1985; Gunnison et al., 1987), it is expected that the 50-cm thick cap will be effective in preventing long-term transfer of contaminants including the effect of bioturbation.

**Sediment Consolidation**

Magnitude and Rate of Settlement

The consolidation behaviour of Hamilton Harbour sediments due to a load applied by a 50-cm thick sand cap was analyzed by Zeman (1992). The samples used for the analysis were obtained from two sites in the Harbour (Cores HH1-90 and HH2-90) and, for comparative purposes, from one site in Lake Ontario (Core LO-90). Samples were obtained with a large box corer and they were tested by large consolidation tests with pore pressure measurements. In addition, Benthos cores were collected at each site to establish vertical geotechnical profiles. The magnitude and rate of settlement were computed using the classical (Terzaghi)

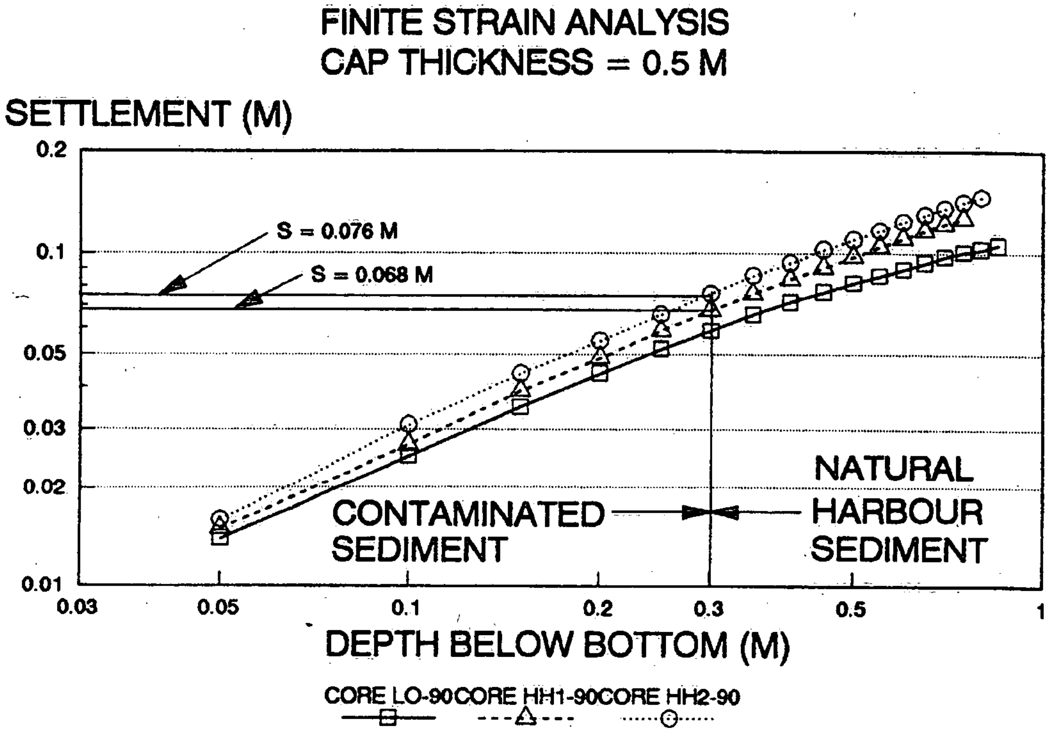


Figure 5. Ultimate settlement due to capping as a function of depth below the sediment-water interface (after Zeman, 1992).

consolidation analysis and the finite strain analysis (Gibson et al., 1981). Both methods of analysis used estimated minimum ultimate settlements to range from about 14 cm to 16 cm for the upper one m of sediment (Figure 5). The finite strain theory predicted the settlements to occur approximately twice as fast in comparison with the Terzaghi theory.

