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Assessment and Remediation Of Contaminated Sediments (ARCS) Program

GUIDANCE FOR IN-SITU SUBAQUEOUS CAPPING OF CONTAMINATED SEDIMENTS

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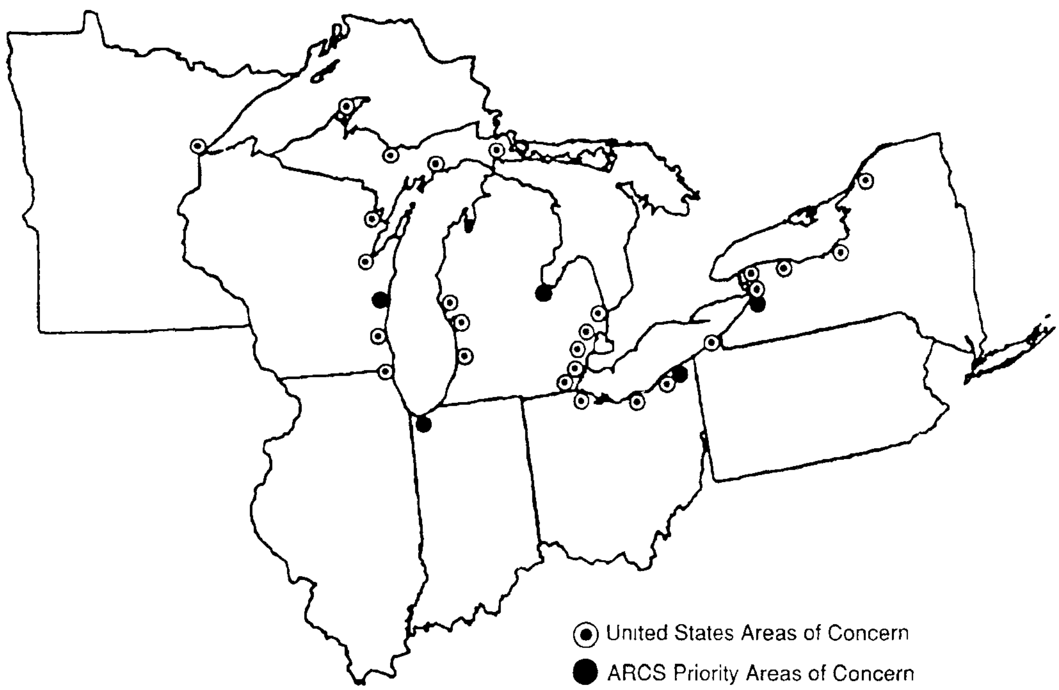

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ASSESSMENT AND REMEDIATION OF CONTAMINATED SEDIMENTS (ARCS) PROGRAM

GUIDANCE FOR IN-SITU SUBAQUEOUS CAPPING OF CONTAMINATED SEDIMENTS

Great Lakes National Program Office
U. S. Environmental Protection Agency
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ACKNOWLEDGMENTS

This document provides technical guidance for subaqueous, in-situ capping as a remediation technique for contaminated sediments. The document was prepared as a part of studies conducted for the U.S. Environmental Protection Agency (USEPA) under the Assessment and Remediation of Contaminated Sediments (ARCS) Program, administered by USEPA's Great Lakes National Program Office (GLNPO), in Chicago, Illinois. This is one of a series of guidance documents developed by the ARCS Engineering/ Technology Work Group (ETWG) to evaluate the feasibility of remediation alternatives and technologies.

This report was written by Dr. Michael R. Palermo, Research Civil Engineer, U.S. Army Engineer Waterways Experiment Station (WES); Dr. Steve Maynord, Research Hydraulic Engineer, WES; Mr. Jan Miller, Environmental Engineer, U.S. Army Engineer Division, Great Lakes and Ohio River; and Dr. Danny D. Reible, Louisiana State University. Contributions of Mr. Tommy Myers, Mr. James Clausner, and Mr. Paul Gilbert, all of WES, and Mr. David Petrovski, USEPA Region 5, are also acknowledged. Appendix B was prepared with the partial support of the US Environmental Protection Agency through the Hazardous Substance Research Center/South and Southwest and through cooperative agreement CR 823029-01-0 from the National Risk Management and Research Laboratory, Cincinnati, Ohio. Appendix C was prepared by Dr. Hoe Peter Ling and Dr. Dov Leshchinsky, both of the University of Delaware, under contract with WES.

The first draft of this document was prepared for EPA technical review in 1995. A second draft was prepared for an in-situ capping seminar held by EPA Region 5 in Chicago in November 1996. This final report addresses comments received from the seminar participants. The report number EPA 905-B96-004 was assigned in 1996, and this number was retained for final publication.

Abstract

In-Situ Capping is defined as the placement of a subaqueous covering or cap of clean isolating material over an in-situ deposit of contaminated sediment. ISC is a potentially economical and effective approach for remediation of contaminated sediment. A number of sites have been remediated by in-situ capping operations worldwide. This document provides technical guidance for subaqueous, in-situ capping as a remediation technique for contaminated sediments. The document was prepared as a part of the studies conducted for the U.S. Environmental Protection Agency (USEPA) under the Assessment and Remediation of Contaminated Sediments (ARCS) Program, administered by USEPA's Great Lakes National Program Office (GLNPO), in Chicago, Illinois.

Caps for in-situ sediment remediation may be constructed of clean sediments, sand, gravel, or may involve a more complex design with geotextiles, liners and multiple layers. In-situ capping can provide several primary functions: physical isolation of the contaminated sediment from the benthic environment; stabilization of contaminated sediments, preventing resuspension and transport to other sites; and, reduction of the flux of dissolved contaminants into the water column. To achieve these results, an in-situ capping project must be treated as an engineered project with carefully considered design, construction, and monitoring. The basic criterion for a successful capping project is simply that the cap required to perform some or all of these functions be successfully designed, placed, and maintained.

This document provides descriptions of the processes involved with in-situ capping, identification of the design requirements of an in-situ capping project, and a recommended sequence for design. Detailed guidance is provided on site and sediment characterization, cap design, equipment and placement techniques, and monitoring and management considerations.

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1 Introduction

This document provides technical guidance for subaqueous, in-situ capping as a remediation technique for contaminated sediments. The document was prepared as a part of the studies conducted for the U.S. Environmental Protection Agency (USEPA) under the Assessment and Remediation of Contaminated Sediments (ARCS) Program, administered by USEPA's Great Lakes National Program Office (GLNPO), in Chicago, Illinois.

Background

Although toxic discharges in the Great Lakes and elsewhere have been reduced in the last 25 years, persistent contaminants in sediments continue to pose a potential risk to human health and the environment. High concentrations of contaminants in bottom sediments and associated adverse effects have been well documented throughout the Great Lakes and associated connecting channels. The extent of sediment contamination and its associated adverse effects have been the subject of considerable concern and study in the Great Lakes community and elsewhere. Contaminated sediments can have direct toxic effects on aquatic life, such as the development of cancerous tumors in fish exposed to polycyclic aromatic hydrocarbons (PAHs) in sediments. The bioaccumulation of toxic contaminants in the food chain can also pose a risk to humans, wildlife, and aquatic organisms. As a result, advisories against consumption of fish are in place in many areas of the Great Lakes. These advisories have also had a negative economic impact on the affected areas.

To address concerns about the deleterious effects of contaminated sediments in the Great Lakes, Annex 14 of the Great Lakes Water Quality Agreement between the United States and Canada stipulates that the cooperating parties will identify the nature and extent of sediment contamination in the Great Lakes, develop methods to assess impacts, and evaluate the technological capability of programs to remedy such contamination.

The 1987 amendments to the Clean Water Act, in § 118(c)(3), authorized GLNPO to coordinate and conduct a 5-year study and demonstration project relating to the appropriate treatment of toxic contaminants in bottom sediments. Five areas were specified in the Act as requiring priority consideration in conducting demonstration projects: Saginaw Bay, Michigan; Sheboygan Harbor, Wisconsin; Grand Calumet River, Indiana; Ashtabula River, Ohio; and Buffalo River, New York. To fulfill the requirements of the Act, GLNPO initiated the ARCS Program. In addition, the Great Lakes Critical Programs Act of 1990 amended the section, now § 118(c)(7), by extending the program by 1 year and specifying completion dates for certain interim activities.

ARCS was an integrated program for the development and testing of assessment techniques and remedial action alternatives for contaminated sediments. Information from ARCS Program activities is being used to guide the development of Remedial Action Plans (RAPs) for all 43 Great Lakes Areas of Concern (AOCs, as identified by the United States and Canadian governments), as well as Lakewide Management Plans (LaMPs).

ARCS Guidance

The decision to remediate contaminated sediments in a waterway and the selection of the appropriate remediation technology(s) are part of a step-wise process using the guidance developed by the three ARCS technical work groups. The guidance developed by the Toxicity/Chemistry Work Group (USEPA 1994a) is used to characterize the chemical and toxicological properties of bottom sediments. The guidance developed by the Engineering/ Technology Work Group (ETWG) is used to evaluate the feasibility of remediation alternatives and technologies (USEPA 1994b). The guidance developed by the Risk Assessment/ Modeling Work Group (USEPA 1993) provides a framework for integrating the information developed in the other two steps and evaluating the ecological and human health risks and benefits of remedial alternatives, including no action.

This document is one of a series developed by the ETWG for evaluation of remediation alternatives and technologies. The ETWG followed a systematic approach to evaluating remediation technologies, beginning with a literature review of available technologies (Averett et al. 1990), followed by laboratory or bench-scale testing of selected technologies (Fleming et al. 1991; USEPA 1994c; Allen 1994), and culminating with field- or pilot-scale demonstrations of at least one technology at each of the five priority AOCs (USACE Buffalo District 1993, 1994; USACE Chicago District 1994; USACE Detroit District 1994). In addition to the technology evaluations, the ETWG developed a series of conceptual plans for full-scale sediment remediation projects (USEPA in prep).

The ARCS Remediation Guidance Document (USEPA 1994b) (RGD) was also developed by the ETWG and describes procedures for evaluating the feasibility of remediation technologies, performing bench- and pilot-scale tests, identifying the components of remedial design, developing cost estimates for full-scale application, and estimating contaminant losses during implementation. Detailed information on specific technologies (Averett et al. 1990) and contaminant loss estimating procedures (Myers et al. 1996) are provided in other reports developed by the ETWG, which should be used as companion documents.

The consideration of in-situ capping as a remedial option should always be preceded by a complete and detailed evaluation of the environmental need for remedial action, assessment of the risks associated with remedial options, and consideration of feasible remedial techniques available. It is not the intention of the authors that in-situ capping be perceived as universally applicable to sediment remediation, or that capping be promoted as the recommended option without careful consideration of the alternatives and consequences, as outlined in the complete set of ARCS guidance documents.

Document Purpose and Scope

The purpose of this document is to provide guidance for planning and design of in-situ capping projects. Descriptions of the processes involved with in-situ capping, identification of the design requirements of an in-situ capping project, and a recommended sequence for design are discussed in this chapter. Detailed guidance is provided on site and sediment characterization (Chapter 2), cap design (Chapter 3), equipment and placement techniques (Chapter 4), and monitoring and management considerations (Chapter 5). The use of this document presumes that a decision to remediate has been made, that remediation objectives have been defined, and that a screening and evaluation of remediation alternatives has indicated that a more detailed evaluation of the in-situ capping alternative is warranted.

In-Situ Capping

Four basic options for remediation of contaminated sediments exist: 1) Containment in-place, 2) Treatment in-place, 3) Removal and containment, and 4) Removal and treatment. In-situ capping is a form of containment in-place.

In-Situ Capping (ISC) refers to placement of a covering or cap over an in-situ deposit of contaminated sediment. The cap may be constructed of clean sediments, sand, gravel, or may involve a more complex design with geotextiles, liners and multiple layers. A variation on ISC could involve the removal of contaminated sediments to some depth, followed by capping the remaining sediments in-place. This is suitable where capping alone is not feasible because of hydraulic or navigation restrictions on the waterway depth. It may also be used where it is desirable to leave the deeper, more contaminated sediments capped in-place (vertical stratification of sediment contaminants is common in many Great Lakes tributaries).

Important distinctions should be made between ISC and dredged material capping which involves removal of sediments, placement at a subaqueous site, followed by placement of a cap. Dredged material capping is a disposal alternative which has been used for sediments dredged from navigation projects, and may also be suitable for disposal of sediments and treatment residues from remediation projects. Two forms of dredged material capping are level bottom capping in which a mound of dredged material is capped, and contained aquatic disposal (CAD) in which dredged material is placed in a depression or other provisions for lateral confinement are made prior to placement of the cap. Examples of in-situ and dredged material capping are illustrated in Figure 1.

Even though the technical aspects of cap design and placement and effectiveness for ISC and dredged material capping are similar, dredged material capping is more likely done for navigation, rather than remediation purposes, and involves the removal and placement of a contaminated sediment prior to capping, while ISC does not involve such removal. Considerations related to the site also differ. For dredged material capping, contaminated sediments are removed from their in-situ location, and site evaluation issues are framed around the selection of an acceptable site for placement and capping. For ISC, the site is a given, and the site evaluation is framed around defining the acceptability of capping for that given site.

A considerable body of literature exists on the subject of subaqueous capping. Much of the work in this area is associated with the handling of contaminated dredged material removed from navigation channels performed by or in cooperation with the U.S. Army Corps of Engineers (USACE). Technical guidelines for dredged material capping have been developed including guidelines for planning capping projects (Truitt 1987a and 1987b and Truitt et al 1989), determining the required capping thickness (Sturgis and Gunnison 1988), overall design requirements (Palermo 1991a), site selection considerations (Palermo 1991b), equipment and placement techniques (Palermo 1991c), and monitoring considerations (Palermo Fredette, and Randall 1992) for capping projects. A comprehensive dredged material capping guidance document is also in preparation (Palermo et al in preparation).

An annotated bibliography prepared for the Canadian Cleanup Fund summarizes most of the capping projects (both in-situ and dredged material) and studies completed through 1992 (Zeman et al., 1992).

The technical guidance on ISC provided in this document is based on experiences with both dredged material and ISC projects. While the focus of this document is ISC of contaminated sediment in riverine and sheltered harbor environments commonly found on the Great Lakes, the guidance provided herein is generally applicable to contaminated sediments in deeper or more open water situations such as estuaries, lake bottoms, or ocean shelf environments.

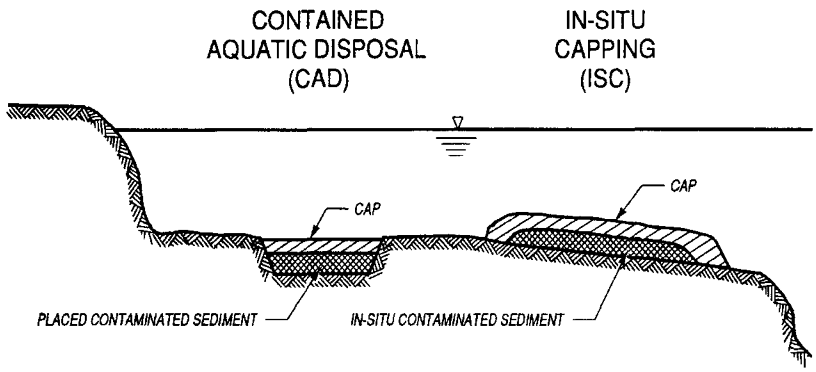


Figure 1. Conceptual Illustration of dredged material capping and in-situ capping options.

In-Situ Capping Functions

Many processes influence the fate of contaminants in bottom sediments. Contaminants can be transported into the overlying water column by advective and diffusive mechanisms. Mixing and reworking of the upper layer of contaminated sediment by benthic organisms continually exposes contaminated sediment to the sediment-water interface where it can be released to the water column (Reible *et al.*, 1993). Bioaccumulation of contaminants by benthic organisms in direct contact with contaminated sediments may result in movement of contaminants into the food chain. Sediment resuspension, caused by natural and man-made erosive forces, can greatly increase the exposure of contaminants to the water column and result in the transportation of large quantities of sediment contaminants downstream (Brannon et. al. 1985).

In-situ capping can remedy some or all of these adverse impacts through three primary functions:

a) physical isolation of the contaminated sediment from the benthic environment,

b) stabilization of contaminated sediments, preventing resuspension and transport to other sites, and

c) reduction of the flux of dissolved contaminants into the water column.

To achieve these results, an in-situ capping project must be treated as an engineered project with carefully considered design, construction, and monitoring. The basic criterion for a successful capping project is simply that the cap required to perform some or all of these functions be successfully designed, placed, and maintained.

Synopsis of Field Experience

A limited number of ISC operations have been performed under varying site conditions, and are summarized in Table 1. ISC has been applied to riverine, nearshore, and estuarine settings. Conventional dredging and construction equipment and techniques have been used for ISC projects, but these practices were precisely controlled. The success of projects to date and available monitoring data at several sites indicates that ISC can be an effective technique for long-term containment of contaminants.

In-situ capping of nutrient-laden sediments with sand has been demonstrated at a number of sites in Japan, including embayments and interior lakes (Zeman et al, 1992). The primary objective of the capping was to reduce the release of nutrients (nitrogen and phosphorous) and oxygen depletion by bottom sediments, which were contributing to degraded water quality conditions. Studies have included measurements of nutrients in interstitial and overlying water at capped sites, development of a numerical model for predicting water quality improvements from capping, and monitoring benthos recovery at capped sites. A number of Japanese studies examining cap placement equipment are discussed in Chapter 4.

Table 1. Summary of Selected In-Situ Capping Projects

Project Location	Contaminants	Site Conditions	Cap Design	Construction Methods	Reference
Kihama Inner Lake, Japan	Nutrients	3,700 m^2	Fine sand, 5 and 20cm		
Akanoi Bay, Japan	Nutrients	20,000 m^2	Fine sand, 20 cm		
Denny Way, Washington	PAHs, PCBs	3 acres nearshore with depths from 20 to 60 ft.	Avg 2.6 of sandy sediment	Barge spreading	Sumeri et al 1995
Simpson-Tacoma, Washington	cresote, PAHs, dioxins	17 acres nearshore with varying depth	4 to 20 feet of sandy sediment	hydraulic pipeline with "sandbox"	Sumeri et al 1995
Eagle Harbor, Washington	cresote	54 acres within empayment	3 ft of sandy sediment	barge spreading and hydraulic jet	Sumeri at al 1995
Sheboygan River, Wisconsin	PCBs	several small areas of shallow river/floodplain	sand layer with armor stone	direct mechanical placement	Eleder
Manistique River, Michigan	PCBs	20,000 ft^2 shoal in river with depths of 10-15 ft	40 mil plastic liner	placement by crane from barge	Hahnenberg, pers com
Hamilton Harbor, Ontario	PAHs, metals, nutrients	10,000 m^2 portion of large, industrial harbor	0.5 m sand	Tremie Tube	Zeman & Patterson 1996a
Eitrheim Bay, Norway	metals	100,000 M^2	geotextile and gabions	deployed from barge	Instanes 1994
St. Lawrence River, Massena, New York	PCBs	75,000 ft^2	6 in sand/6 in gravel/ 6 in stone	placed by bucket from barge	Kenna, pers com

A variety of ISC projects have been conducted in the Puget Sound area. At the Denny Way project, a layer of sandy capping sediment was spread over a three-acre contaminated nearshore area with water depths of 20 to 60 feet. A combination of a sewer outfall discharge and combined sewer overflow (CSO) had contaminated the site with lead, mercury, zinc, PAHs and PCBs. The capping was a cooperative effort between the Municipality of Metropolitan Seattle (METRO) and the Seattle District, USACE (Sumeri 1989, 1995). At the Simpson-Tacoma Kraft paper mill, ISC was conducted as part of a Superfund project. Discharges of paper and pulp mill waste had contaminated the site with PAHs, naphthalene, phenol, dioxins, and other contaminants. A 17 acre area was capped with material from a sand bar in the adjacent Puyallup River. An in-situ capping project at the Eagle Harbor Superfund site at Brainbridge Island placed a 3 to 6 foot layer of sand over creosote contaminated sediments in water depths of 40-60 feet. Sediments dredged from the Snohomish River navigation project were transported to Eagle Harbor and placed over a capped area of about 54 acres (Sumeri 1995). Other ISC projects in the Puget Sound area include those at the West Waterway and Piers 51, 53, and 54.

ISC, with an armoring layer, has also been demonstrated at a Superfund site in Sheboygan Falls, Wisconsin. This project involved placement of a composite cap, with layers of gravel and geotextile to cover several small areas of PCB-contaminated sediments in a shallow (<5 feet) river and floodway. A total area of about one acre of cap was placed with land-based construction equipment and manual labor (Eleder, 1992).