Displacement of Contaminated Pore Water

Based on the results presented in detail elsewhere (Zeman, 1992), it is assumed that the ultimate settlement of the cap surface will range from about 14 cm to 21 cm, depending on the thickness of the underlying compressible sediment. The primary consolidation is estimated to occur within the period of about 10 to 50 days. The water displaced by consolidation will migrate upwards and will replace the initial pore water contained within the cap. The total volume of pore water in the 0.5-m thick cap consisting of medium to coarse sand with porosity in the range 40-50 % (Kezdi, 1974) will be in the range of 200-225 $l/m^2$. The total volume of water displaced by consolidation will be in the range of 140-210 $l/m^2$, out of which only about 68-76 $l/m^2$ will be squeezed from the uppermost 30-cm thick contaminated layer (Figure 5). Consequently, it is expected that all displaced pore water will be confined within the cap and no significant long-term migration of contaminants will occur.

**Observation Tank Test**

Laboratory studies have been carried out in a 3.6-m x 3.6-m x 3.7-m observation tank with the objective to qualitatively investigate sand and sediment behaviour during and after capping. Although an attempt was made to

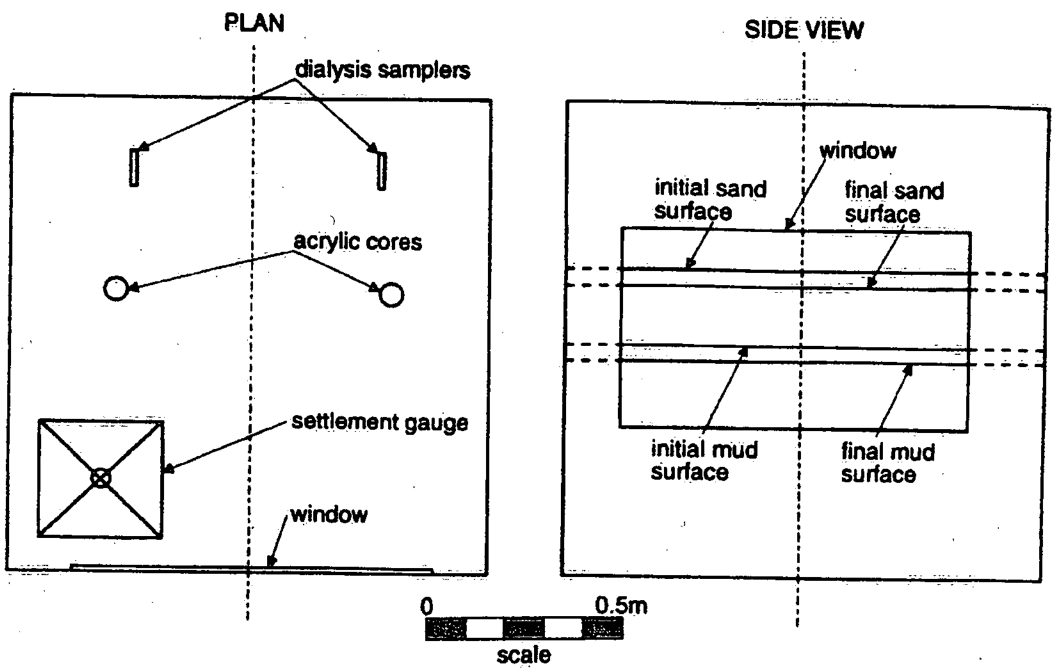


Figure 6. Inside tank filled with the sediment and the sand cap.

simulate field conditions as much as possible, in-situ geotechnical properties and boundary conditions could not be adequately reproduced in the test.

A 60-cm layer of Lake Ontario silty clay simulating the Harbour sediment was placed in a 1.3-m x 1.3-m x 1.3-m inside tank (Figure 6) centred on the bottom of the observation tank. The sediment was placed into the inside tank with the uniform initial void ratio of about 6.7 (the average of nine determinations). The observation tank was then filled with water and the sediment was allowed to consolidate due to its weight. Following the self-weight consolidation, the void ratio of the mud surface was about 4.3. A 20-cm layer of the 0.5-mm dia. sand was then sedimented through the water column onto the sediment surface. The observed consolidation due to the weight of the sand cap was about 4 cm (Figure 7). No appreciable penetration of sand into the underlying sediment occurred. These results are in agreement with earlier theoretical analysis that estimated the impact velocity of the sand and the penetration of the sand cap into the sediment (Zeman and Graham, 1991). No problems were encountered with the design of a settlement gauge, a dialysis sampler for pore-water monitoring and a core liner for cap/sediment laboratory physical and chemical testing (Figure 6).

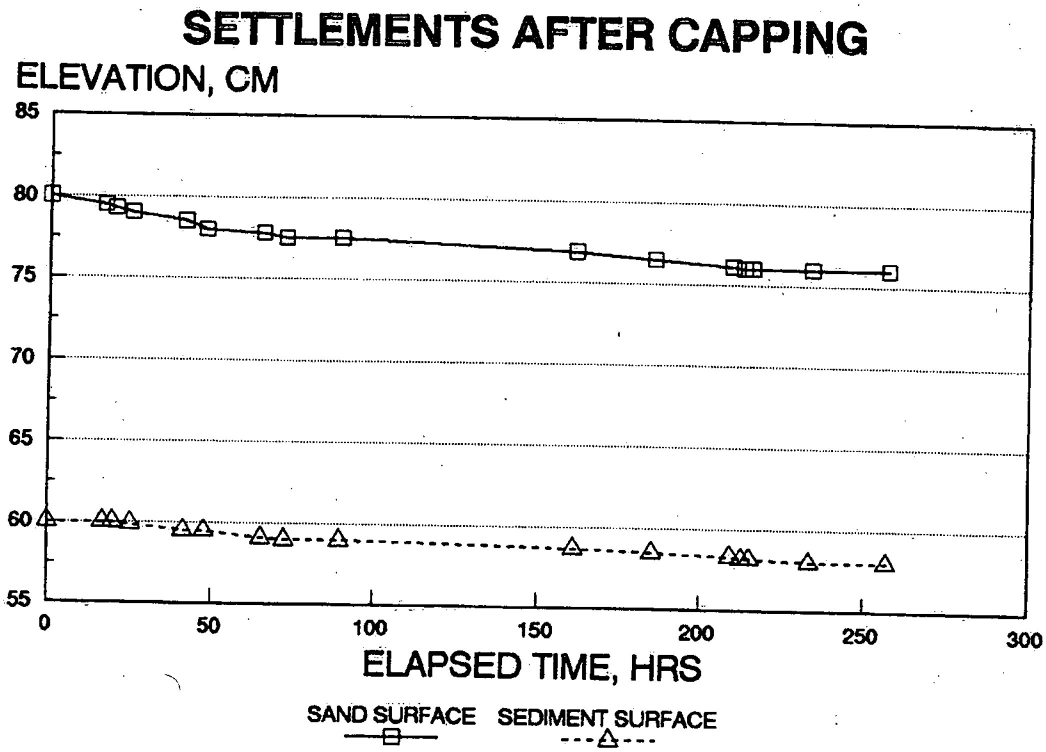


Figure 7. Observed settlements in the capping tank test.

## Monitoring Programs

### Physical Monitoring

Side-scan sonar will be used to map bottom relief and disturbance at the demonstration site prior to capping. The thickness and distribution of capping sand will be mapped using advanced acoustic-survey equipment and procedures. Geotechnical properties of sediments and capping sand will be investigated by gravity coring before capping and by light-weight vibratory coring after capping. The thickness of the cap and consolidation behaviour will be monitored by a grid of thickness/settlement gauges, which will be similar in design to those employed by Kikegawa (1983).