At Eitrheim Bay in Norway, a composite cap of geotextile and gabions was constructed as a remediation project in a fjord at an area contaminated with heavy metals (Instanes 1994). A total area of 100,000 square meters was capped, in water depths of up to 10 meters.

At Manistique, Michigan, an interim cap of 40-mil thick plastic liner was placed over a small (0.5 acre) deposit of PCB-contaminated sediments in order to prevent the resuspension and transport of sediments until a final remediation was implemented.

At Hamilton Harbor, in Burlington, Ontario, a 0.5 m thick sand cap was placed over a 10,000 m^2 area of PAH-contaminated sediments as a technology demonstration conducted by Environment Canada (Zeman and Patterson 1996a and 1996b).

PCB-contaminated sediments at the General Motors Superfund site in Massena, New York were removed from the St. Lawrence River by dredging. The remedial objective for the site was 1 ppm, but areas remaining at concentrations greater than 10 ppm after repeated dredging attempts were capped. An area of approximately 75,000 square feet was capped with a three-layer ISC composed of 6 inches of sand, 6 inches of gravel and 6 inches of armor stone (Kenna, pers com, 1995).

Some field studies have been conducted on long term effectiveness of caps. Sequences of cores have been taken at capped dredged material sites in which contaminant concentrations were measured over time periods of up to 15 years (Fredette et al. 1992, Brannon and Poindexter-Rollings 1990, Sumeri et al. 1994). Core samples taken from capped sites in Long Island Sound, the New York Bight, and Puget Sound exhibit sharp concentration shifts at the cap/contaminated layer interface. For the Puget Sound sites, these results showed no change in vertical contaminant distribution in five years of monitoring with 18 mo and 5 yr vibracore samples taken in close proximity to each other. In the New York Bight and Long Island Sound sites, respectively, cores were taken from capped disposal mounds created approximately 3 and 11 years prior to sampling. Visual observations of the transition from cap to contaminated sediment closely correlated with the sharp changes in the sediment chemistry profiles. The lack of diminishing concentration gradients away from the contaminated sediments strongly suggests that there has been minimal long-term transport of contaminants up into the caps. Additional sampling for longer time intervals is planned.

Design Sequence for In-Situ Capping

A recommended sequence of steps involved with the design of an in-situ capping project is illustrated in the flowchart in Figure 2. The sequence involves the following general steps:

1. Set a cleanup objective, i.e. a contaminant concentration or other benchmark. The cleanup objective will be developed as a prerequisite to the evaluation of all remediation alternatives. [Refer to the logical framework in the ARCS Remediation Guidance Document, (USEPA 1994b)].

2. Characterize the contaminated sediment site under consideration for remediation. This includes gathering data on waterway features (water depths, bathymetry, currents, wave energies, etc), waterway uses (navigation, recreation, water supply, wastewater discharge, etc), and information on geotechnical conditions (stratification of underlying sediment layers, depth to bedrock, physical properties of foundation layers, potential for groundwater flow, etc). Determine if advective processes are present and the ability of the cap to control advective contaminant losses. Determine any institutional constraints associated with placement of a cap at the site.

3. Characterize the contaminated sediments under consideration. This includes the physical, chemical, and biological characteristics of the sediments. These characteristics should be determined both horizontally and vertically. The results of the characterization, in concert with the cleanup objective, will determine the areal extent or boundaries of the area to be capped.

4. Make a preliminary determination on the feasibility of ISC based on information obtained about the site and sediments. If site conditions or institutional constraints indicate that ISC is not feasible, other remediation options must be considered.

5. Identify potential sources of capping materials, including clean sediments that might be dredged and upland sites or commercial sources for soil, gravel and stone.

6. Design the cap composition and thickness. Caps will normally be composed of clean sediments, however, other materials such as armor stone or geotextiles may be considered. The cap design must consider the need for effective short and long-term chemical isolation of contaminants, bioturbation, consolidation, erosion, and other pertinent processes. If the potential for erosion of the cap is significant, the cap thickness can be increased, provisions can be made for placement of additional cap material following erosion, other capping materials could be considered, or an armor layer could be incorporated into the design.

7. Select appropriate equipment and placement techniques for the capping materials. The potential for short term contaminant losses associated with cap placement should be considered in selecting a placement approach.

8. Evaluate if the capping design meets the cleanup objectives. If not, either reevaluate cap design or consider other alternatives.

9. Develop an appropriate monitoring and management program to include construction monitoring during cap placement and long-term monitoring following cap placement. The site management program should include actions to be taken based on the results of monitoring and provisions for future maintenance.

10. Develop cost estimates for the project to include construction, monitoring and maintenance costs. If costs are acceptable, implement. If costs are unacceptable reevaluate design or consider other alternatives.

More detailed descriptions of the design aspects related to each step are given in the remaining chapters of this report.

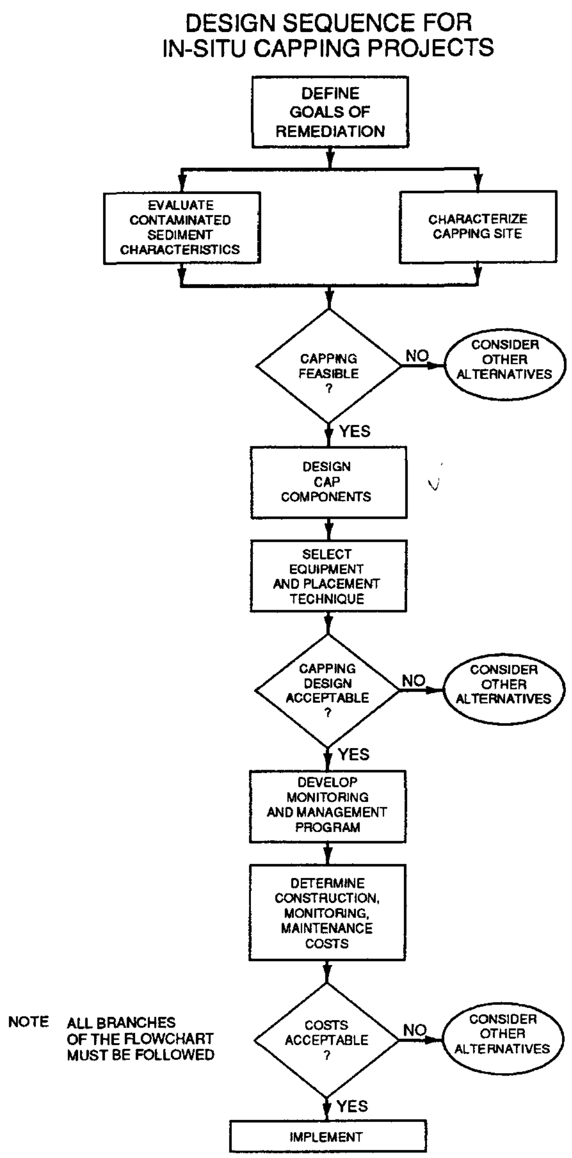


Figure 2. Flowchart showing sequence of steps involved with the design of an in-situ capping project.

2 Site Evaluation

This chapter briefly discusses the types of considerations needed to determine if in-situ capping will meet the objectives and scope of a sediment remediation project. The chapter also describes considerations in characterizing the in-situ contaminated sediments and the site conditions from the standpoint of determining in-situ capping feasibility. The types of data which should be collected and where they enter into an in-situ capping design are also discussed.

Remediation Objectives

Other documents developed by the ARCS Program provide information and guidance regarding techniques for the assessment of contaminated sediments to determine their impacts on the aquatic ecosystem and approaches for determining if some form of remedial action is warranted (USEPA 1994a, 1994c). This document assumes that a decision to remediate some contaminated sediments has been made. Although detailed discussion of the methods to reach a decision to remediate (USEPA 1994a, 1994c) are not included in this document, the ability of ISC to meet the objectives of a sediment remediation project will be discussed.

The objectives of contaminated sediment remediation may be quite site-specific. ISC is compatible with some remedial objectives and not others. For example, ISC would not meet an objective to destroy or remove some particular sediment contaminant from the aquatic environment. On the other hand, ISC might be able to reduce exposure of aquatic organisms to sediment contaminants thereby reducing contaminant uptake.

In-situ capping can be evaluated in two ways. The first is to determine if ISC will functionally satisfy specific remedial objectives. Where remedial objectives are vague or poorly quantified, a comparison can be made of ISC with other remedial alternatives.

Functional Analysis

In order to determine if ISC will achieve the remedial objectives at a site, one needs to consider the three primary functions of a cap discussed in Chapter 1. In some cases, the remedial objectives may be satisfied by a single ISC function. In other cases, two or all functions may be needed to satisfy the remedial objectives.

If the remedial objectives are defined in terms of a reduction in risk associated with exposure of the contaminants to benthic organisms, potential bioaccumulation, and potential movement of contaminants up the food chain, the physical isolation of the contaminated sediment from aquatic organisms may be the basic function and design requirement for the in-situ cap. The physical isolation effects of the cap may be localized at the capped site, or may be more widespread as a result of the stabilization function (as discussed below).

The ability of an ISC to isolate aquatic organisms from sediment contaminants is, in part, dependant upon the character of any "new" sediments, i.e. those that could potentially be transported from other contaminated areas and be deposited on the cap. If external sources of contamination have not been sufficiently controlled, an in-situ cap may simply be a barrier between two layers of contaminated sediments. Therefore, where physical isolation of sediment contaminants is required to meet remedial objectives, ISC should only be considered if source control has been implemented.

Stabilization of sediments in-place may be a basic design function where the remedial objective is to prevent impacts caused by the resuspension, transport and redeposition of contaminated sediments at remote areas. For example, a waterway where conditions are expected to remain degraded may be considered for capping in order to keep sediments from contaminating higher quality areas downstream. In such a case, a cap, designed solely to keep contaminated sediments in-place might meet the short-term objectives of a remediation plan. An example is the temporary cap used to stabilize contaminated sediments at Manistique River, Michigan until a permanent remedial action could be implemented.

If a remedial objective is tied to the quality of the overlying water column, the design function for the cap may be chemical isolation from the sediments. Such was the case for several of the capping applications in Japan, where the primary objective was to reduce the loadings of nutrients from sediments to the water column in order to improve the eutrophic conditions. The control of the flux of dissolved contaminants should consider diffusive and advective transport processes.

Comparative Analysis

Remediation objectives are often framed in generalities that make it difficult to eliminate remedial technologies from further consideration. Where more than one technology is feasible and capable of meeting remedial objectives, a comparative approach is needed. Because it is one of the least costly sediment remediation alternatives, in-situ capping is likely to be evaluated fully. In performing comparative analyses of ISC and other sediment remediation alternatives there are a number of issues, both technical and policy, to be addressed.

In-situ capping has some fundamental differences from other sediment remediation alternatives that may complicate a comparative analysis. Alternatives that remove contaminated sediments from the waterway generally release some contaminants to the waterway during removal (dredging) with short and, in some alternatives, long-term releases at a site (CDF or treatment site) away from the water. ISC has both short- and long-term releases to the waterway. Losses occurring at a terrestrial site may not be directly comparable to losses to the waterway especially since the rationale for sediment remediation was based on aquatic impacts.

The duration or timeframe for such comparative analysis of impacts or contaminant loss is an issue that can greatly alter the results. Most alternatives involving removal will have the majority of losses occurring during removal and placement in a disposal facility or treatment. ISC is expected to have some minor releases during construction. Following construction, any releases will largely depend on the nature of any advective processes. There may be a higher initial rate of release due to compression of pore water during and for some time following cap installation. If a groundwater flow condition exists at the site, there will be a continuous release due to advection. If no advection is present, there will be a very slow, but continuous diffusive release occurring after a lag time. Remedial actions under Superfund are typically evaluated for timeframes of 30 years. The differences between ISC and more "conventional" remedial alternatives have raised questions about the adequacy of such a limited temporal analysis. A comparative analysis performed for proposed remedial alternatives at Manistique Harbor, Michigan considered timeframes of hundreds of years, based on calculations of flux and assuming sorption of PCBs onto the capping materials (Blasland Bouck and Lee Inc. 1994, 1995).

Finally, when comparing ISC with other remedial alternatives, there is an element of cap design that should be considered. The part of ISC design that addresses the susceptibility of the cap to erosion must consider forces that are highly dynamic (i.e. river flows, propeller wash, wave heights, etc.). ISC design analyses contain probabilistic factors that are not commonly present in the design of treatment or confined disposal alternatives. The ability to predict these forces, and the acceptability of risk associated with failure are concerns that are especially relevant for in-situ capping.

Uncertainties will be encountered in evaluating the expected performance of any remedial alternative. Direct comparison of alternatives to meet remedial objectives and the relative performances of alternatives will be complicated by these uncertainties. Typically best professional judgement and sensitivity analyses of the effects of input variables on predictive models is the best approach to weighing the benefits of remedial alternatives.

Remediation Scope

The scope of a remediation project defines the physical extent of the remediation in terms of both space and time. Scope may be defined in terms of site or funding constraints, through a negotiated or adjudicated settlement, or by a detailed risk assessment or modeling effort. While the scope of a removal-based remedial action is typically expressed as a volume (e.g., 50,000 cubic yards of sediment to be removed and treated or disposed), the scope of an ISC alternative is more appropriately considered in spatial or areal terms (e.g.,14 acres of bottom surface area to be capped). The volume of sediments under the cap may not effect the decisionmaking, although the total mass of contaminants remaining may be a consideration. The thickness and vertical distribution of contaminated sediments will enter into decisions regarding cap design or selection of capping materials.

It should be recognized that there may be other differences between the scope of a removal-based alternative and an ISC alternative. For instance, a set of remedial objectives that would require sediments to be dredged from an area or reach of a waterway may require capping over an entirely different "footprint".

Site Conditions

Site conditions, more than any other consideration, will dictate the feasibility of in-situ capping. Site characteristics affect all aspects of a capping project, including design, construction equipment, monitoring and management programs. Only some limitations in site conditions can be accommodated in the ISC design. A thorough examination of site conditions should generally determine if further consideration of ISC is appropriate. Site conditions that must be considered include the physical environment, hydrodynamic conditions, sediment characteristics, and existing or potential uses of the waterway.

Because in-situ caps are intended to function for extended periods of time, if not in perpetuity, it is not sufficient to just examine the existing conditions of the site. The evaluator must also consider future conditions that might significantly alter cap integrity or function. Examples might include the removal of a dam or controlling structure on a river, decay or removal of breakwaters or other protective structures, changes in the type or draft of vessels navigating the waterway, or long-term trends in land or groundwater use. The permanence or stability of site conditions for the long-term future should be factored into the evaluation of site conditions.

Physical Environment

The physical environment of a proposed ISC site to be considered includes waterway dimensions, water depths (bathymetry), tidal patterns, ice formation, aquatic vegetation, bridge crossings and proximity of lands or marine structures (i.e., docks, piers, breakwaters). The bathymetry of the site has an influence on the degree of spread during placement and stability of capping material. The flatter the bottom slope the more desirable, especially if capping material is to be placed hydraulically. It is difficult to estimate the effects of slope alone, since bottom roughness plays an equally important role in the mechanics of the spreading process.

Water depths and tidal patterns may limit cap construction options, and cause effects on cap design and waterway uses discussed later. The potential for ice jams and scour at riverine sites in northern climates should be considered. The proximity of the ISC site to land areas or marine structures may impact construction options and present legal issues concerning riparian owners.

Some types of physical information are available from nautical charts and the "U.S. Coast Pilot" (published by the National Ocean Service) and topographic maps (developed by the U.S. Geological Survey). More detailed bathymetric surveys are maintained by the USACE for authorized federal navigation channels. Local governments (i.e., port authorities, planning commissions, sewer and drainage districts) may also have detailed maps of waterways.

Hydrodynamic Conditions

Capping should be used in environments where the long term physical integrity of the cap can be maintained. Low energy environments in protected harbors, low flow streams, or estuarine systems are more appropriate for in-situ capping projects than waterways with high flows since the long-term integrity of the cap will be of less concern and less extensive armoring (or none) will be required. In open water, deeper sites will be less influenced by wind or wave generated currents and are generally less prone to erosion than shallow, nearshore environments. However, armoring techniques or selection of erosion resistant capping materials may make capping technically feasible in some higher energy environments as well, recognizing that risks increase.

Water column currents affect the degree of dispersion during cap placement and may influence the selection of equipment for cap placement. Of more importance are bottom currents which could potentially cause resuspension and erosion of the cap. In addition to ambient currents due to normal channel flows, tidal fluctuations, etc., the effects of storm-induced waves or other episodic events such as flood flows on bottom current velocities must also be considered.

Capping operations should not be conducted during storms, flood flows, or other extreme events, so the designer doesn't need to consider such events in selection of equipment or placement technique for the cap. However, ambient currents, waves and water levels may limit construction techniques and hamper monitoring or maintenance activities.

The presence of an in-situ cap can alter existing hydrodynamic conditions. In harbor areas, or estuaries, the decrease in depth or change in bottom geometry may affect current patterns. In a riverine environment, the placement of a cap, by reducing depths and restricting flows may significantly alter the flow carrying capacity of the channel. Changes in channel geometry may also affect flow velocities, increasing shear stresses on a cap or to opposite or downstream streambanks. Historic flow data may therefore not be adequate to characterize velocities at the capping site. Modeling studies may be required to assess such changes in site conditions due to placement of an in-situ cap.

The types of information needed to evaluate hydrodynamic conditions at a proposed ISC site include currents, waves and flood flows. These phenomena are not static, but will vary with meteorologic conditions. Information on recorded ranges (i.e., max and min water levels or river flows) may be available from: National Ocean Service navigation/mariners guides; USACE records of Great Lakes water levels; U.S. Geological Survey publications of water level/flow monitoring stations, and; flood insurance studies. Some states also collect river flow data. Additional sources of information include studies conducted by the USACE or local governments in relation to flood protection and shoreline or streambank erosion.

Where published information is not available, or where projections of maximum levels are needed, standard predictive methods and models may be used (Hydrologic Engineering Center 1995; Coastal Engineering Research Center 1984). The consideration of hydrodynamic conditions in the assessment of cap thickness or need for armoring are described in Chapter 3, Cap Design.

Geotechnical/ Geological Conditions

The geotechnical conditions at the site must be assessed to include stratification of underlying sediment layers, depth to bedrock and physical properties of foundation layers. This information will be needed to evaluate the potential for consolidation of the underlying sediment layers after cap placement. This evaluation is needed to properly interpret information on layer thickness during placement and any observed movement of the bottom surface following cap placement.

Hydrogeological Conditions

The environmental importance of ground water/surface water interactions is well documented (USEPA, 1991). The significance of the ground water/surface interactions are determined by the hydrogeologic characteristics of the site. A detailed evaluation and understanding of the site's hydrogeology is a critical component in evaluating the acceptability of a capping proposal at a proposed capping site and a prerequisite to proper cap design.

Groundwater flows from locations associated with high hydraulic head to locations of low hydraulic head, moving from recharge areas along the path of flow to discharge areas. Discharge areas can be defined as locations where the groundwater flow path has an upward component (Freeze and Cherry 1979). The near shore portions of lakes and streams in the midwestern portions of the United States commonly function as ground water discharge areas. These are areas where ground water exits the ground water regime and enters the surface water regime. Sediments reside at the interface of the ground water and surface water regimes.

From a hydrogeologic perspective, most cap designs can be viewed as a thin granular layer at the sediment-water interface. Such a cap would not differ in most ways from the sediment which accumulates naturally at the bottom of the body of surface water under consideration. Consequently, capping contaminated sediments with porous granular materials should not significantly alter the groundwater flow characteristics of the site in most hydrogeologic settings.

In the presence of contaminated sediments, upward hydraulic gradients would sequentially drive ground water from the underlying geologic materials through the layer of contaminated sediments and the overlying porous cap into the surface water. Depending on the properties and thickness of the capping materials, a fraction of the contaminants will be transported to the overlying surface water. A knowledge of the groundwater flow is therefore needed to evaluate the significance of this contaminant flux.

The development of instruments for the measurement of ground water surface water interactions dates from the mid 1940's (USGS, 1980). Presently, methodologies for the measurement of the quantity and quality of ground water being discharged to surface water are also well documented (USEPA, 1991; USGS, 1980) and have been applied in the field (USGS, 1993; USGS 1994; Lee and Cherry, 1978; Taniguchi and Fukuo, 1993). Piezometers have been used to quantify the magnitude of the upward hydraulic gradient and the hydraulic conductivity (Lee and Cherry, 1978; USGS, 1993). Seepage meters can provide a direct measure of the quantity of ground water being discharged to surface water and have been used to determine the volume of flow per unit area per unit time at the sediment/water interface (termed the specific discharge or flux) (USGS, 1993). If properly used, seepage meters can also be used to determine the quality of the water being discharged to surface water. This is done through the use of seepage meters as water sample collection devices. The samples are later analyzed for the water quality parameters of concern (USGS, 1994).