### Chemical and Biological Monitoring

The effectiveness of the cap to isolate chemically and biologically Hamilton Harbour sediments from the overlying water column will be investigated both by laboratory tests, which are currently in progress, and by field monitoring. Sediment cores and dialysis chambers will be used to study possible migration of nutrients and trace metals. Migration of organic contaminants will be investigated in the laboratory due to difficulties of determining organic contaminants in small quantities of water collected by dialysis samplers. The biological isolation of contaminants will be monitored by the examination of benthic invertebrate community structure, sediment toxicity and bioaccumulation.

**CONCLUSIONS**

The initial results presented herein have indicated that subaqueous capping is a feasible and effective remedial option for the deeper portion of Hamilton Harbour where, due to large volume of contaminated sediments, it is impractical to recommend dredging and upland disposal. The results will be further evaluated following the outcome of the demonstration project and its associated monitoring programs.

**ACKNOWLEDGEMENTS**

The work undertaken in connection with the preparation of the capping demonstration project has been sponsored by the Great Lakes Cleanup Fund of Environment Canada. The shear stress computations to determine cap stability against waves and currents were provided by M. G. Skafel, NWRI. The observation tank test was carried out in cooperation with N. A. Rukavina, NWRI. The consolidation testing of Hamilton Harbour and Lake Ontario sediments was carried out by Golder Associates Ltd., Mississauga, Ont.

**REFERENCES**

Brannon, J., Hoeppel, R., Sturgis, T., Smith, I., and Gunnison, D. 1985. Effectiveness of Capping in Isolating Contaminated Dredged Material from Biota and the Overlying Water. Technical Report D-85-10, US Army Engineer Waterways Experiment Station, Vicksburg, MS.

Cartier Construction Inc. 1992. Capping Contaminated Subaqueous Materials. Unpublished report prepared for Public Works Canada, 20 p.

Clausner, J. E. and Abel, C. E. 1987. Disposal Alternatives for PCB-Contaminated Sediments from Indiana Harbor, Indiana. Miscellaneous Paper EL-87-9, US Army Engineer Waterways Experiment Station, Vicksburg, MS, Appendix J, 28 p.

Edgar, C. E. and Engler, R. M. 1984. An Update on the London Dumping Convention and its Application to Dredged Materials. Proceedings, Dredging '84, ASCE, Clearwater Beach, Florida, pp. 140-149.

Gibson, R. E., Schiffman, R. L. and Cargill, K. W. 1981. The Theory of One-Dimensional Consolidation of Saturated Clays. II. Finite Nonlinear Consolidation of Thick Homogeneous Layers. Can. Geotech. J., 18: pp. 261-273.

Gunnison, D. L., Brannon, J. M., Sturgis, T. G. and Smith I. 1987. Disposal Alternatives for PCB-Contaminated Sediments from Indiana Harbor, Indiana. Miscellaneous Paper EL-87-9, US Army Engineer Waterways Experiment Station, Vicksburg, MS, Appendix F, 40 p.

Hamilton Harbour RAP Team, 1987. Remedial Action Plan for Hamilton Harbour, Stage I Report: Environmental Conditions and Problem Definitions, 162 p.

Kezdi, A. 1974. Handbook of Soil Mechanics, Volume 1. Elsevier Scientific Publishing Company, 294 p.

Kikegawa, K. 1983. Sand Overlaying for Bottom Sediment Improvement by Sand Spreader. Proceedings, 7th US/Japan Experts Meeting, US Army Engineer Waterways Experiment Station, Vicksburg, MS, pp. 79-103.

Krishnappan, B. G. and Skafel, M. G. 1976. Interactions of Waves with the Pelee Shoal Sediments. Unpublished Report, Hydraulics Research Division, Canada Centre for Inland Waters, Burlington, Ont., 18 p.

Palermo, M. A. 1991. Design Requirements for Capping, Dredging Research Technical Notes DRP-5-03. U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS, 14 p.