Sediment Characterization

The physical characteristics of the contaminated sediment are of importance in developing the cap design, selecting appropriate equipment for cap placement, modeling and monitoring cap performance. Physical tests and evaluations on sediment should include: visual classification, natural (in-situ) water content/solids concentration, plasticity indices (Atterberg limits), organic content (specifically total organic carbon (TOC), grain size distribution, specific gravity, and Unified Soil Classification System (USCS) classification. Standard geotechnical laboratory test procedures, such as those of the American Society for Testing and Materials (ASTM) or the USACE, should be used for each test. Table 2-1 gives the standard ASTM and USACE designations for the needed tests, and also cross-references these procedures to those of several other organizations that have standardized test methods.

The thickness of the contaminated sediment layer and the physical properties of the soil underlying this layer need to be determined in order to evaluate the consolidation of the cap. The thickness of contaminated sediment layers can be obtained by probings, remote sensing techniques, or core sampling. The same type of physical data are needed for the underlying material as obtained for the contaminated sediments. If the contaminated sediment or underlying sediment layers are compressible, consolidation will occur due to cap placement. The degree of potential consolidation should be evaluated based on standard consolidation testing procedures (USACE 1970), modified to account for the high water content of sediment samples (USACE 1987).

Shear strength of the contaminated sediment layer should be considered for evaluation of the stability of the cap during placement. However, data and design guidance on bearing capacity and slope stability considerations for subaqueous caps are presently limited (see Chapter 3).

Physical analysis of site water may also be required, e.g. suspended solids concentration and salinity. These data must be developed using standard techniques.

The in-situ sediment will typically be characterized for chemical concentrations of contaminants of interest in terms of both areal extent and vertical distribution. Chemical characterization data is needed for modeling contaminant migration as well as for interpretation of monitoring data during and following capping.

Table 2-1. Standard Geotechnical Laboratory Test Procedures

Test	Designation				
	ASTM[1]	AASHTO[2]	USACE[3]	DOD[4,5]	Comments
Soils					
Water Content	D 2216	T265	I	Method 105, 2-VII	
Grain Size	D 422	T88	V	2-III, 2-V, 2-VI	
Atterberg limits	D 4318	T89 T90	III	Method 103, 2-VIII	
Classification	D 2487		III		
Specific gravity	D 854	T100	IV	2-IV	
Organic content	D 2974				Use Method C
Consolidation*	D 2435	T216	VIII		
Permeability**	D 2434	T215	VII		
Shear Tests	D 2573				Field Test

[1] American Society for Testing and Materials
[2] American Society of State Highway and Transportation Officials
[3] Dept. of the Army Laboratory Soils Manual EM 1110-2-1906 (USACE 1970)
[4] Dept. of Defense Military Standard MIL-STD-621A (Method 100, etc.)
[5] Dept. of the Army Materials Testing Field Manual FM (50530 (2-III, etc.)

*Do not use the standard laboratory test for determining consolidation. Instead, use the modified standard consolidation test and the self-weight consolidation test as described in USACE 1987.

**One value of permeability must be calculated from the self-weight consolidation test.

Waterway Uses

The technical and socioeconomic feasibility of ISC at a particular site is, in part, dependant on how the capping would impact or be impacted by existing or planned uses of the waterway. Waterway uses that may conflict with a proposed in-situ cap include:

- navigation (commercial and recreational);
- flood control
- recreation (swimming, fishing, etc.);
- water supply and withdrawal (presence of intakes, etc.);
- stormwater or effluent discharge;
- sensitive or important aquatic habitats
- waterfront development; and,
- utility crossings.

The construction of an ISC may limit or eliminate some of the above waterway uses. Potential sources of information on waterway uses include: local waterfront development plans; wastewater discharge permits; remedial action plans; harbor authority masterplans; and, municipal street/sewer improvement plans.

If the site under consideration is adjacent to or within a navigation or flood control channel, the effects of cap placement on those functions of the channel must be evaluated. Placement of a cap decreases the water depth and cross-sectional area, reducing the flow carrying capacity of a channel and the navigable depth. By reducing water depths in a harbor or river channel, commercial and recreational vessels may have to be restricted or banned entirely depending on their draft. The acceptable draft of vessels allowed to navigate over a capped area must consider water level fluctuations (seasonal, tidal and wave) and the potential effects of groundings on the cap. Because of the potential erosion caused by propeller wash, restrictions may also be needed on vessels based on engine size. Anchoring must not be allowed at locations on or near the ISC site. Fishing and swimming may have to be restricted to avoid vessels from dragging anchors across the cap.

If the area being considered for ISC is within a Federally authorized channel, the process involved with the modification of that authorization or de-authorization should be considered. The effects of de-authorization or a change in authorization on the project purposes and on uses of the channel, the value of those uses, and any secondary impact should be considered fully.

The presence of an in-situ cap may limit future uses of the waterway. For instance, the locations of water supply intakes, stormwater or effluent discharge outfalls, utility crossings, and the construction of bulkheads, piers, docks and other waterfront structures would have to be evaluated with consideration of their potential impacts on cap integrity and maintenance.

Utility crossings (water, sewer, gas, oil, telephone, cable, and electrical) are commonly located in urban waterways. Existing utility crossings under portions of waterways to be capped may have to be relocated if their deterioration or failure might impact cap integrity or because they could not be repaired without disturbing the cap. Future utility crossing my be prohibited in the cap area with resulting social/economic considerations.

The ability to enforce use restrictions necessary to protect the integrity of an in-situ cap (e.g., vessel size limits, bans on anchoring, etc.) is an area with little or no operating experience. Voluntary restrictions on uses of public lands and waters are often ineffective. Compliance, enforcement, and the effectiveness of these measures as well as the consequences of non-compliance on ISC should be considered.

Regulatory and Legal Considerations

Any sediment remediation alternative must address, and comply with a number of legal and regulatory requirements. The ability of ISC to comply with some environmental laws and regulations has been questioned, and full-scale applications of this technology are so limited that some legal issues have not yet been resolved. Because of the potential effect of compliance on the feasibility of this remedial alternative, legal and regulatory considerations should be closely examined at the earliest possible time. An overview of legal and regulatory considerations for sediment remediation is provided in the "ARCS Remediation Guidance Document" (USEPA 1994b). This section will not detail all of the regulatory requirements for ISC, but will discuss those that are unique or especially significant for the construction of an in-situ cap.

Construction in Waterways

Any structures or work that impact the course, capacity, or condition of a navigable water of the United States must be permitted under Section 10 of the Rivers & Harbors Act of 1899 (33 CFR 403). The permit program for Section 10 permits is managed by the USACE. Federal regulations on the USACE permit program are contained in 33 CFR Parts 320-330 (Regulatory Programs of the Corps of Engineers).

For an ISC project, Section 10 permitting will require consideration of the cap as an obstruction to navigation. The Coast Guard and local and regional navigation users are contacted. In addition, the potential for the cap to obstruct flows, cause flooding or erosion are considered. If the ISC is within an authorized Federal navigation project, Congressional action is needed to deauthorize the project or modify the authority.

Discharge of Dredged or Fill Materials

The disposal of dredged or fill materials to waters of the United States is regulated under sections of the Clean Water Act of 1972 (PL 92-500), as amended. Section 404 designates the USACE as the lead Federal agency in the regulation of dredge and fill discharges, using guidelines developed by the USEPA in conjunction with the USACE. Federal regulations on the Corps permit program are contained in 33 CFR Parts 320-330 (Regulatory Programs of the Corps of Engineers).

Cap material is a dredged or fill material (depending on its origin), and its placement in "waters of the U.S.", which includes wetlands, requires a permit under Section 404 and a certification of water quality compliance from the state under Section 401. Permits are not required for superfund projects, but the technical evaluations required for a permit must be made. Capping material that is dredged may require testing to determine it is not contaminated. The "Inland Testing Manual" (USEPA/USACE in preparation) and "Great Lakes Dredged Material Testing & Evaluation Manual" (USEPA/NCD 1994).

RCRA and TSCA

The ability of ISC to comply with the requirements of the Resource Conservation and Recovery Act (RCRA) or the Toxic Substances Control Act (TSCA) has not been fully established. In-situ capping of sediments with PCB contamination subject to regulation (> 50 ppm) was approved by the USEPA at the Superfund project in Manistique Harbor, Michigan. In this case, it was reasoned that since the sediments were not removed, TSCA was not invoked.

Preliminary Feasibility Determination

Following the assessment of remediation objectives, scope, sediment characteristics, and site conditions, a preliminary determination of the overall feasibility of ISC at the site under consideration should be made (as shown on figure 2). Since there are no specific criteria for site suitability for ISC, such a determination must be largely qualitative in nature.

The ability of ISC to meet remedial objectives may be determined at this stage, or may require contaminant migration modeling, as discussed in Chapter 3. It may be easier to determine that ISC will not meet to specific objectives than concluding that it will.

The incompatibility of ISC with existing or planned waterway uses may be a direct indication of infeasibility, especially where the use is of high value to the local community or represents a significant economic benefit. Any consideration of limiting or eliminating waterway uses represents a potentially controversial matter. All levels of government (Federal, state and local) share the responsibility for the management of most waterways, and the interests of all users must be considered.

Where there are incompatibilities between ISC and waterway uses, alternatives to an infeasibility determination include a modified project design. For example, where an in-situ cap would create water depths too shallow for essential navigation traffic, an alternative might be to dredge just enough of the contaminated sediments to allow the cap to be constructed without limiting navigation. Where a project modification can't be developed to alleviate incompatibilities, users might be mitigated for lost use or revenue. At the Waukegan Harbor Superfund project, a marina operation was relocated so that a slip with contaminated sediments could be remediated in-place.

3 In-Situ Cap Design

General Considerations

The composition and dimensions (thickness) of the components of a cap can be referred to as the cap design. This design must perform one or more of the three functions discussed in Chapter 1 (physical isolation, stabilize sediment, and reduce flux of dissolved contaminants). The design must also be compatible with available construction and placement techniques.

Dredged material caps are typically constructed with a single layer of "clean" sediments because: relatively large volumes are usually involved; "clean" sediments from other dredging projects are often available as cap materials; and, a disposal/capping site with low potential for erosion can ususally be selected. Guidance on dredged material cap design (Palermo et al in preparation) focuses on the thickness of the cap as the major design criterion.

In contrast, in-situ capping projects usually involve smaller volumes or areas, clean sediments are not always readily available as capping material, and site conditions are a given. For these reasons, caps composed of multiple layers of granular materials as well as other materials such as armor stone or geotextiles are often considered, and the in-situ cap design cannot always be developed in terms of cap material thickness alone.

This chapter describes the considerations and procedures used to determine the necessary cap components for the three basic functions discussed in Chapter 1. At present, the design of in-situ caps is based on a combination of laboratory tests and models of the various processes involved: (advective/diffusive contaminant flux, bioturbation, consolidation, and erosion), field experience, and monitoring data. Since the number of carefully designed, constructed, and monitored capping projects is limited, the design approach is presently based on the conservative premise that the cap components are additive. No dual function performed by cap components is considered. As more data become available on the interaction of the processes affecting cap effectiveness, this additive design approach can be refined.

The general steps for in-situ cap design include:

a. Identify candidate capping materials and compatibility with contaminated sediment at the site.

b. Assess the bioturbation potential of indigenous benthos and design a cap component to physically isolate sediment contaminants from the benthic environment.

c. Evaluate potential erosion at the capping site due to currents, waves, propeller wash, and design a cap component to stabilize the contaminated sediments and other cap components.

d. Evaluate the potential flux of sediment contaminants and design a cap component to reduce the flux of dissolved contaminants into the water column.

e. Evaluate potential interactions and compatibility among cap components, including consolidation of compressible materials.

f. Evaluate operational considerations and determine restrictions or additional protective measures (e.g., institutional controls) needed to assure cap integrity.

A flowchart illustrating these steps is shown in Figure 3. More detailed discussion of these design steps are discussed in the following paragraphs. If the objective of the cap does not require all three basic functions (e.g., a temporary cap whose sole function is to stabilize the sediments), a simpler design sequence could be followed.

Identification of Capping Materials

In the beginning of an ISC cap design, all potential cap material sources should be identified. Sources of cap materials should be identified at the beginning of the design process because these materials will generally represent the largest single item in the overall project cost, and the utilization of locally available sediments, soils or other granular capping materials can have a significant impact on ISC feasibility and implementation. The selection among cap materials (or use of more than one) will be determined by subsequent analysis.

Most in-situ capping projects conducted to date have used sediment or soil materials, either dredged from nearby waterways or obtained from upland sources, including commercial quarries. At some locations, a simple layer of granular material can effectively perform all three cap functions. In other cases, more complex cap designs may be required. Capping materials such as geotextiles and plastic liners may be able to perform one or more of the basic cap functions. These materials may also be used in conjunction with granular materials for constructability or stabilization purposes. Examples of multi-layer cap designs are illustrated in Figure 4.

Granular Materials

In most cases, granular materials such as quarry sand, natural sediments or soil materials should be considered as a necessary part of the cap design to physically isolate the sediments from the benthos and water column, prevent sediment resuspension and transport, and reduce the flux of dissolved contaminants.

Previous studies have shown that both fine-grained materials and sandy materials can be effective capping materials (Brannon et al 1985). Fine grained materials (clays) have been used in Europe in connection with control of eutrophication (Klapper 1991, 1992). Suszkowski (1983) found fine grain material to be a better chemical barrier than a sand cap. The chemical containment afforded by a granular cap material is dependent on the sorption capacity of the material, and sandy (non-cohesive) materials usually have low sorption capacity compared to silt or clay materials. For this reason, a naturally occuring sandy soil or sediment, containing a fraction of finer grain sizes and organic carbon, is a more desirable capping material from the standpoint of isolation than a clean, quarry-run or washed sand.

Hydrophobic organic pollutants of concern are typically strongly bound to the organic fraction of the contaminated sediment which is largely found in the silty and smaller particle fraction of the sediment. Fresh sorption sites in the cap will greatly reduce the rate at which the chemicals move through the cap both during consolidation and long-term diffusive processes.

The migration of metals is more complex than that for hydrophobic organic chemicals because several additional factors affect the chemistry of metals. Most importantly, the oxidation state influences the solubility of the metal and thus its affinity for the stationary sediment matrix. Thus the Eh, pH, bacterial activity, and presence sulfides, chlorides, carbonates, etc., all influence metal migration. Due to the complexity of sediment chemistry with regard to metal migration, the design presented in this document focuses primarily on the containment of neutral hydrophobic organic chemicals which is enhanced by finer, higher organic carbon content material.

Although fine grained sediments, especially those with significant amounts of organic carbon would be an optimal cap material for reducing the flux of organic contaminants by advection/-diffusion, there are several other considerations in favor of sandy materials. The placement of non-cohesive materials is generally far easier than with fine grained materials. Silty materials are more readily resuspended and therefore difficult to place in conditions with even low currents or water velocities and more likely to require armoring. Sandy materials are stable at steeper slopes than fine grained materials. As a result, the footprint of a silty cap will be larger than a sand cap, and more fine grained material needed to cap the same deposit as a sandy material.

Another potentially significant advantage of sandy cap material, is related to potential benthic recolonization and bioturbation. As discussed below, the potential for penetration into the cap by burrowing animals is far greater for unconsolidated, fine grained sediments than it is for sandy sediments with little organic matter.

Information about potential upland sources of granular cap materials can be obtained from organizations that design or perform all types of construction, such as state highway departments, county or city departments of engineering, roads, parks, and sewers, general contractors, and local quarry operators. Potential sources of sediments that are scheduled for dredging and might be used for cap material can be obtained from the Corps of Engineers, local harbor authorities, and private marina operators.

The physical and chemical characteristics of materials under consideration for the cap should be determined. Physical characteristics of importance include densities, plasticity indices (for fine-grained materials), organic content, grain size distribution, and specific gravity (methods cited in Table 2-1). These characteristics can be used to develop a Unified Soil Classification System (USCS) classification for the material.

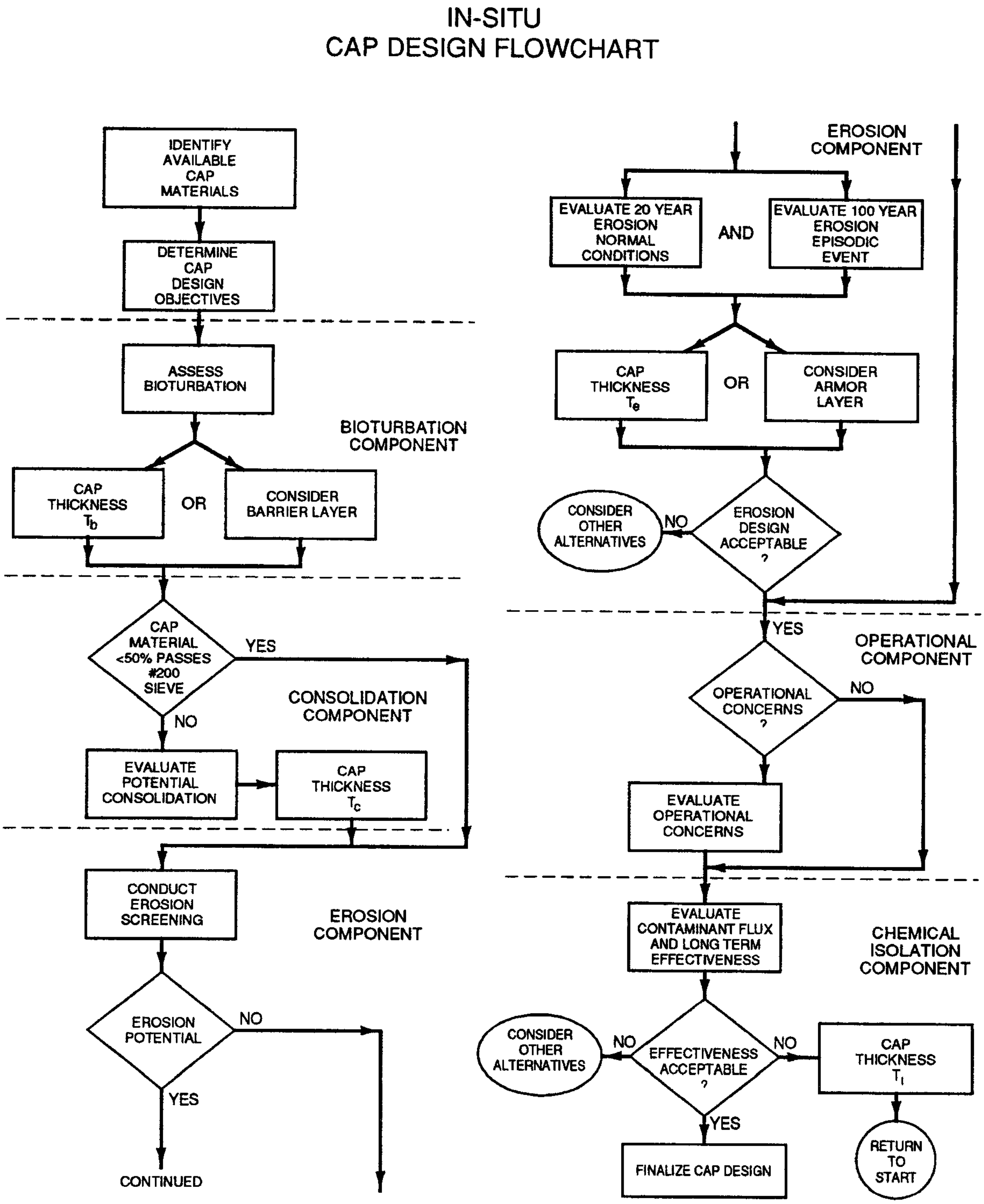


Figure 3. Flowchart showing steps involved in design evaluation of various insitu cap components.

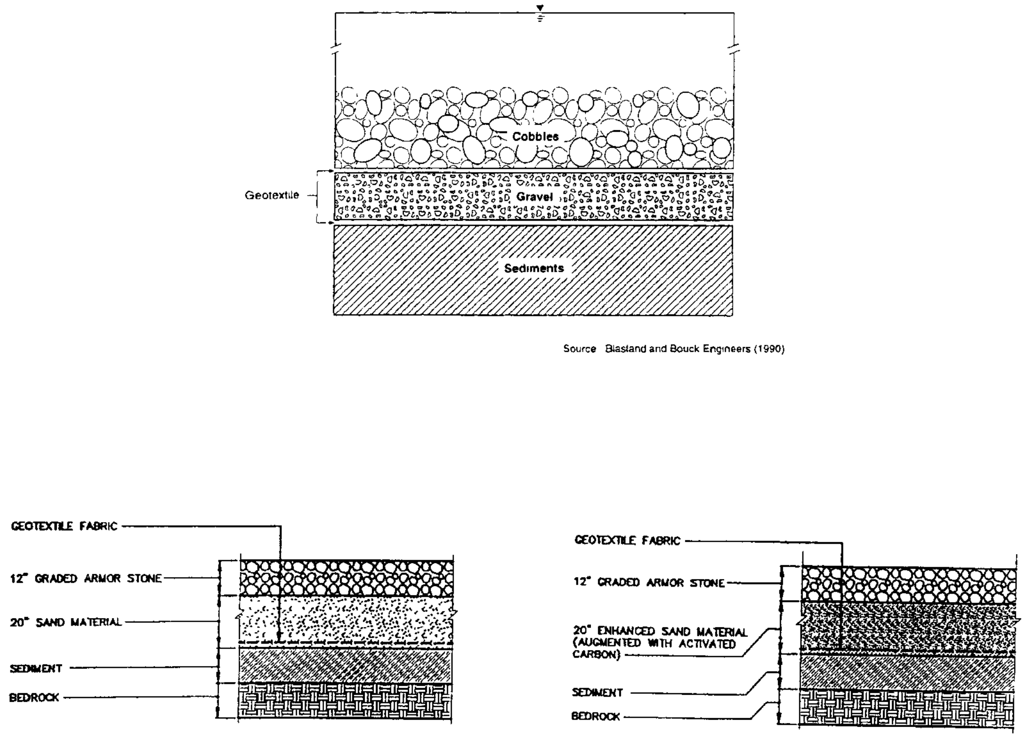


Figure 4. Illustrations of alternative combinations of cap components.

From the standpoint of contaminants, the capping material must be one which is acceptable for unrestricted open-water placement (that is a clean material). For sediments or soils, procedures normally used to assess the acceptability of dredged material for open water disposal should be used for the assessment of the suitability of a material for capping (USEPA/ USACE 1991, USEPA/ USACE in preparation, USEPA/ NCD 1995). Acceptability of such a material from the standpoint of both potential water column and potential benthic effects must be determined and some chemical and biological characterization of the material may be required.

Geosynthetic Fabrics and Membranes

Geomembranes are impermeable, synthetic materials, commonly used as landfill liners and other applications. Geotextiles are porous, synthetic fabrics, and have been used in many construction applications in recent years. A common example is the use of a geotextile for increased stability of a constructed earth embankment such as a dredged material disposal dike. Tubes or containers composed of geotextile material have also been used for containment applications, where the tubes are filled with sandy or fine-grained dredged material (Fowler and Sprague 1995).

Geosynthetics (geomembranes and geotextiles) have also been used for subaqueous capping applications, but field experience is limited. Potential functions of geosynthetics in ISC designs include: provide a bioturbation barrier; stabilize the cap; reduce contaminant flux; prevent mixing of cap materials with underlying sediments; promote uniform consolidation, and; reduce erosion of the capping materials.

Geotextiles have been used in conjunction with granular material for the in-situ cap constructed at Sheboygan River (Figure 4a) and at an ISC constructed in Eitrheim Bay, Norway (Instanes 1994). The design function of the geotextiles in these applications was not specified, although it is believed to have been primarily for stabilization of sediments and constructability. The cap design which had been proposed for Manistique River/Harbor (Figure 4b) included a geotextile for stability and constructability purposes.

Geomembranes have been installed under water in association with the construction of a dredged material confined disposal facility (Savage 1986). There is also field experience with use of membranes for controlling plant growth in lakes (Cooke et al 1993). In principle,geomembranes should be able to provide effective chemical isolation. However, there are unresolved issues of constructability and long-term integrity. One such issue is the impact of gas generation by contaminated sediments, and the potential lifting of the geomembrane. This problem has occurred with lake applications (Cooke et al 1993).

A 40-mil HDPE membrane was placed over a 26,400 square foot area at Manistique River as an interim control to temporarily prevent the erosion of contaminated sediments until a permanent remediation was implemented (Hahnenberg, pers com). This membrane was fitted with stop valves to allow gas venting and was weighted with concrete block anchors. Following installation, the membrane was observed to have billowed (ballooned), although it was not determined if this was due to gas generation or water entry under the cap (Hahnenberg, pers com; Blasland, Bouck & Lee 1994).

No data are available on the performance of geomembranes for chemical isolation in an in-situ cap. Geosynthetics are available from many commercial sources, and are available in a variety of composition materials with specific characteristics, including woven/non woven, thicknesses, weight/density, fitted with weights, vent holes, etc. It is conceivable that a composite geosynthetic could be manufactured to perform multiple cap functions.

Armor Stone

An armoring layer for resistance to erosion can also be considered in the cap design (Environmental Laboratory 1987; Maynord and Oswalt 1993). The caps constructed at Sheboygan River and Massena, and the design which had been proposed for Manistique River/Harbor (Figure 4) represent cases where a cap component has been included solely for erosion protection. In other cap designs, the exterior cap material has generally performed other functions besides erosion protection. Armor stone are available from commercial quarries in a variety of size gradations and stone types. Details on use of armor stone as a cap component are found in Appendix A.

Physical Isolation Component

In many cases, sediment remediation is driven by concerns about the uptake of bioaccumulative contaminants by aquatic organisms either directly from the sediments or by foraging on benthos. In order to eliminate this pathway for contaminant uptake, an in-situ cap must physically isolate the sediments from benthic or epibenthic organisms. To design a cap component for this function, the bioturbation potential of indigenous benthic infauna must be evaluated. The physical isolation component of the cap may include separate sub-components for isolation, bioturbation and consolidation.

Isolation Component

The basic function of the required sediment cap is that associated with physical and/or chemical isolation. For granular cap materials, the thickness which provides an effective physical/chemical barrier may be defined as T_i. If the desired function of the cap is physical isolation from benthic organisms, the isolation component provides a buffer between the organisms at their burrowing depth and the contaminated materials. A thickness of one foot for the granular capping material for this purpose is considered conservative. This approach to design of the isolation cap component is satisfactory if the cap is intended to physically isolate the contaminated sediments from benthic organisms or to physically isolate nutrient-rich sediments or sediments with relatively low levels of contamination.

If the desired function of the cap is reduction of contaminant flux, a more involved analysis to include capping effectiveness testing and modeling would be required as discussed below for design of a chemical isolation cap component. In this case, a value of one foot for the thickness of granular capping material may be considered as a trial value for the isolation component for purposes of the modeling effort.

Bioturbation Component

In the context of capping, bioturbation may be defined as the disturbance and mixing of sediments by benthic organisms. Aquatic organisms that live on or in bottom sediments can greatly increase the migration of sediment contaminants through the direct movement of sediment particles, increasing the surface area of sediments exposed to the water column, and as a food for epibenthic or pelagic organisms grazing on the benthos. The specific assemblage of benthic species which recolonizes the site, the bioturbation depth profile, and the abundances of dominant organisms are key factors in determining the degree to which bioturbation will influence cap performance.

The depth to which organisms will bioturbate is dependent on the organism's behavior and the characteristics of the substrate (i.e., grain-size, compaction, organic content, pore water geochemistry, etc.). In general, the depth of bioturbation by marine benthos is greater than that of freshwater benthos. The recolonization by the benthic infauna at marine dredged material caps is primarily suspension feeders as opposed to burrowing organisms (Cullinane *et al.*, 1990; Morton, 1989; Myers, 1979).

The intensity of bioturbation is greatest at the sediment surface and generally decreases with depth. A surficial layer thickness of sediment will be effectively overturned by shallow bioturbating organisms, and can be assumed to be a continually and completely mixed sediment layer for purposes of cap design. This layer is generally a few centimeters in thickness. Depending on the site characteristics, a number of mid-depth burrowing organisms overtime recolonize the site. The level of bioturbating activity for these organisms will decrease with depth. The species and associated behaviors of organisms which occupy these surface and mid-depth zones are generally well known on a regional basis. There may also be potential for colonization by deep burrowing organisms (such as certain species of mud shrimp) which may borrow to depths of 1 meter or more. However, knowledge of these organisms is very limited.

In preparation for this document, a survey was made of noted aquatic biologists from several research facilities around the Great Lakes. The survey described two hypothetical cap designs under shallow water conditions typical of the Great Lakes; one with a cap surface of medium to fine sand, and the other with a sand cap armored with gravel-sized stone.

The surveyed researchers generally agreed that the most likely benthic organisms to colonize a sand cap in the Great Lakes would be Chironomids (midges) and Oligochaetes (worms). One researcher indicated that Spaerids (fingernail clams), Trichopteran larvae and nematodes might also colonize the sand cap. The armored cap would attract a greater diversity of macroinvertebrates than the sand cap, including those that attach to surfaces (including Zebra mussels) or inhabit the larger interstitial spaces. As the interstices of the gravel are filled with "new" sediments, the benthos would likely become dominated by Oligochaetes and Chironomids.

While some organisms indigenous to the Great Lakes can burrow 10-40 cm in soft silt or clay sediments, most of the researchers surveyed felt that bioturbation in a sand cap would be limited to the top 5-10 cm. The presence of armor stone should inhibit colonization by deep-burrowing benthic organisms. The researchers indicated that the colonization of a sand or armored cap would be sparse until "new" sediments with sufficient organic matter deposited on the cap. If the "new" sediments are contaminated, the diversity of benthos colonizing the cap would remain limited.

Based on these opinions, a minimal component (or thickness) of an in-situ cap constructed with sand or one having an armored surface appears to be needed to accommodate bioturbation at Great Lakes sites. Benthos at such a capped site is likely to be limited to the fine-grained, organic-rich sediments which may deposit on top of the cap or settle in the interstices of armor stone. However, if a cap is constructed with a fine-grained material, the potential for bioturbation penetration is more significant. Designers should always consult with aquatic biologists about the bioturbation habits of benthic organisms native to the capping area.

Where a cap component to accommodate bioturbation must be designed, there are several options. If the cap contains granular material for chemical isolation or other functions, an additional thickness of the same granular material (T_b), equivalent to the depth to which the deepest burrowing organism can reach, may be added as a component for physical isolation. Another option is to select a different granular material with properties that are less "attractive" as a substrate for benthic infauna. A relatively thin layer of sand or gravel with little organic matter may be as effective as a thick layer of silt in limiting bioturbation into the cap. Geotextiles might also be used as bioturbation barriers in an in-situ cap design, although there is no experience with their use for this purpose.

Consolidation Component

If the selected material for the cap is fine-grained granular material (defined as material with less than 50% by weight passing a #200 sieve), the change in thickness of the material due to its own self weight or due to other cap components should be considered in the overall design of the isolation cap component. An evaluation of cap consolidation should be made in this case, and an additional cap thickness component for consolidation, T_c, should be added to the granular thickness for isolation so that the appropriate granular cap thickness is maintained. Such consolidation occurs over a period of time following cap placement, but does not occur more than once.

If the cap material is not a fine grained granular material, no consolidation of the cap may be assumed, and no additional increase in the isolation thickness is necessary. However, consolidation of the underlying contaminated sediments may occur, and a consolidation analysis may be necessary to properly interpret monitoring data. Procedures for evaluation of consolidation are given below under the discussion of geotechnical considerations.

Consolidation of underlying sediments due to placement of a cap may also result in advection of pore water upward into the cap. This is an important process in evaluation of potential advective flux of contaminants. A consolidation evaluation is therefore necessary for an evaluation of potential advective flux.

Stabilization/Erosion Protection Component

General Considerations

The cap component for stabilization/erosion protection has a dual function. On the one hand, this component of the cap is intended to stabilize the contaminated sediments being capped, and prevent them from being resuspended and transported offsite. The other function of this component is to make the cap itself resistant to erosion. These functions may be accomplished by a single component, or may require two separate components in an in-situ cap.

For example, a cap might be constructed to prevent erosion of contaminated sediments, using a geotextile. The dimensions and opening size of the geotextile fabric might be selected to cover the area and not allow sediment particles to pass through. This geotextile is performing the first function, that of stabilizing the sediments. However, a separate component, perhaps a layer of sand or gravel, is likely needed to keep the geotextile in place.

The potential for erosion at the capping site highlights one of the most significant differences between ISC and other sediment remediation alternatives; the role of dynamic conditions and probability in the design. Most treatment and confined disposal alternatives are designed assuming a relatively static physical environment at the remediation site. Topographic and geologic conditions are assumed to be static for most upland sites outside the floodplain. In contrast, the physical conditions at an ISC site are quite dynamic. Water levels, river currents, ice and debris scouring, or wave conditions can create erosive forces at the cap-water interface which are highly variable. The design of the ISC must account for these dynamic forces.

In the design of conventional marine or flood protection structures (i.e., breakwaters, dams or levees), probability is used to make key design decisions. Such structures are typically designed to withstand an event of a specific recurrence interval (e.g., 100-year flood), which may be dictated by policy, legislation or funding constraints. The design of erosion protection features of an ISC (i.e., armor layers) may also be based on the magnitude of erosive forces projected at the capping site. There is no existing guidance in Superfund regarding the selection of a recurrence interval or acceptable probability of failure for such applications. As such, design criteria may have to be established on a case-by-case basis.

Sediment Stabilization

In most ISC applications to date, the stabilization of contaminated sediments has not been a driving function of the cap design. In these cases, stabilization is generally accomplished by the granular cap component for chemical isolation. Immobilization of contaminated sediments is most likely to be the primary cap function where the potential for resuspension and transport of in-place sediments is a concern. Conventional methods for analysis of sediment transport are available to evaluate erosion potential can range from simple analytical techniques to numerical modeling.

The design of a cap component to stabilize in-situ sediments must consider the ability of the sediments to migrate vertically. A layer of coarse gravel, with interstitial voids many times larger than the contaminated sediments, would not be an efficient stabilization component. The grain size of granular cap material suitable for stabilizing contaminated sediments can be determined using guidance developed for the design of sand and gravel filters (USACE 1986; SCS 1994). These filter design methods are discussed further in Chapter 4.

Evaluation of Erosion Potential

The potential for erosion of the cap should be carefully considered. As discussed in Chapter 2, capping should be used in environments where the long term physical integrity of the cap can be maintained, and low energy environments are generally more appropriate for in-situ capping projects. However, higher energy environments may be considered for capping, recognizing that risks increase. The potential severity of the environmental impacts associated with cap erosion and potential dispersion of the sediment contaminants in an extreme event should determine the level of protection against erosion.

The potential for erosion depends on streamflow or tidal velocity forces, depth, turbulence, wave-induced currents, ship/vessel drafts, engine and propellor types, maneuvering patterns, sediment particle size, and sediment cohesion. Therefore, detailed evaluations of erosion must be based on analysis of the frequency of erosion of a specific capping material (grain size and cohesion) for expected wave and current conditions over time (to include storms) predicted in the area. The results from such an analysis will provide data that can be used to predict the expected cumulative amount of erosion over time along with confidence intervals on the answers. These numbers can then be used to define the need for, and design of an ISC erosion component.

Knowledge of the frequency of occurrence of scour or degradation (i.e., how often a given amount of vertical erosion will occur) is a critical component of a probabilistic cap design. An underdesigned erosion component will compromise the cap, potentially allowing the contaminants to be dispersed over the site and surrounding area. Conversely, an overdesigned erosion component will have an unnecessarily high cost and also may result in unacceptable site use constraints.

In most dredged material capping applications to date, granular materials used for chemical and physical isolation were determined to be generally resistant to erosion under local site conditions. In these cases, allowance was made for the gradual loss of small amounts of cap material by erosion either with an additional thickness of granular material or through planned periodic replenishment of cap material. The potential for granular cap materials used for other functions (physical isolation, chemical isolation or sediment stabilization) to be eroded should be evaluated to determine if a specific cap component for erosion protection is needed.

The hydrodynamic conditions driving potential erosion may include bottom velocity forces due to stream flow or tidal fluctuations, wave-induced currents, or propeller-induced current velocities. At an ISC site, each of these need to be considered to determine which represents the greatest erosion potential. An examination of five Great Lakes sites for ISC feasibility found that propellor-wash was the dominant factor influencing armor layer design in four of the sites, and river currents in the other (Maynord and Oswalt 1993). In contrast, the armor layer of the cap design which had been proposed for Mannistique River/Harbor was dominated by wave conditions (BBL 1995).

The following sections describe methods to design the erosion component for sites where erosion is expected to be a problem, based on which erosive force is dominant.

River/Tidal Current-Induced Erosion

The investigation of erosion potential at selected Great Lakes sites (Maynord and Oswalt 1993) suggests that currents and flood flows are most likely to be the dominant erosive factor in unnavigable portions of rivers, or areas where navigation has ceased. In shallow rivers, like the Sheboygan River, in-situ caps may extend onto the bank and flood plain and resemble streambank erosion structures. In deeper rivers and estuaries, like Puget Sound, tidal currents may be the dominant erosive force, although no special erosion component may be required.

Several screening approaches could be used to evaluate potential for erosion of a granular material of given grain size due to given unidirectional current and/or wave conditions (Teeter 1988, Dortch et al. 1990, Hands and Resio 1994, Scheffner 1991a and b, ASCE 1975). A simple Shields diagram can be used to compare the stability of given materials against unidirectional currents. Procedures for using this approach are found in Dortch et al. (1990).

The site evaluation and associated investigations described in Chapter 2 should provide the current velocities and frequencies associated with episodic events which are needed for the evaluation of erosion potential. The return interval or frequency of events such as storms or flood flows which should be used for the design would depend on several factors, such as the degree of risk if the contaminants were re-exposed and the possible degree of self-armoring which may occur during erosion.

The selection of a design interval should be based on reasonable assumptions. The design life of most civil works projects such as bridges or dams is 50 years. The confidence in ability to predict the forces due to a 50 or 100 year event is high, because of the available data from historic records usually includes events with comparable return intervals. Consideration of events with return intervals in the range of 100 years is therefore appropriate for these types of projects. In contrast, an in-situ cap is conceptually built to last forever. However, consideration of extreme low probability, high impact events (e.g., a 500 year storm) may not always be appropriate because the confidence in accurately describing the forces resulting from such an extreme event is low. Further, the impact due to erosion of the cap from such an event should be placed in context with other environmental effects including the loss of life and property in the surrounding area.

Design procedures for armor stone as a cap component are found in Appendix A.

Wave-Induced Erosion

Wave-induced erosion is the dominant factor at virtually all dredged material capping sites, and is likely to be dominant at open water ISC sites, including lakes, estuaries and harbors. Most in-situ caps constructed in open water environments resemble a mounded dredged material cap.

An extensive analysis of combined flood flow and wave induced erosion was performed for the proposed capping option at Manistique Harbor (BBL 1994 and 1995). This analysis relied on several computer models and design approaches including flood flow models developed by the U.S. Army Corps of Engineers Hydrologic Engineering Center (HEC xx) and wave models developed by the U.S. Army Corps of Engineers Coastal Engineering Research Center (ACES reference).

Palermo et al.(in preparation) describes detailed procedures for erosion screening for open-water sites dominated by wave conditions and computing frequency of erosion studies for open water sites.

The USACE has developed a model to evaluate the long-term fate of a sediment or cap deposit (mound), i.e., mound stability over periods ranging from months to years, and this model can be applied to predict cap erosion rates for open water sites such as estuaries, lakes, etc. This model is called the Long Term FATE of dredge material (LTFATE) model (Scheffner, Thevenot, and Mason, 1995). In LTFATE, hydrodynamic conditions at a site are considered using simulated databases of wave and current time series or actual wave and current data as driving forces. These boundary conditions are used to drive coupled hydrodynamic, sediment transport, and bathymetry change models which predict erosion of dredged material mounds (of specific dimensions, grain size, and water depth) over time. Results from this model indicate whether a given site is predominantly dispersive or non-dispersive and predict potential erosion and migration of a mound for the given current and wave conditions, mound geometry and sediment characteristics. Because this model was developed for open water conditions, it may have only limited utility for some ISC applications such as riverine sites.

Propellor-Induced Erosion

Contaminated sediments are generally associated with urban/industrial waterways, most of which are active channels for commercial and recreational vessels. The ability of propellor jet (or wash) from ships, towboats and even recreational watercraft to resuspend bottom sediments is well documented. The ISC placed at Eagle Harbor, Washington has experienced some erosion at the areas nearest a car ferry dock. The only case of an erosion component specifically designed for navigation-effects was associated with a dredged material cap considered for Indiana Harbor (Environmental Laboratory 1987). This design included armor stone, and was ultimately rejected as infeasible.

Methods for predicting navigation-induced erosive forces were developed for design of river bank protective and navigation structures. Erosive forces are calculated from information on the propellor type, diameter, engine horsepower, and vertical distance from the propellor to the cap. These methods are described in Appendix A. The uncertainty in the the design of a cap for conditions dominated by river/tidal currents or waves is based on the predictability of future meteorological events. The uncertainty in the design of an erosion component for a cap at a site where navigation-impacts dominate is based on the predictability of navigation use and traffic patterns. This requires foresight into the types of vessels that will be using a waterway and where and how they will maneuver. It also requires knowledge of any short- or long-term fluctuations in water surface elevations.