Pankow, W. E. and Trawle, M. J. 1987. Disposal Alternatives for PCB-Contaminated Sediments from Indiana Harbor, Indiana. Miscellaneous Paper EL-87-9, US Army Engineer Waterways Experiment Station, Vicksburg, MS, Appendix I, 15 p.

Postma, H. 1967. Sediment Transport and Sedimentation in the Estuarine Environment. In Estuaries, G. H. Lauff (ed.), Publication No. 83, AAAS, Washington, D.C., pp. 158-179.

Rukavina, N. R. 1991. Variability of the Physical Properties of Hamilton Harbour Bottom Sediments. Abstracts, 34th Conf. Great Lakes Research, Buffalo, NY, p. 130.

Sumeri, A., Fredette, T. J., Kullberg, P. G. Germano, J. D., Carey, D. A. and Pechko, P. 1991. Sediment Chemistry Profiles of Capped In-Situ and Dredged Sediment Deposits: Results from Three US Army Corps of Engineers Offices. Western Dredging Association Conf., 14-15 May 1991, Las Vegas, NV, 27 p.

Thibodeaux, L. J., Reible, D. D., Bosworth, W. S. and Sarapas, L. C. 1990. A Theoretical Evaluation of the Effectiveness of Capping PCB Contaminated New Bedford Harbor Bed Sediment. Final Report, Hazardous Waste Research Center, Baton Rouge, LA, 92 p.

Toa Construction. 1990. Report of Sand Placement Operation (Akanoi Bay Subaqueous Capping Pilot Project), Japan; Translation from Japanese by the Multilingual Translation Directorate Bureau, Ottawa.

Togashi, H. 1983. Sand Overlaying for Sea Bottom Sediment Improvement. Proceedings, 7th US/Japan Experts Meeting, US Army Engineer Waterways Experiment Station, Vicksburg, MS, pp. 59-78.

Truitt, C. L. Clausner, J. E. and McLellan, T. N. 1989. Considerations for Capping Subaqueous Dredged Material Deposits. J. Waterway, Port, Coastal, and Ocean Eng., ASCE, 115 (6): pp. 741-759.

Zeman, A. J. 1992. Consolidation of Very Soft Sediments due to Subaqueous Capping. NWRI Contribution No. 92-67, 7 p.

Zeman, A. J. and Graham, J. E. 1991. Design Considerations for Subaqueous Capping in Hamilton Harbour - Impact Velocity of Sand and Sand Penetration into Very Soft Cohesive Sediments. NWRI Contribution No. 91-26, 11 p.

Zeman, A. J., Sills, S., Graham, J. E. and Klein, K. A. 1992. Subaqueous Capping of Contaminated Sediments: Annotated Bibliography. NWRI Contribution No. 92-65, 124 p.

Environment Canada Environnement Canada

Canada


**Canada Centre for Inland Waters**
P.O. Box 5050
867 Lakeshore Road
Burlington, Ontario
L7R 4A6 Canada

**National Hydrology Research Centre**
11 Innovation Boulevard
Saskatoon, Saskatchewan
S7N 3H5 Canada

**St. Lawrence Centre**
105 McGill Street
Montreal, Quebec
H2Y 2E7 Canada

**Place Vincent Massey**
351 St. Joseph Boulevard
Gatineau, Quebec
K1A 0H3 Canada

**Centre canadien des eaux intérieures**
Case postale 5050
867, chemin Lakeshore
Burlington (Ontario)
L7R 4A6 Canada

**Centre national de recherche en hydrologie**
11, boul. Innovation
Saskatoon (Saskatchewan)
S7N 3H5 Canada

**Centre Saint-Laurent**
105, rue McGill
Montréal (Québec)
H2Y 2E7 Canada

**Place Vincent-Massey**
351 boul. St-Joseph
Gatineau (Québec)
K1A 0H3 Canada