Chemical Isolation Component

Chemical Flux Processes

If a cap has a properly designed physical isolation component, contaminant migration associated with the movement of sediment particulates should be controlled. Most contaminants of concern also tend to remain tightly bound to sediment particles. However, the movement of contaminants by advection (movement of porewater) upward into the cap is possible, while movement by molecular diffusion over long time periods is inevitable.

Advection refers to the movement of porewater. Advection can occur as a result of compression or consolidation of the contaminated sediment layer or other layers of underlying sediment. Movement of porewater due to consolidation would be a finite, short-term phenomena, in that the consolidation process slows as time progresses and the magnitude of consolidation is a function of the loading placed on the compressible layer. The weight of the cap will "squeeze" the sediments, and as the porewater from the sediments moves upward, it displaces porewater in the cap. The result is that contaminants can move part or all the way through the cap in a short period of time. This advective movement can cause a short-term loss, or it can reduce the breakthrough time for long-term diffusive loss.

Through-cap transport due to consolidation can be minimized by using a cap that has sufficient thickness to contain the entire volume of pore water that leaves the contaminated deposit during consolidation. For example, Bokuniewicz (1989) has estimated that the pore water front emanating from a consolidating two-meter-thick mud layer would only advance 24 cm into an overlying sand cap (Sumeri et al. 1991).

Advection can also occur as an essentially continuous process if there is an upward hydraulic gradient due to groundwater flow. In most upland hydrogeologic settings, advection due to groundwater flow is thought to be the most significant mechanism of mass transport (Bear and Verruijt 1987; Fetter 1993; Domenico and Schwartz 1990). In ground water, advection is generally described in terms of Darcy's law. Darcy's law defines a linear relationship between the groundwater flux (volume/unit area/unit time) and the hydraulic gradient (Domenico and Schwartz 1990), and, with a slight modification, Darcy's law can be used to determine the average rate of ground water flow (Freeze and Cherry 1979).

An estimation of the rate of groundwater discharge can either be obtained empirically through the use of seepage meters, or calculated through the use of Darcy's law and a knowledge of the site hydrogeology (see Chapter 2). In addition, seepage meters can also be used to evaluate the quality of the ground water discharging to surface water through the collection of ground water samples for chemical analysis.

Diffusion is the process whereby ionic and molecular species in water are transported by random molecular motion from an area associated with high concentrations to an adjacent area associated with a low concentration (Fetter 1994). Diffusional mass transport assumes that the rate of transport is directly proportional to the concentration gradient. In an isotropic medium, this occurs in a direction perpendicular to the plane of constant concentration at all points in the medium. If the diffusional flux is steady-state, mass transport by diffusion is described by Flick's first law (Fetter 1993). Fick's second law is used to describe systems in which the contaminant concentrations are dependent upon time.

From an environmental perspective, diffusion is as slow as contaminant transport processes can become in a porous medium. However, although diffusion is notoriously slow, diffusional driven mass transport will always occur if concentration gradients are present. Consequently, diffusion can transport contaminants through a saturated porous media in the absence of advection.

Advection and/or diffusion transport processes can be viewed as end-members of a continuum. Based upon random molecular motion attempting to equalize contaminant concentrations, diffusion is commonly the slower of these two processes (Fetter 1993). In contrast, advection as the bulk movement of ground water due to differences in hydraulic head is generally a much more rapid transport process. In many/most geologic settings, mass transport is driven by advection (Fetter 1993; Bear and Verruijt 1987). Generally, predictions of contaminant transport based upon diffusion alone would only become appropriate for geologic settings and/or cap designs which incorporate a porous layer associated with a very low hydraulic conductivity value, or in the absence of hydraulic gradients (the hydrostatic case) (Fetter 1993).

Even if contaminant concentrations are high in the pore water, a granular cap component would act as both a filter and buffer during advection and diffusion. As pore waters move up into the relatively uncontaminated granular cap material, these cap materials can be expected to remove contaminants (through sorption, ion exchange, surface complexation, and redox mediated flocculation) so that pore water that traveled completely through the cap would theoretically have a reduced contaminant concentration. The extent of the contaminant removal in the cap is very much dependent upon the nature of the cap materials. For example, a cap composed of quarry run sand would not be as effective as a naturally occurring sand with an associated fine fraction and organic content.

Consideration of Advective/ Diffusive Flux in Cap Design

If the desired function of the cap is to chemically isolate the contaminants in the long term or reduce long term flux of contaminants such that a water quality standard or sediment cleanup level can be maintained, both advective and diffusive processes should be considered in determining the necessary design for isolation.

For example, if a ground water/surface water interaction study indicated that advection is not significant at a given location, the cap design may only need to address diffusion and the physical isolation of the contaminated sediments, ignoring dissolved and/or colloidially facilitated transport due to advection. In contrast, should ground water/surface water contaminant release routes be significant, the hydraulic properties of the cap should also be determined and factored into the cap design. These properties should include the hydraulic conductivities of the cap materials, the contaminated sediments, and underlying sediments or geologic deposits.

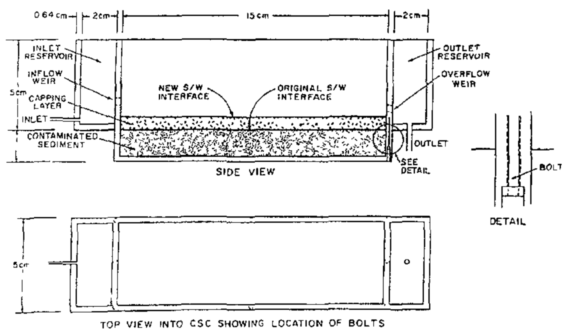
Laboratory Tests for Capping Effectiveness

Laboratory tests were first developed to evaluate cap thicknesses required for physical isolation of dredged material. However, several testing approaches have been applied to define cap thicknesses and the sediment parameters necessary to model their effectiveness in chemical isolation. Laboratory tests may be used to define sediment specific and capping material specific values of diffusion coefficients and partitioning coefficients. But, no standardized laboratory test or procedure has yet been developed to fully account for advective and diffusive processes and their interaction.

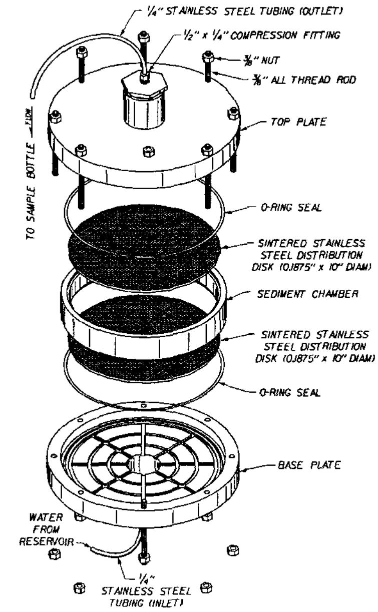
The USACE developed a first generation capping effectiveness test in the mid 1980s as part of the initial examination of capping as a dredged material disposal alternative. The test was developed based on the work of Brannon et al. (1985, 1986), Gunnison et al. (1987), and Palermo et al. (1989). This test (Sturgis and Gunnison 1988) has been used to determine the thickness, T_i, of a capping sediment required to isolate a contaminated sediment. The tests basically involve layering contaminated and capping sediments in columns and experimentally determining the cap sediment thickness necessary to chemically isolate a contaminated sediment by monitoring the changes in dissolved oxygen, ammonium-nitrate, orthophosphate-phosphorous, or other tracers in the overlying water column (Figure 5-2). The thickness of granular cap material for chemical isolation determined using this procedure is on the order of one foot for most sediments tested to date.

In retrospect, this testing procedure may be suitable for evaluating the short-term advective movement of sediment pore water associated with consolidation. However, this column testing procedure does not account for ground water induced advection of pore water or the long term flux of contaminants due to diffusion which may involve time scales of tens to hundreds of years.

Louisiana State University has conducted laboratory tests to assess diffusion rates for specific contaminated sediments to be capped and materials proposed for caps. A capping simulator cell was used in which a cap material layer is placed over a contaminated sediment, and flux due to diffusion is measured in water which was allowed to flow over the cap surface (see Figure 5a). Initial tests measured flux of 2,4,6-trichlorophenol (TCP) through various cap materials. These tests showed that the breakthrough time and time to steady state were directly dependent on the partitioning coefficient and that cap porosity and thickness were the dominant parameters at steady state (Wang, Thibodeaux, Valsaraj, and Reible 1991).



5a. LSU experimental cell.



5b. WES leach test.

Figure 5. Laboratory methods to evaluate chemical isolation by caps.

Environment Canada has performed tank tests on sediments from Lake Ontario to qualitatively investigate the interaction of capping sand and compressible sediments. The tests were carried out in 3.6 x 3.6 x 3.7 meter observation tanks in which the compressible sediments were placed and allowed to consolidate and sand was placed through the water column onto the sediment surface. In the initial tests, physical layering and consolidation behavior were observed. Additional tests are planned in which migration of contaminants due to consolidation-induced advective flow will be evaluated (Zeman 1994).

Diffusion coefficents for long-term modeling of diffusive transport of contaminants from contaminated sediment into cap material have also been measured using diffusion tubes (DiToro, Jeris, and Clarcia 1985). In this method, sediment is spiked with radiolabled contaminant, placed in small tubes, and covered with capping material. At times extending up to 3 years, selected tubes are sliced (100-250um) using a microtome, and the thin slices are analyzed for radioactivity. The results are used to develop contaminant profiles from which diffusion coefficients that account for the sorptive properties of the cap materials can be calculated. The diffusion tube approach is being used in a capping study for the U.S. Army Engineer District, New York (Myers 1995, Personal Communication).

The USACE has also developed leach tests to assess the quality of water moving through a contaminated sediment layer into groundwater in a confined disposal facility environment (Myers and Brannon 1991) (see Figure 5b). This test is being applied to similarly assess the quality of water potentially moving upward into a cap due to advective forces (Myers 1995, Personal Communication).

Results of laboratory tests such as those described above should yield sediment specific and capping material specific values of diffusion coefficients, partitioning coefficients. In addition, other parameters such as the magnitude and rate of consolidation, changes in sediment permeability/ porosity, and any advective flow conditions are needed to model long term cap effectiveness. Model predictions of long term effectiveness using the laboratory derived parameters should be more reliable than predictions based on so called default parameters.

Modeling Applications for Cap Effectiveness

A model has been developed by EPA to predict long-term movement of contaminants into or through caps due to advection and diffusion processes. This model has been developed based on accepted scientific principles and observed diffusion behavior in laboratory studies (Bosworth and Thibodeaux 1990; Thoma et al 1993; Myers et al 1996). The model considers both diffusive and advective fluxes, the thickness of sediment layers, physical properties of the sediments, concentrations of contaminants in the sediments, and other parameters. This model is described along with example calculations in Appendix B.

The results generated by the model include flux rates, breakthrough times, and pore water concentrations at breakthrough. Such results can be compared to applicable water quality criteria, or interpreted in terms of a mass loss of contaminants as a function of time which could be compared to similar calculations for other remediation alternatives. The model in Appendix B is applicable to the case of a single contaminated material layer and a single cap material layer, each with a homogenous distribution of material properties. The diffusion relationships used in the model have been verified against laboratory data. However, no field verification studies for the model have been conducted.

There is a need for a comprehensive and field verified predictive tool for capping effectiveness and additional research on this topic is planned. The USACE has applied a refined version of an existing sediment flux model (Boyer et al 1994) for capping evaluations, and more refinements to the model are planned to account for a comprehensive treatment of all pertinent processes. But in absence of such a tool, analytical models such as that in Appendix B should be used in calculating long term contaminant loss for capped deposits as long as conservative assumptions are used in the calculations.

Chemical Isolation Component Design for Granular Cap Materials

In most in-situ caps constructed to date, granular material, including gravel, sand, and silt and clay, has been used for chemical isolation.

Modeling can be used to obtain an estimate of the required thickness of granular cap material for chemical isolation. However, the thickness and properties (grain size distribution and total organic carbon (TOC) content) of the granular cap material are necessary input parameters for the models. Therefore, an efficient approach for design of the chemical component is to determine the representative grain size and TOC of candidate capping materials, account for other requirements such as bioturbation, consolidation and erosion in the cap design, then evaluate long term effectiveness using the model provided in Appendix B.

When evaluating potential chemical isolation component designs, the properties of granular cap materials should represent those that would be present in the materials after construction. The method of placement and site conditions can alter the properties of capping material. For example, the distribution of organic matter in some sandy materials may not be uniform, with a high percentage of the TOC in a small fraction of fines. During cap placement, the loss of these fines could result in a significant reduction to the ultimate TOC in the cap material after placement.

If the modeling results indicate the design objectives are not met, additional cap thickness can be added or granular cap materials with differing properties (grain size and TOC) can be considered to further decrease the contaminant flux. The evaluation process could then be run in an iterative fashion if necessary to determine the chemical isolation component design needed to meet the remedial objectives. Of course, if no reasonable combination of cap thickness and cap material properties can meet the objectives, other remediation alternatives or control measures must be considered or the remedial objectives reconsidered.

Chemical Isolation Component Design
for Membranes and Fabrics

Geosynthetic membrane materials (essentially impermeable) may be incorporated in a cap design to reduce contaminant flux. However, the use of impermeable plastic liners as a chemical isolation component is limited by concerns regarding gas generation in the underlying sediments, and the need to vent this gas. Membranes have been placed with vents for release of generated gas.

Geotechnical fabrics (permeable) have been incorporated in cap designs to prevent the mixing of cap material with underlying contaminated sediments and to prevent potential migration of contaminated sediment particles into the cap. Permeable fabrics would have little effect with regard to reduction in flux due to advection of pore water or diffusion. Conceptually, geotextiles or geotextile blankets may be fabricated to allow placement of materials with high TOC (e.g., activated carbon) which would otherwise be difficult to place due to low density or potential for resuspension.

Component Interactions

The most conservative design approach for an in-situ cap is to consider components necessary for the three basic cap functions independently (as done above). Using this approach, components are additive. This approach is most appropriate for caps designed with a single type of granular material, where the total thickness of cap material is the sum of the thicknesses for physical isolation, chemical isolation and stabilization/erosion protection. Additional amounts of granular material might be added to account for consolidation (discussed below), or for other construction or operational considerations.

The design of cap components for multiple functions will generally not be as conservative as the additive approach. For example, say a 2-foot layer of sand is considered adequate for chemical isolation and a 1-foot layer of the same material is considered adequate for physical isolation. It might be reasoned that a 2-foot layer of sand could perform both functions. However, the bioturbation of benthic infauna into the top foot of such a cap could result in their exposure to contaminants migrating through the cap, or might alter the permeability of the cap, increasing the contaminant flux.

The cap components for physical isolation and erosion protection would seem to have the greatest potential for dual function. If a granular cap has a thickness at the surface that is "sacrificial" for erosion, this layer might be lost during a storm event and would have to be replenished afterward. Such an erosion component could not be relied on to perform other functions. However, if an armored layer was placed on top of a cap, and designed to be stable under all but very extreme events, the ability of such a layer as a deterrant to bioturbation might be considered in addition to its erosion protection function.

Geotechnical Considerations

In-situ contaminated sediments to be capped will usually be predominately fine grained, and may have high water contents and low shear strengths. Such materials are generally compressible, and may be easily displaced or resuspended during placement of capping materials unless appropriate controls are implemented. The cap stability against displacement or sliding and settlement due to consolidation are two main geotechnical issues.

Bearing Capacity/ Slope Stability Considerations

As with any geotechnical problem of this nature, the shear strength of the sediments will influence their resistance to localized bearing capacity or sliding failures which may cause localized mixing of capping and contaminated materials. Stability immediately after placement is most critical, before any excess pore water pressure due to the weight of the cap layer has dissipated. Gradual placement of capping materials over a large area will reduce the potential for such localized failures in most cases. For example, the sand cap placed in Hamilton Harbor, Ontario was placed in three separate passes (Zeman and Patterson 1996a). Settlement of the cap occurs as the sediments consolidate simultaneously with the dissipation of excess pore water pressure while gaining additional strength.

A review of case studies on geotechnical aspects of capping projects where shear strengths of the in-situ sediments were measured was conducted for the ARCS program (Ling et al 1996), and is provided as Appendix C. Conventional bearing capacity and slope stability analysis using the measured shear strengths indicated stable conditions for most of the capping projects evaluated (all of which used a sand cap).

Field monitoring data has definitively shown that contaminated sediments with low strength have been successfully covered with sand caps. However, engineering data on the behavior of soft deposits during placement of materials in the form of a cap is limited. Conventional geotechnical design approaches should therefore be applied with caution to subaqueous cap design, since such design approaches would likely be conservative for conditions normally encountered in cap design. For example, a cap placed over an area of several acres at a thickness of several feet would not be subject to a "punching" failure mode normally evaluated by conventional bearing capacity analysis. Similarly, caps with flat transition slopes at the

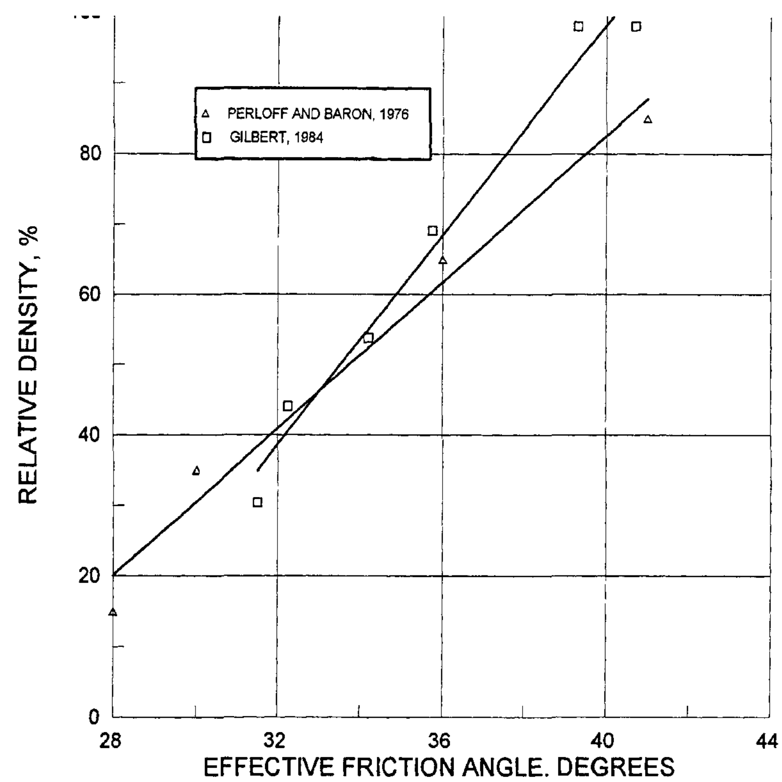


Figure 6. Relationship between relative density and effective friction angle for clean sands.

edges would not be subject to a sliding failure normally evaluated by conventional slope stability analysis.

The capping material should be applied slowly and uniformly to avoid problems with bearing capacity or slope failures if the contaminated sediment deposit is soft. Uncontrolled release of a large amount of material or the buildup of a localized mound can cause a bearing capacity failure. If this occurs, cap material penetrates into the contaminated deposit and could cause contaminated material to resuspend and disperse into the water column.

It is likely that contaminated sediments are subject to pore pressure buildup as cap material is deposited on the surface. The buildup of excess pore water pressure reduces the shear strength of the contaminated soil and increases the susceptibility to bearing capacity failure. Therefore it is important to allow sufficient time for excess pore water pressure dissipation in materials with low permeability. In materials susceptible to induced excess pore water pressure, sand deposition and cap construction must proceed more slowly and deliberately. The geotechnical engineering parameters associated with bearing capacity and their connection with soil strength are discussed in more detail in Appendix C.

Edge Effects/ Overlap Requirements

Accommodations in the cap design for bearing capacity and slope stability may only be applicable in the case of a cap several feet in thickness which must be placed over a small area or within a constricted site with little opportunity for transitions. In such cases, potential slope failures at the edges of the cap can be accommodated by overlapping the cap beyond the edge of the contaminated sediment deposit. Therefore, an important consideration becomes the distance beyond the edges that the cap must cover.

Data relating the effective friction angle of sand with the relative density is shown in Figure 6 (Gilbert, 1984, and Perloff and Baron, 1976). If the cap materials are typically clean sands that are loosely deposited by pluviation (settling of material through water), the relative density is zero and, using Figure 6, the limiting effective friction angle is about 28°. If the angle of

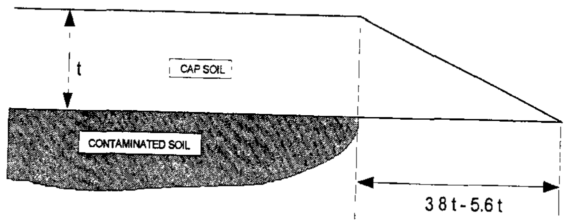


Figure 7. Recommended cap edge overlap.

repose of the sand is equal to the effective friction angle as suggested by Taylor (1948) and Hough (1957), then the slope at the edge for a clean sand of low density becomes 1 V : 1.88 H. A safety factor of 2 to 3 is recommended for these conditions, therefore, the end slope becomes 1 V : 3.8 H to 5.6 H. The recommended cap overlap distance is therefore 3.8 to 5.6 times the thickness of the cap as shown in Figure 7.

Liquefaction

Liquefaction is a phenomenon in which a deposit of loose, saturated, cohesionless material (such as sand) develops high pore water pressure as the result of a disturbance, progressively loses a large portion of its shear strength, and flows like a frictional fluid. Liquefaction may be triggered by seismic activity, wave action, blasting, or propwash from a vessel on the surface. Submarine deposits have been documented to have experienced liquefaction and moved/flowed thousands of feet before coming to rest (Terzaghi, 1956). Contaminated deposits of sand or caps constructed of sand may be susceptible to liquefaction because sand that has settled through water typically forms deposits of low density (Terzaghi, 1956, Gilbert, 1984). Gilbert (1984) showed in laboratory experiments that deposits of sand that are formed by particles settling through water can have negative relative density (meaning that the deposit achieved a lower density under water than is possible in air). Sands that are fine and uniform are most susceptible to liquefaction. Depending on a number of factors such as the size of the contaminated deposit, the engineering properties of the capping and contaminated sediments, bottom slope, and probability of seismic activity, a full scale investigation for liquefaction susceptibility may be warranted.

Consolidation Analysis

Fine-grained granular capping materials may undergo consolidation due to self-weight. Underlying contaminated sediment will almost always undergo consolidation due to the added weight of capping material or armor stone. The cap design should therefore consider consolidation from the standpoint of cap material thickness and interpretation of monitoring data. The thickness of granular cap material should have an allowance for consolidation so that the minimum required cap thickness is maintained following consolidation. Evaluation of the consolidation expected will allow proper interpretation of any observed decreases in cap surface elevation during monitoring.

If the granular capping material selected for physical or chemical isolation can be classified as a sand based on its physical properties (i.e., the material has a distribution of grain sizes with less than 50% passing the #200 sieve) no cap thickness component to offset cap consolidation is necessary. If the material is classified as a silt or clay, i.e. has a distribution of grain sizes with more than 50% passing the #200 sieve, an evaluation of cap consolidation should be made, and an additional cap thickness component for cap consolidation, T_c, should be added to the granular thickness for each component so that the appropriate granular cap thickness is maintained.

Even if the cap material is not compressible, a consolidation analysis of the underlying contaminated sediment is usually necessary. Most contaminated sediments are highly compressible, and an evaluation of consolidation is important in interpreting monitoring data to differentiate between changes in cap surface elevation or cap thickness due to consolidation as opposed to those potentially due to erosion. Also, the degree of consolidation will provide an indication of the volume of water expelled by the contaminated layer and capping layer due to consolidation. This can be used to estimate the movement of a "front" of porewater upward into the cap. Such an estimation of the consolidation driven advection of pore water could be considered in the evaluation of contaminant flux.

Potential strains due to consolidation are large, and therefore a finite strain approach which accounts for large strains should be used to evaluate consolidation. Coarse-grained materials will not consolidate appreciably. In evaluating consolidation, the magnitude of contaminated sediment and capping material consolidation should be separately determined.

The finite strain approach for consolidation evaluation (Brandes et al. 1991) has been coded for computer solution in a model called MOUNDS (Poindexter-Rollings 1990). This model provides information on the magnitude and rate of consolidation of a mound and on gains in shear strength as consolidation progresses. Consolidation test data from self-weight consolidation tests and/or standard oedometer tests (USACE 1970 and USACE 1987) are required to run the model.

The MOUNDS model and a second consolidation model, CONSOL (Gibson, Schiffman, and Cargill 1981 and Wong and Duncan 1984), were used to predict consolidation of three capped dredged material mounds in Long Island sound (Silva et al. 1994). Bathymetry of these sites showed reductions in mound elevations of up to 3.5 m over time periods of 10 to 13 years after cap placement. Comparisons between consolidation and bathymetry estimates were made to show that the reductions in mound elevation could be attributed to consolidation rather than cap erosion. Results showed the two models were reasonably accurate in predicting consolidation. The work also pointed out the need to obtain more accurate geotechnical information on the void ratios and initial effective stress of the contaminated materials.

Filter Design Analysis

As part of the design of an in-situ cap component for sediment stabilization, or where the cap design has more than one layer of granular material, one must consider the ability of the sediments and cap materials to migrate vertically. The initial design for the proposed cap at Manistique River/Harbor included an armor layer with stone of 7-10 inches in diameter for erosion protection on top of a 20-inch thick layer of sand for chemical and physical isolation (Blasland, Bouck & Lee 1994). Because of concerns about the movement of sand through the voids in the armor stone, the initial armor layer design was modified to a more well-sorted gradation of stone (Blasland, Bouck & Lee 1995).

Where one granular material is placed on top of another, the potential for vertical migration can be determined using guidance developed for the design of sand and gravel filters (USACE 1986; SCS 1994).

Operational Considerations

A detailed discussion of equipment and procedures that might be used for the placement of an in-situ cap is provided in Chapter 4. Operational considerations discussed here are practices and controls that may need to be implemented in order to assure that the in-situ cap functions as designed and remains intact. These considerations may include planned maintenance of the cap, restrictions on uses of the waterway at the capping site and other institutional controls.

Routine cap maintenance generally is limited to the repair or replenishment of erosion protection component material. The design of some dredged material caps includes a thickness of granular material that is expected to be eroded during storm events of a known magnitude or recurrence interval. For such a design, maintenance can be scheduled or planned for in advance. This type of erosion control is not appropriate unless there is a dependable source of capping material readily available. For an ISC, the ability to detect and quickly respond to a loss of the erosion protection layer should also be taken into consideration. On the Great Lakes, seasonal limitations, such as ice formation or closure of navigation structures (locks), can limit the ability to monitor in-situ caps after a significant erosion event and respond with maintenance if needed.

Aside from erosion caused by natural phenomena, the greatest threat to the integrity of an ISC is from navigational activity. As discussed above, and in Appendix A, the erosive forces created by propellers of ships, tug boats, and even recreational watercraft can be quite powerful, especially where water depths are reduced by the presence of an in-situ cap. Other activities, such as bottom drag fishing, direct hull contact, and anchoring create bottom stresses that can damage a cap (Truitt 1987a). An in-situ cap, particularly one with an armor layer, may be attractive to some fish, and consequently may be attractive to fisherman.

In order to inform navigation users of the presence of the ISC, navigation maps, mariners guides, and local land-use documents should be updated to show the presence of the cap and any use restrictions. Information about the cap and restrictions might also be posted at boat launch areas, bait shops, and provided with fishing licenses. Signs should be posted at prominent locations near the cap, and marker buoys deployed where appropriate. Active local public education programs on the presence and purpose of the ISC may improve voluntary compliance.

The ability to enforce restrictions on navigation activities in and around ISC sites should be weighed in considering the overall feasibility of capping. Restrictions that are codified as local or state statutes are more likely to be adhered to than voluntary ones. However, enforcement may require considerable resources. The cost of enforcement, posting, and education should be considered in the evaluation of the feasibility of ISC.

4 Equipment and Placement Techniques

This chapter describes considerations in selecting equipment and placement techniques for in-situ cap placement. Considerations for both granular capping materials such as sediments and soils and geosynthetic fabrics and armoring materials are provided.

A variety of equipment types and placement techniques have been used for capping projects. Conceptual illustrations of equipment which can be considered for capping are shown in Figure 8.

General Considerations

For granular cap components, the major consideration in selection of equipment and placement of the cap is the need for controlled, accurate placement and the resulting density and rate of application of capping material. In general, the cap material should be placed so that it accumulates in a layer covering the contaminated material. The use of equipment or placement rates which might result in the capping material displacing or mixing with the contaminated material should be avoided. Sand caps have been successfully placed over fine-grained contaminated material with minimal mixing of the cap with the contaminated sediment (Mansky, 1984a, 1984b; Bokuniewicz, 1989; Bruin, Hattem and Wijnen, 1985, Zeman and Patterson 1996 a and 1996b). Since the surface area to be capped may be several hundred feet or more in diameter, placement of a cap of required thickness over such an area may require placement techniques to spread the material to some degree to achieve coverage.

Site considerations that can influence equipment selection include water depths and wave/current conditions. Other site conditions such as bottom topography, other vessel traffic, thermal/salinity stratification of the water columns (for deep water sites), etc. may also have an influence. Pipeline and barge placement of dredged material for ISC projects is appropriate in more open areas such as harbors or wide rivers. In constricted areas, narrow channels, or shallow nearshore areas, conventional land-based construction equipment may also be considered.

Potential resuspension of in-situ contaminated material by impact of capping material should be considered in selecting equipment and placement technique for the cap. There is no standardized method presently available to calculate the potential resuspension of sediment and associated contaminant release due to such resuspension. Monitoring conducted at capping sites has generally focused on cap thickness and coverage rather than sediment resuspension. At an ISC demonstration in Hamilton Harbor, Environment Canada monitored the water column and tracked a small plume of suspended material. Analysis of the material in suspension indicated that it was predominantly fines that had been washed off the sand capping material during placement and not resuspended contaminated sediments (Zeman and Patterson 1996a and 1996b).

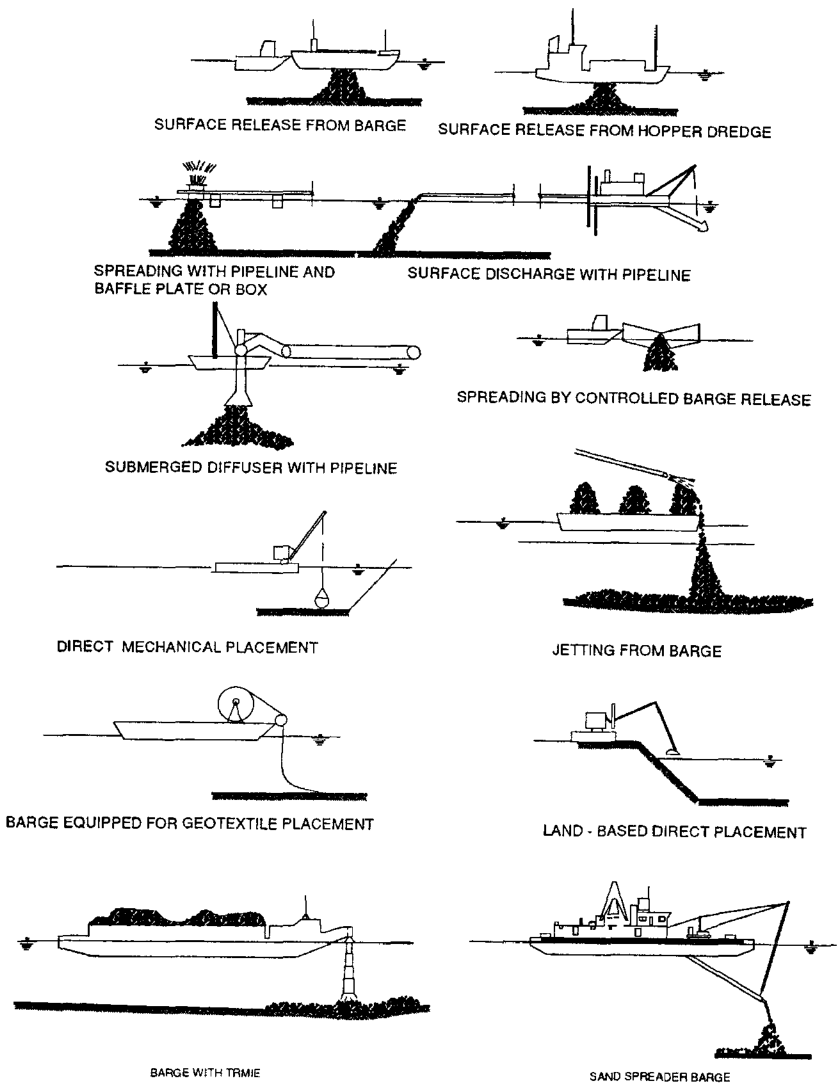


Figure 8. Conceptual illustrations of equipment which can be considered for capping.

Equipment and Placement Techniques for Granular Cap Materials

Granular cap material can be handled and placed in a number of ways. Materials that have been mechanically dredged and soils excavated from an upland site or quarry have relatively little free water, and can be handled mechanically in a "dry" state until released into the water over the ISC site. These mechanical methods rely on the gravity settling of cap materials in the water column, and may be depth-limited in their application. Granular cap materials can also be entrained in a water slurry, and carried to the cap site where they are discharged into the water column at the surface or at depth. These hydraulic methods offer the potential for a more precise placement, although the energy required for slurry transport may require dissipation to prevent resuspension of contaminated sediments.

Direct Mechanical Placement

If the area to be capped is nearshore and appropriate access is available, direct mechanical placement of capping material with land-based equipment can be considered. The reach of the equipment is the major limitation. The capping material would likely be trucked to the site with this method, so access for the trucks and traffic should be considered. Land-based methods might include backhoes, clamshells, end-dumping from trucks, spreading with dozers (during low water periods) etc. A cap with layers of gravel and geotextile was placed using land-based equipment (Figure 9) at a site on the Sheboygan River (Eleder 1992). At the GM

Figure 9. Land-based cap placement at Sheboygan River.

Superfund site in Massena, New York, sand and gravel cap materials were placed in the St. Lawrence River with a backhoe bucket from a work barge (Kenna, pers com).

Surface Discharge Using Conventional Dredging Equipment

Field experiences with dredged material capping operations in Long Island Sound and the New York Bight have shown that contaminated sediment mounds have been successfully capped with both mechanically-dredged material released from barges and with material released from hopper dredges (O'Conner and O'Conner 1983, Morton 1987). The surface release of mechanically-dredged material from barges results in a faster descent, tighter mound, and less water column dispersion as compared to surface discharge of hydraulically-dredged material from a pipeline, while surface release of hydraulically-dredged material from a hopper dredge has characteristics somewhat between barge and pipeline discharges.

Surface discharge of material from barges or hopper dredges would not normally be considered for in-situ capping unless special provisions were made for gradual release of the material and spreading the material over a larger area. Point discharges from hopper dredges or barges would normally not be applicable for in-situ capping of soft fine-grained contaminated sediments.

Spreading by Barge Movement

A layer of capping material can be spread or gradually built up using bottom-dump barges if provisions are made for controlled opening or movement of the barges. This can be accomplished by slowly opening a conventional split-hull barge over a 30 to 60 minute interval, depending on the size of the barge. Such techniques have been successfully used for controlled placement of predominantly coarse-grained, sandy capping materials at the Denny Way and other sites in Puget Sound (Sumeri 1989 and 1995). The gradual opening of the split-hull or multi compartmented barges allows the material to be released slowly from the barge in a sprinkling manner.

If two tugs are used to slowly move the barge sideways during the release, the material can be spread in a thin layer over a large area (Figure 10). Multiple barge loads are necessary to cap larger areas in an overlapping manner. The gradual release of fine-grained silts and clays mechanically loaded into barges may not be possible due to potential "bridging" action; that is, the cohesion of such materials may cause the entire bargeload to "bridge" the split-hull opening until a critical point is reached at which time the entire bargeload is released. If the water content of fine-grained material is high, as in the case of hydraulic filling of barges, the material may exit the barge in a matter of seconds as a dense slurry, even though the barge is only partially opened.

Spreading of thin layers of cap material over large areas can also be accomplished by gradually opening a conventional split-hull barge while underway by tow. This technique has been successfully used for capping operations at Eagle Harbor, WA (Nelson, Vanerberden and Schuldt 1994, Sumeri 1995). Use of barges for spreading cap materials may not be suitable in shallow water depths, because of the water depths needed for barge draft, door openings and consideration of the propeller wash from tug boats.

Figure 10. Spreading technique for capping by barge movement at Denny Way, Puget Sound.

Figure 11. Hydraulic washing of coarse sand, Eagle Harbor, Puget Sound.

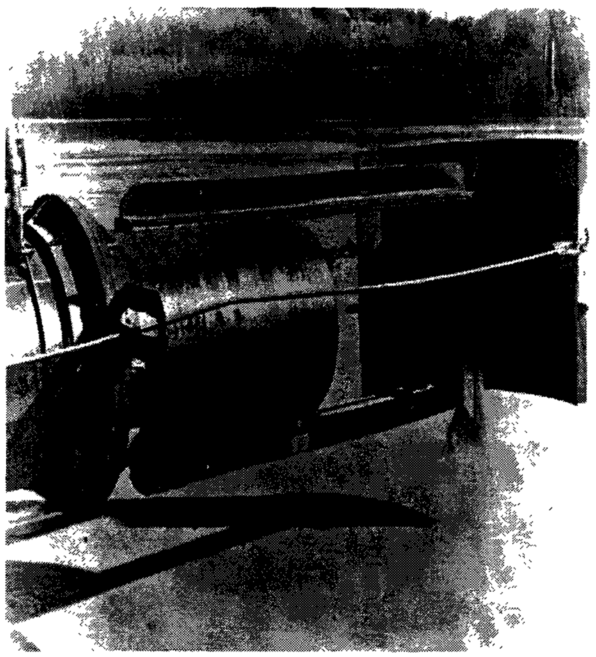


Figure 12. Spreader plate for hydraulic pipeline discharge.

Hydraulic Washing of Coarse Sand

Granular capping materials such as sand can be transported to a site in flat-topped barges and washed overboard with high-pressure hoses. Such an operation was used to cap a portion of the Eagle Harbor Superfund site, forming a cap layer of uniform thickness (Figure 11). This technique produces a gradual buildup of cap material, prevents any sudden discharge of a large volume of sand, and may be suitable for water depths as shallow as 10 feet or less.

Pipeline with Baffle Plate or Sand Box

Where granular cap material is excavated by a hydraulic dredge or transported in a slurry form through a pipeline, spreading placement capping operations can be easily accomplished with surface discharge by an energy dissipating device such as a baffle plate or sand box attached to the end of the pipeline. Hydraulic placement is well-suited to placement of thin layers over large surface areas.

A baffle plate (Figure 12), sometimes called an impingement or momentum plate, serves two functions. First, as the pipeline discharge strikes the plate, the discharge is sprayed in a radial fashion and the dscharge is allowed to fall vertically into the water column. The decrease in velocity reduces the potential of the discharge to erode material already in place. Second, the angle of the plate can be adjusted so that the momentum of the discharge exerts a force which can be used to swing the end of the floating pipeline in an arc. Such plates are commonly used in river dredging operations where material is deposited in thin layers in areas adjacent to the dredged channel (Elliot 1932). Such equipment can be used in capping operations to spread very thin layers of material over a large area, thereby gradually building up the required capping thickness.

A device called a "sand box" (Figure 13) serves a similar function. This device acts as a diffuser box with baffles and side boards to dissipate the energy of the discharge. The bottom and sides of the box are constructed as an open grid or with a pattern of holes so that the discharge is released through the entire box. The sand box was used to successfully apply a sand cap at the Simpson Kraft Tacoma site in Puget Sound (Sumeri 1989).

Submerged Diffuser

A submerged diffuser (Figure 14) can be used to provide additional control for submerged pipeline discharge (Neal, et al. 1978; and Palermo 1994). The diffuser consists of conical and radial sections joined to form the diffuser assembly, which is mounted to the end of the discharge pipeline. A small discharge barge is required to position the diffuser and pipeline vertically in the water column. By positioning the diffuser several feet above the bottom, the discharge is isolated from the upper water column. The diffuser design allows material to be radially discharged parallel to the bottom and with a reduced velocity. Movement of the discharge barge can serve to spread the discharge to cap larger areas. The diffuser can also be used with any hydraulic pipeline operation including hydraulic pipeline dredges, pump-out from hopper dredges, and reslurried pump-out from barges.

Sand Spreader Barge

Specialized equipment for hydraulic spreading of sand for capping has been used by the Japanese (Kikegawa 1983, Sanderson and McKnight 1986). This equipment employs the basic features of a hydraulic dredge with submerged discharge (Figure 15). Material is brought to the spreader by barge, where water is added to slurry the sand. The spreader then pumps the slurried sand through a submerged pipeline. A winch and anchoring system is used to swing the spreader from side to side and forward, thereby capping a large area.

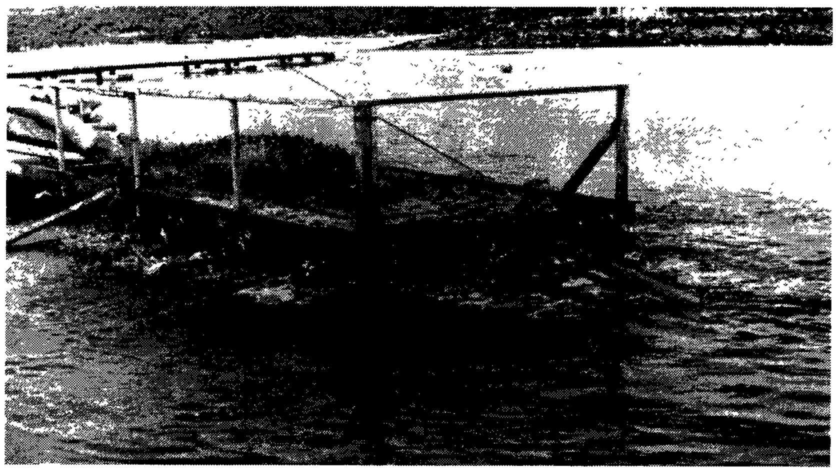


Figure 13. Spreader box or sand box for hydraulic pipeline discharge, Simpson Kraft Tacoma, Puget Sound

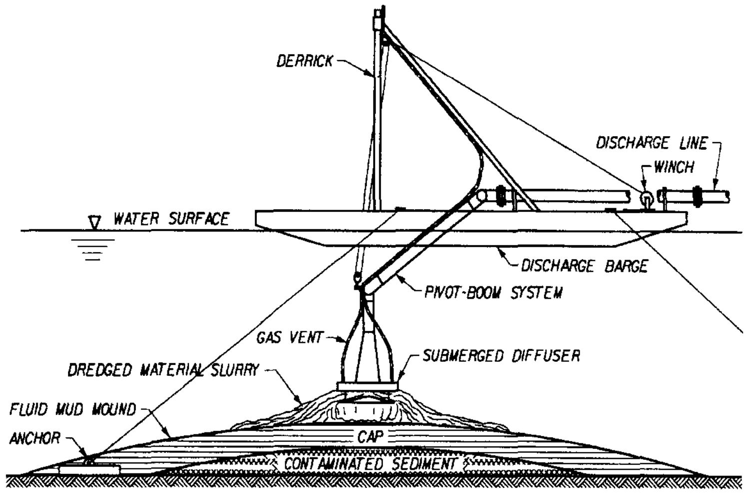


Figure 14. Submerged diffuser system, including the diffuser and discharge barge.

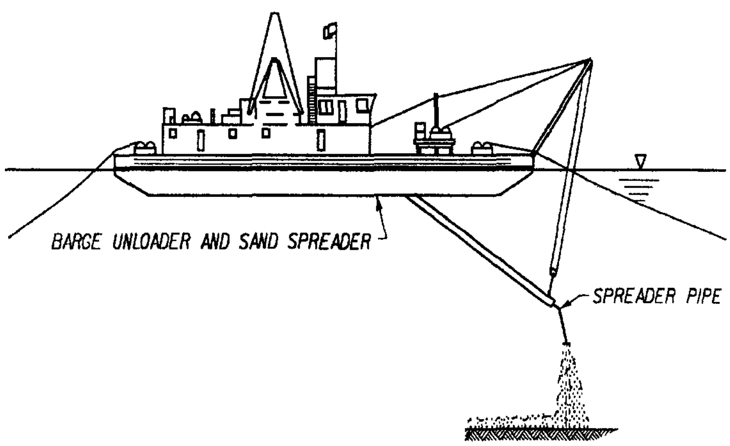


Figure 15. Hydraulic barge unloader and sand spreader barge (from Kikegawa 1983).

Gravity-fed Downpipe (Tremie)

Tremie equipment can be used for submerged discharge of either mechanically or hydraulically handled granular cap material. The equipment consists of a large-diameter conduit extending vertically from the surface through the water column to some point near or above the bottom. The conduit provides the desired isolation of the discharge from the upper water column and improved placement accuracy. However, because the conduit is a large-diameter straight vertical section, there is little reduction in momentum or impact energy over conventional surface discharge. The weight and rigid nature of the conduit requires a sound structural design and consideration of the forces due to currents and waves.

The Japanese have used tremie technology in the design of specialized conveyor barges for capping operations (Togashi 1983, Sanderson and McKnight 1986). This equipment consists of a tremie conduit attached to a barge equipped with a conveyor (Figure 16). The material is initially placed in the barge mechanically. The conveyor then mechanically feeds the material to the tremie conduit. A telescoping feature of the tremie allows placement at depths of up to approximately 40 feet. Anchor and winch systems are used to swing the barge from side to side and forward so that larger areas can be capped, similar to the sand spreader barge.

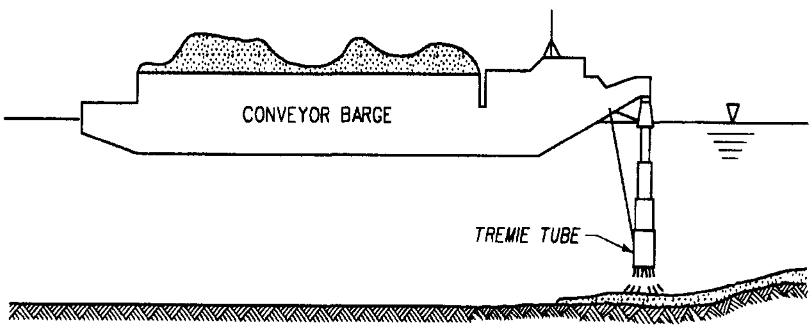


Figure 16. Conveyor unloading barge with tremie (from Togashi 1983).

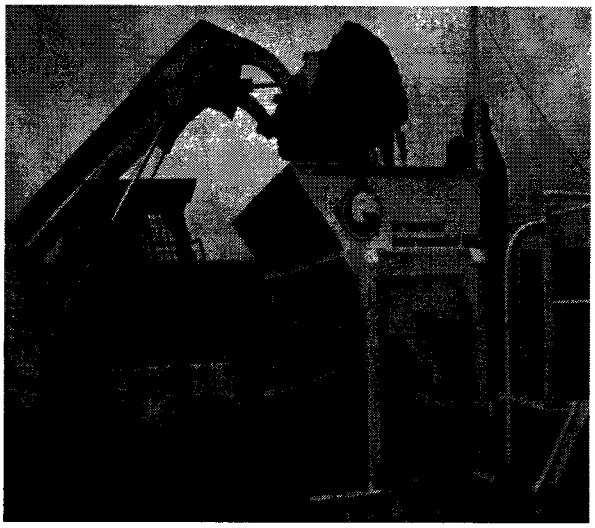


Figure 17. Tremie system employed at Hamilton Harbor.

A variation on the tremie system was used at the ISC demonstration in Hamilton Harbor (Zeman and Patterson 1996a and 1996b). Sand, piled on a flat-deck barge, was placed into a hopper using a small front-end loader. Inside the hopper, the sand was slurried and routed into a number of 6-inch diameter, PVC plastic tubes (Figure 17). The tubes extended 30-feet down, where the sand exited about 5-10 feet above the sediment. An anchor and winch system was used to position the barge.

Hopper Dredge Pump-down

Some hopper dredges have pump-out capability by which material from the hoppers is discharged like a conventional hydraulic pipeline dredge. In addition, some have further modifications that allow pumps to be reversed so that material is pumped down through the dredge's extended dragarms. Because of the expansion at the draghead, the result is similar to using a diffuser section. Pump-out depth is limited, however, to the maximum dredging depth, typically about 60-70 ft.

Equipment and Placement Techniques for Armoring Layers

Placement of armor layers on in-situ caps can apply techniques commonly used for purposes of streambank and shoreline erosion protection. The Sheboygan River ISC was constructed using stone (1-2 inch cobbles) for erosion protection. Armor stone was also used at GM Massena site. Although there is very little experience with armor stone at ISC applications, guidance from streambank and shoreline erosion protection (USACE 1990, 1994) may be applicable to some ISC sites.

Methods that have been used for placing armor stone include placing by hand; machine placing, such as from some form of bucket; and dumping from trucks and spreading by bulldozer. Placement of cobbles at the Sheboygan River ISC was by bucket from a land-based crane with support from workers wading in the shallow river (see Figure 18). Gravel-sized armor stone was placed onto the cap at Massena using a backhoe which was emptied a few feet above the cap. Where gravel, cobbles or small stone must be placed in deeper water, it may be possible to push them over the side of a flat deck barge or down a modified tremie. Potential effects with such methods that should be considered include the disruption or penetration of other cap components by the armor stone impact and the differential settling of graded stone. In order to reduce the force of impact it may be necessary to handle the stone by bucket and release it closer to the cap surface or pass the material down some type of slide towed behind the barge.

As noted in the previous chapter, because of the uncertainties associated with underwater placement of stone, the design thickness of the erosion component should be increased by 50 percent.

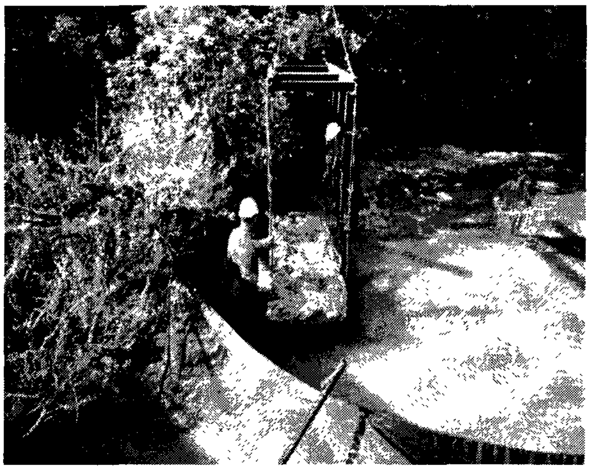


Figure 18. Stone placement at Sheboygan River.

Placement of Geosynthetic Fabrics and Membranes

Experience with placement of geosynthetic fabrics in subaqueous conditions is limited. At the Chicago Area Confined Disposal Facility (CDF), a plastic liner was pulled from a workbarge in sections which were heat welded together on the barge surface (Savage 1986). Cranes have been used to place geotubes prior to filling, directly lifting folded fabric tubes from working barges. Longer lengths of tube have been deployed from large reels mounted on barges. A membrane measuring 110 feet by 240 feet was placed as a temporary subaqueous cap at Manistique River by crane from a workbarge and anchored using concrete blocks (Hahnenberg, pers com). This operation required some manipulation of the cover by divers. A geotextile cap was deployed using a reel at Eitrheim Bay in Norway (Instanes 1994). Geosynthetic fabric was also used at Sheboygan, comprising two layers of the armoring.

Geosynthetics have been fabricated with anchors around the perimeter and other locations to simplify aquatic deployment. In most cases, the placement of geosynthetic fabrics at an ISC will require the coordinated actions of several crews and vessels. The material will have to be anchored quickly, especially where currents, waves or tidal conditions are subject to rapid changes.

Positioning Requirements

The ability to keep barges and work vessels in position may require considerable effort at sites subject to currents, waves and tidal movements. Where granular cap material is placed by surface discharge, barge spreading, or hydraulic washing, vessels can be positioned by tug boats or other support vessels. Spuds, long steel posts attached to some barges that are lowered into sediments to maintain position, may not be appropriate for use during cap placement, as the spuds might penetrate and damage the cap. Cables attached to large "deadman" anchors deployed outside the cap footprint have been used to position work barges for ISC construction at Hamilton Harbor (Zeman and Patterson 1996a and 1996b).

Once the equipment and placement techniques for the various cap components are selected, the needs for land-based surveys or navigation and positioning equipment and controls can be addressed. The survey or navigation controls must be adequate to insure that the cap can be placed (whether by land-based equipment, bargeload, hopperload or by pipeline) at the desired location in a consistently accurate manner. Global positioning equipment (GPS) using the differential mode (DGPS) was used at the Hamilton Harbor capping demonstration (Zeman and Patterson 1996b).

5 Monitoring and Management

Monitoring Requirements

A monitoring program should be required as a part of any capping project design. The main objectives of monitoring for ISC would normally be to insure that the cap is placed as intended and that the cap is performing the basic functions (physical isolation, sediment stabilization and chemical isolation) as required to meet the remedial objectives. Specific items or processes that may be monitored include cap integrity, thickness, and consolidation, the need for cap nourishment, benthic recolonization, and chemical migration potential.

Intensive monitoring is necessary at capping sites during and immediately after construction, followed by long-term monitoring at less frequent intervals. In all cases, the objectives of the monitoring effort and any management or additional remedial actions to be considered as a result of the monitoring should be clearly defined as a part of the overall project design. The cost and effort involved in long term monitoring and potential management actions should be evaluated as part of the initial feasibility study.

Design of Monitoring Programs and Plans

The design of monitoring programs for any project should follow a logical sequence of steps. Several excellent publications containing general guidance for monitoring in aquatic environments and specific guidance on physical and biological monitoring at aquatic sites for purposes of site designation/specification and for permit compliance are available (Marine Board 1990; Fredette et al. 1990a; Fredette et al. 1990b; and Pequegnat et al. 1990). These basic references should be consulted in developing appropriate monitoring plans for capping projects which suit the site and material specifics.

Fredette et al. (1990a) outlines five steps for developing a physical/biological monitoring program for open water dredged material disposal:

a. Designating site-specific monitoring objectives,

b. Identifying elements of the monitoring plan,

c. Predicting responses and developing testable hypotheses,

d. Designating sampling design and methods (to include selection of equipment and techniques),

e. Designating management options.

These steps should be applicable in developing a monitoring program for ISC projects.

Guidance for dredged material disposal and dredged material capping recommends that the monitoring program be multi-tiered (Palermo et al 1992; Fredette et al. 1986). Each tier has its own unacceptable environmental thresholds, null hypotheses, sampling design, and management options should the thresholds be exceeded. These are best determined by a multidisciplinary advisory group whose technical advice is sought in organizing and conducting the monitoring program. A sample tiered monitoring program developed for dredged material capping projects is outlined in Table 2, showing how a tiered monitoring program could be structured. This sample program is generally applicable to an in-situ capping project.

The monitoring program for in-situ capping does have some differences from those for dredged material capping. At Great Lakes areas of concern, or other locations where in-situ capping is conducted for purposes of sediment remediation, existing degraded conditions will have been well defined as the justification for remedial action. The remedial objectives should outline the desired impacts of the in-situ cap, which may include specific end points such as reductions in fish contamination levels, improved water quality conditions or the restoration of beneficial uses. The monitoring plans for ISC projects are therefore directed by the objectives of the remedial action.

Each of the steps in developing an in-situ capping monitoring program is discussed in more detail in the following paragraphs.

Monitoring Objectives

Monitoring can be generally considered in two phases; that occurring during and immediately after construction, and long-term monitoring. The objectives of monitoring at these two timeframes may be somewhat different.

The objectives of construction monitoring are to assure that the contractor follows the terms of contract plans and specifications in the placement of the ISC, to identify any changes in site conditions that may impact cap design or performance and modify the design or construction techniques as necessary.

The objectives of long-term monitoring at an in-situ cap are rooted in the remedial objectives. For instance, if the primary objective of sediment remediation was to reduce the contaminant body burden in fish, the monitoring program might be devised to measure the performance of the cap in physical and chemical isolation to determine if that objective had been met. If the cap was designed primarily to stabilize the contaminated sediments, an entirely different monitoring program might be developed.

Table 2. Sample Tiered Monitoring Program for dredged material capping				
Monitoring Program	Monitoring Frequency	Threshold	Management (Threshold Not Exceeded)	Options (Threshold Exceeded)
Define chemical baseline conditions.				
Tier I *Bathymetery *Subboottom profiles *Side scan sonar *Surface grab samples *Cores *Settling plates *Water samples	Post Placement, Annual	*Mound approaches being navigation hazard *Cap thickness decreases slightly *Contaminant exceeds limit in sediment or water sample	*Continue to monitor at same level *Reduce monitoring level *Stop monitoring	*Go to next Tier *Increase cap thickness
Tier II *Bathymetry *Subbottom profiles *Side scan sonar *Sediment profile cam. *Cores *Water samples *Settling Plates *Consolidation instrumentation *Tissue samples	Quarterly to Semi Annually	*Cap thick decreases significantly *Contaminant exceeds limit in sediment or water sample	*Continue to monitor at same level *Reduce monitoring level	*Go to next Tier *Replace cap material *Increase cap thickness *Place armor layer
Tier III *Bathymetery *Subbottom profiles *Sediment profile camera *Surface grab samples *Cores *Water samples *Tissue samples	Monthly to Semi Annual	*Cap thick decreases significantly *Contaminant exceeds limit in sediment or water sample *Contaminant exceeds limit in tissue	*Continue to monitor at same level *Reduce monitor level	*Replace cap material *Increase cap thickness *Change cap sediment *Place armor layer *Redredge and remove

Note: This is only an example of a possible monitoring program. Each monitoring program is site specific.

Aside from the evaluation of cap functional performance, another important objective of long-term monitoring is to track the physical integrity of the cap under variable hydrodynamic conditions and any man-made stresses. Cap designs are based on conditions and forces with a significant degree of uncertainty, and long-term monitoring is needed to check the reasonableness of those assumptions and determine how the cap responds to unforeseen conditions. Long-term monitoring is also used to guide cap maintenance plans and modify future monitoring activities.

Construction Monitoring

Cap Materials

The elements of construction monitoring are typically defined in the quality assurance plan for the remedial construction contract, and may be conducted by the construction contractor, subcontractors and/or by independent agencies or contractors. The contract documents will typically define criteria or standards for all capping materials. Samples of materials provided by vendors and suppliers will be analyzed periodically to assure that they meet criteria specified in the contract, such as:

- acceptable grain size distribution of granular materials
- maximum/minimum levels of TOC in granular materials
- geologic characteristics of armor stone
- strength or puncture resistance of geotextiles

Granular materials and geosynthetics should be analyzed using accepted laboratory methods (USACE 1970; ASTM 1992).

Monitoring of granular cap materials will require inspections or the collection of samples at various places and times, including:

- inspection/certification of quarry by geologist
- laboratory analysis of samples collected at quarry
- laboratory analysis of samples collected after placement

Quarry inspection/certification is important to ensure that armor stone is cut from rock with no argillaceous inclusions or seams, which tend to swell when submerged (Johnson, pers com). Samples collected at the quarry are typically analyzed for grain size distribution (and other parameters as necessary) for compliance with contract specifications.

Analysis of granular materials following placement is especially important for in-situ caps. Differential settling of granular materials during placement has the potential to cause segregation of materials by grain size. Fine-grained or less dense materials may be transported off-site during placement in waters with even small currents. Some cap placement methods can reduce these effects. However, the collection and analysis of samples of granular materials, post-placement, is the only way to determine if the cap, as constructed, meets the contract requirements.

Granular cap materials (post placement) should be sampled as cores. Grab samplers are not recommended because they don't maintain vertical integrity and may result in a loss of fines. Gravity coring devices are generally suitable for deeper water than than typical of most ISC sites, and may not penetrate adequately except where the cap is more fine-grained and poorly consolidated. Vibracore samplers, as used to monitor cap thickness at Hamilton Harbor (Zeman and Patterson 1996b) can penetrate sand and finer materials. For coarse-grained cap materials, divers may also be an effective means of collecting representative cores during construction. A variety of sediment coring techniques are available (Mudroch and MacKnight 1991; USEPA/NCD 1994).

Construction Methods

Depending on how the construction contract is advertised and awarded, the methods for placement may be specifically defined or left to the contractor's selection so long as certain performance goals and criteria are met. Construction performance criteria for ISC projects might include:

- maximum/minimum tolerance for cap placement (laterally)
- maximum/minimum tolerance for cap component thickness
- maximum tolerance for "mixing" of sediment and cap material
- maximum levels of sediment resuspension
- maximum levels of sediment contaminants on cap surface following construction

Appropriate techniques for monitoring cap placement include bathymetric surveys, sediment core sampling, and sediment profiling camera. For some sites, visual observation in relatively shallow waters (i.e., up to 20ft. at GM Massena site) or diver observations may also be useful.

Precision bathymetric surveys are perhaps the most critical monitoring tool for capping projects. Such surveys allow determination of the location, size, and thickness of the contaminated material deposit and cap. For ISC, a series of surveys should be taken immediately prior to placement of the cap, periodically during placement, and at the completion of placement. The differences in bathymetry as measured by the consecutive surveys yields the location and thickness of the deposits. Contractors will probably make bathymetric measurements on a daily basis to keep track of their progress and plan work for the following days.

Lillycrop et al. (1991) discusses tidal elevations, bathymetry measurements, and equipment capabilities. Acoustic instruments such as depth sounders (bottom elevations accurate to +/- 0.6 ft under favorable conditions), side scan sonar (mapping of areal extent of sediment and bedforms), and subbottom profilers (measures internal mound and seafloor structure) are used for these physical measurements. Survey track spacing can be 50 to 200 ft depending on the areal coverage of the cap. Multi-beam depth sounding systems provide 100 percent coverage of the bottom. Their additional expense may be justified for some projects.

The attainable accuracy of bathymetric surveys must be considered and limit the area and thickness of the deposit which can be detected. Limits of accuracy are governed by a variety of factors which include accuracy of positioning systems, water depth, wave climate, etc. Engineer Manual EM 1110-2-1003 contains additional information on hydrographic survey equipment and techniques.

The interpretation of bathymetric data needs to be coupled with an understanding of consolidation processes. Consolidation that occurs in the cap, contaminated sediment, and the original base material can result in substantial changes in bathymetry (Silva et al. 1991, Poindexter-Rollings 1990) that could mistakenly be considered as an indication of inadequate cap thickness. The ability to measure or predict consolidation can limit the utilization of bathymetric data for monitoring the total cap thickness. A schematic of a settling plate used for monitoring cap consolidation is shown in Figure 19. This technique can provide a means of measuring the consolidation of the contaminated sediments and underlying bed material

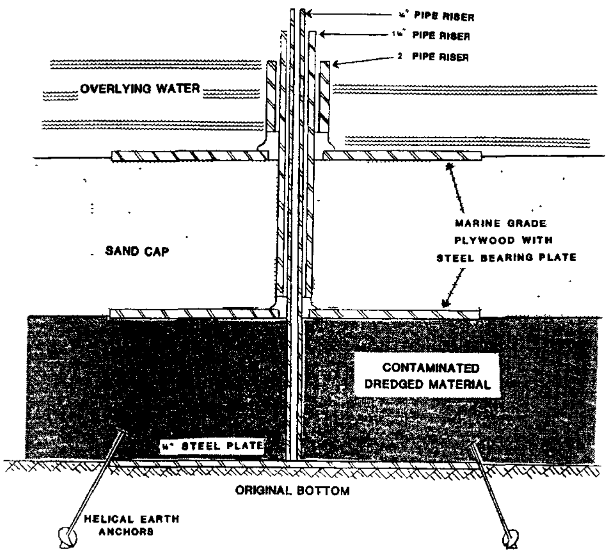


Figure 19. Schematic of a settling plate used for monitoring cap consolidation.

(together), which enables bathymetric data to be used to monitor total cap thickness and to confirn predictions of sediment consolidation which are controlling short-term advective flux. It should be noted that the installation of settling plates can be difficult and some cap placement methods can easily disturb/destroy these plates.

The Sediment Profiling Camera (SPC) is a recently developed tool which can be used to detect thin layering within sediment profiles. The SPC is an instrument which is lowered to the bottom and is activated to obtain an image of sediment layering and benthic activity by penetrating to a depth of 15-20 cm (Figure 20). SPC can be used to monitor the thickness of granular cap components and examine the "mixing" of granular cap material and contaminated sediments. As with bathymetric surveys, the SPC approach also has its limits. The depth of penetration limits the thickness which can be viewed. The SPC was designed for penetration of relatively soft cap materials, would not be appropriate for an armored cap (unless the armor layer was removed by divers), and may be difficult to push more than a few inches into a cap of medium or coarse sand.

The thickness of granular cap components and the presence of sediment contaminants in any component can be determined from cores or borings of the ISC. In general, a core should sample the full thickness of a cap and the underlying contaminated material. The selection of boring techniques may be limited by site conditions and the cap design.

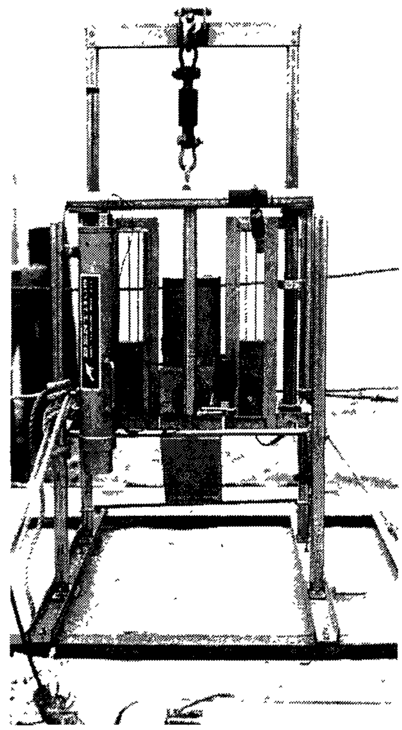


Figure 20. Illustration of Sediment Profiling Camera.

Contract criteria for limiting sediment resuspension during ISC placement may require monitoring. At the Hamilton Harbor capping demonstration, water samples were collected around the placement operation and analyzed for total suspended solids. The color of particulates on the filter paper indicated that the suspended solids in the plume around the capping operation were fines washed off the sand during placement, rather than resuspended bottom sediments (Zeman and Patterson 1996a). At the Wyckoff/Eagle Harbor Superfund site, water samples were collected during cap placement and analyzed for dissolved oxygen, total suspended solids, ammonia and total sulfides (Nelson, Vanerberden, and Schuldt 1994). In addition, sediment traps were deployed near the ISC site to collect and measure resuspended bottom sediments.

Navigation and positioning equipment are needed to accurately locate sampling stations or survey tracks in the disposal site area. State of the art positioning systems are recommended for offshore sites. Land-based survey techniques may be acceptable for sites near shore. Taut wired buoys are also excellent for marking disposal locations and as a reference for sampling station locations.

Cap Performance Monitoring

Monitoring that is conducted to evaluate the performance of the ISC in regard to specific cap functions can be conducted on a short- or long-term basis. Some elements of a monitoring program, such as those evaluate the consolidation-induced advection) may only occur during construction and weeks to months afterwards. Other elements of a monitoring program that might be conducted for a longer, but finite period (a few years) might include measurements of changes in flow patterns and erosion at adjacent and downstream locations. Still other elements of a monitoring program may be required to be conducted indefinitely, but at a diminishing frequency. Methods for monitoring each of the basic cap functions (stabilizatyion, physical isolation, and chemical isolation) are discussed in the following sections.

Sediment Stabilization

To evaluate the performance of the ISC in sediment stabilization, a monitoring program must demonstrate that the stabilization component is intact and the cap completely covers the contaminated sediment deposit. The elements of such a monitoring program might include measurements of:

- bathymetry of the capped area
- cap/component thickness
- component integrity

Methods for measuring cap bathymetry and the thickness of cap components are the same as discussed for construction monitoring. Component integrity refers to the physical integrity of the stabilization component. Armor stone are subject to cracking and weathering. After many years, even 7-inch armor stone can be reduced to gravel and monitoring is needed to measure the character, as well as the thickness of the stabilization component.

The frequency of measurements in a long-term monitoring plan will vary with site conditions and cap design. One approach is a time-based schedule, where monitoring occurs at a fixed or expanding frequency. Another approach is an event-based schedule, where monitoring occurs only after significant erosion events (i.e., storms, floods, etc.). The design of an ISC erosion protection component is based on predictions of one or more hydrodynamic processes. The design presumes that an event of some magnitude and recurrence interval will be able to dislodge part of the cap, and that repair or replenishment of the cap will be needed following such an event. Monitoring after erosion events is preferable, since it is after such events that emergency maintenance or repair of the cap is more likely to be needed. In addition, the development of monitoring data after events of known magnitude will enable the predictive methods used in the design to be "fine-tuned" so that the magnitude of events capable of causing major damage to the cap might be predicted more accurately. As the predictive methods are "fine-tuned", monitoring can be scheduled to occur only after events capable of causing damage to the cap.

An event-based monitoring program requires the ability to perform monitoring with little advance notice. It also requires some means of measuring the event that triggers the monitoring, such as the flood stage at a river gage, measured wave height at recording station, or meteorological conditions at a recording station (e.g., the amount of precipitation or wind velocity from a certain direction over a specified period of time). Flood stages are recorded at a number of river gages operated by the U.S. Geological Survey, USACE and some state and local agencies. The National Oceanic and Atmospheric Administration maintains nine wave rider buoys on the Great Lakes during the navigation season which transmit meteorologic and wave conditions in real time. The installation of a recording gage should be considered at ISC sites in order to get the most representative and dependable source of information.

Physical Isolation

To evaluate the performance of the ISC in physical isolation, a monitoring program must demonstrate that the cap is intact, covers the contaminated sediment deposit, prevents the physical loss of contaminants, and that benthos are not able to penetrate the cap. The elements of such a monitoring program might include measurements of:

- bathymetry of the capped area
- cap/component thickness
- benthos colonizing the cap
- sediment traps

The methods for measuring bathymetry and cap/component thickness are described above.

Benthic organisms colonizing the cap may be surveyed to determine if organisms capable of burrowing through the physical isolation component are present. Benthic sampling devices include trawls, drags, box corers, and grab samplers. Trawls and drags are qualitative samplers which collect samples at the bottom interface, and therefore are good for collecting epifauna and shallow infauna (top few centimeters). Quantitative samples are usually obtained with box corers and grab samplers. Generally these samplers collect material representing 0.02 to 0.5 m^2 of surface area and sediment depths of 5 to 100 cm. Divers may be needed for the collection of samples from caps with coarse material or an armor layer.

An armor layer rock coverage can be monitored by divers or remote sensing techniques. Sonar and ground penetrating radar may assist in evaluating the presence of armor stone and tracking changes in the armor layer elevation. Erosion pins, typically constructed of rebar, can be used to measure changes in the relative elevation of the top of the armor stone. An erosion pin mounted on a steel plate placed at a level under the cap may provide a more reliable relative vertical reference point. Painted rock studies have been used to measure the transport of cobbles in high energy streams and could be employed to monitor cap stone integrity. Uniquely marked stones of the same size as the armor stone may assist in monitoring off-site losses of stone. Recently Rosenfeld, et al (1996) has proposed to use passive radio transponders to track stone movement in open channel studies. Other researchers have used magnetic tracers, radioactive tracers and active radio transponders to track the movement of rock and gravels.

Chemical Isolation

In order to evaluate the chemical isolation function of an in-situ cap, the long-term migration of contaminants must be measured. This is likely the most difficult element of a monitoring program to perform because the predicted rates of long term chemical flux are so low, the variability in physical and chemical properties of the capped sediments are so great, and the logistical problems of collecting representative samples at an underwater cap are so numerous. Methods for measuring the movement of contaminants through an ISC are in the early stages of development. Predictive models (see Appendix B) suggest that available techniques should not be able to discern a flux, other than the short-term flux during consolidation, unless there is a significant advective movement (groundwater) through the cap.

Methods for measuring contaminant migration that have been used or considered at in-situ caps include chemical analysis of cap materials, collection chambers, solvent-filled bags, and caged fish. Methods that rely on samples of water, fish or bioaccumulative materials collected at the surface of the cap are less likely to be useful in tracking contaminant migration than those which collect samples within the cap.

Chemical analysis of cap materials may used to detect any mixing of contaminated sediments with these materials during placement, and has been used as an indicator of chemical migration at dredged material caps (Sumeri et al 1994).

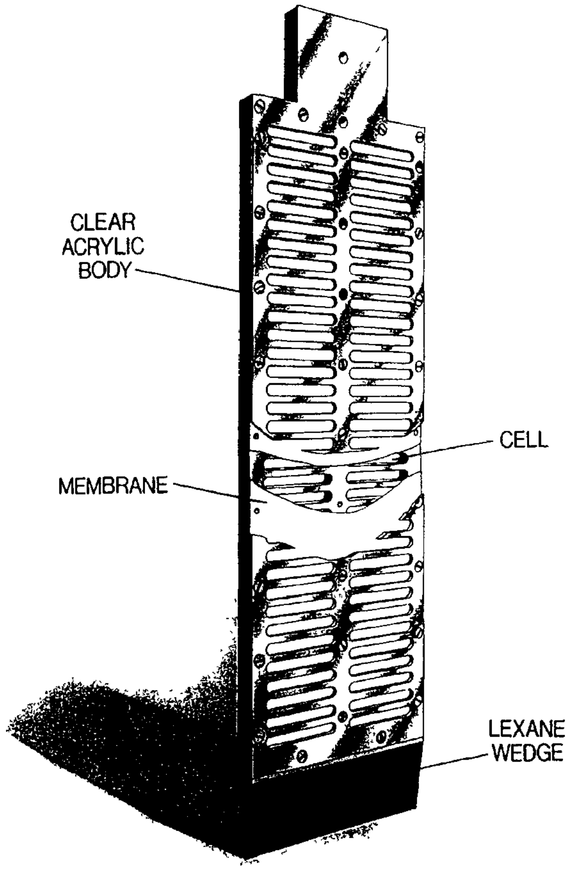


Figure 21. Semi-permeable bags or "peepers" filled with an organic solvent used for monitoring the levels of hydrophobic contaminants in sediment pore water.

Small, semi-permeable bags filled with doubly distilled water have been used for monitoring the levels of nutrients and metals in sediment pore water. These devices, known as "peepers", have been adapted for use, as shown in Figure 21, at the Hamilton Harbor capping demonstration (Rosa and Azcue 1993; Azcue, Rosa, and Lawson 1996; Zeman and Patterson 1996b).

A seepage meter considered for the Manistique Harbor ISC employed a 55-gallon drum that had been cut in half, with the open end inserted into the cap surface (Figure 22). Water seeping upward from the cap into the drum would be channeled into a collection vessel which could be removed/replaced without disturbing the cap (Blasland, Bouck & Lee 1995). Such a monitoring device has not yet been employed at an ISC site.

Figure 22. Seepage meter used to measure groundwater flow.

Other Monitoring Methods

The elements of long-term monitoring that are directed by the remedial objectives are not always measured immediately at the ISC. The impacts of sediment contamination may be over a large area, and the effects of remediation may need to be evaluated at the same scale. For example, if the remedial objective is to reduce the body burden of a contaminant in fish, this might be best evaluated using the same monitoring approach used to define the problem in the first place (e.g., periodic collection of fish at specific locations in a river/lake or collection of selected fish tissues at fish cleaning stations).

Management Actions

An in-situ cap is not an operating facility in the sense that a treatment facility or CDF is operated. Nonetheless, an ISC does have some operational practices and controls that may need to be implemented in order to assure that the in-situ cap functions as designed and remains intact. These considerations may include planned maintenance of the cap, restrictions on uses of the waterway at the capping site and other institutional controls. The management plan for the ISC must also be adjusted as monitoring data indicates.

During Construction

The results of monitoring conducted during cap placement need to be evaluated rapidly so that problems with materials or placement methods can be identified in time to effect the necessary changes. For this reason, monitoring techniques that can generate results in real time, or with a rapid turnaround are preferable. The construction contractor is typically responsible for proposing actions to remedy any shortcomings in cap materials or placement methods. Because of the difficulty in fixing deficient material or placement methods after the fact, it may be appropriate to construct a small portion of ISC as a "test plot" before proceeding with the larger capped area(s).

Routine Maintenance & Protection

Routine cap maintenance generally is limited to the repair or replenishment of erosion protection component material. The design of some dredged material caps includes a thickness of granular material that is expected to be eroded during storm events of a known magnitude or recurrence interval. For such a design, maintenance can be scheduled or planned for in advance. This type of erosion control is not appropriate unless there is a dependable source of capping material readily available. For an ISC, the ability to detect and quickly respond to a loss of the erosion protection layer should also be taken into consideration. On the Great Lakes, seasonal limitations, such as ice formation or closure of navigation structures (locks), can limit the ability to monitor in-situ caps after a significant erosion event and respond with maintenance if needed.

The long-term integrity of a cap requires that conditions which affect erosive forces are not changed (for the worse). For instance, after a cap is constructed, the removal of an upstream dam or modification to a breakwater could have significant impacts on the current- or wave-induced erosion at the cap. The “owner” of the cap must be capable of protecting its integrity from man-made activities.

Aside from erosion caused by natural phenomena, the greatest threat to the integrity of an ISC is from navigational activity. As discussed in Chapter 3, and in Appendix A, the erosive forces created by propellers of ships, tug boats, and even recreational watercraft can be quite powerful, especially where water depths are reduced by the presence of an in-situ cap. Other activities, such as bottom drag fishing, direct hull contact, and anchoring create bottom stresses that can damage a cap (Truitt 1987a). An in-situ cap, particularly one with an armor layer, may be attractive to some fish, and consequently may be attractive to fisherman.

In order to inform navigation users of the presence of the ISC, navigation maps, mariners guides, and local land-use documents should be updated to show the presence of the cap and any use restrictions. Information about the cap and restrictions might also be posted at boat launch areas, bait shops, and provided with fishing licenses. Signs should be posted at prominent locations near the cap, and marker buoys deployed where appropriate. Active local public education programs on the presence and purpose of the ISC may improve voluntary compliance.

The ability to enforce restrictions on navigation activities in and around ISC sites should be weighed in considering the overall feasibility of capping. Restrictions that are codified as local or state statutes are more likely to be adhered to than voluntary ones. For instance, development of waterfront facilities, marinas, and docks that might increase navigation in proximity to the cap could be restricted in State Coastal Zone Management plans or local zoning ordinances. Enforcement of any use restrictions in the waterway may require considerable resources. The costs and ability to enforce use restrictions should be considered in the evaluation of the feasibility of ISC.

Repair & Modification

If monitoring of cap performance indicates that one or more cap functions are not being met, options for modifying the cap design may or may not be available. If monitoring shows that the stabilization component is being eroded by events of lesser magnitude than planned, or the erosive energy at the capping site was underestimated, eroded material may be replaced with larger stone. If monitoring indicates that benthic organisms are penetrating the cap in significant numbers, a layer of sand or gravel might be placed on top of the cap to inhibit benthic colonization. These types of management options are feasible where additional cap thickness, and the resulting decrease in water depths at the site do not conflict with other waterway uses. Where an ISC has been closely designed to a thickness that will not limit waterway use (i.e., recreational or commercial navigation), the options for modifying a cap design after construction may be very limited.

When the cap design is performing as expected, monitoring results can be used to optimize maintenance monitoring activities. If there is a failure of the ISC design to meet remedial objectives (e.g., unanticipated advection of groundwater through the cap causes unacceptable contaminant migration), removal may be the only management alternative available. Because of the additional cost of removing, treating and/or disposing of cap materials in addition to contaminated sediments, in-situ caps should only be proposed where the performance of cap design functions required to meet remedial objectives can be assured.

6 Summary

This document presents technical guidance for planning and design of in-situ subaqueous capping projects. The guidance is summarized as follows:

a. In-Situ Capping (ISC) refers to placement of a covering or cap over an in-situ deposit of contaminated sediment. The cap may be constructed of clean sediments, sand, gravel, or may involve a more complex design with geotextiles, liners and multiple layers.

b. ISC is one of many options for the remediation contaminated sediments, which should be considered using the full suite of guidance development under the ARCS Program.

c. An ISC operation must be treated as an engineered project with carefully considered design, construction, and monitoring to ensure that the design is adequate.

d. There is a strong interdependence between all components of the design for a capping project. By following an efficient sequence of activities for design, unnecessary data collection and evaluations can be avoided and a fully integrated design is obtained.

e. The basic criteria for a successful capping operation is simply that the cap components required to isolate the contaminated material from the environment be successfully placed and maintained.

f. The contaminated sediment to be capped must be characterized as part of the project design. The capping materials (granular sediments or other materials) must also be characterized.

g. The evaluation of the site is a critical requirement for an ISC capping design. Bathymetry, currents, water depths, waterway uses, bottom sediment characteristics, potential groundwater flow, and operational requirements must be evaluated.

h. A number of different equipment types and placement techniques can be considered for ISC operations. Conventional discharge of granular capping material from barges and hydraulically dredged material from hopper dredges or pipelines can be considered as well as use of diffusers, tremies, and other equipment needed for submerged discharge. Controlled discharge and movement of barges and use of spreader plates or boxes with hydraulic pipelines can be considered for spreading a capping layer over a larger area. Specialized equipment may be needed for placement of geotextile or membrane components. Armor stone may be placed using conventional placement methods for riprap. Compatibility between equipment and placement technique for contaminated and capping material is essential for any capping operation.

i. Accurate navigation and precise positioning during material placement are required for capping operations. State-of-the-art equipment and techniques must be employed to assure accurate placement to the extent deemed necessary. Diligent inspection of operations to insure compliance with specifications is essential.

j. The composition and dimensions (thickness) of the components of a cap can be referred to as the cap design. This design must perform one or more of the three functions of a cap (physical isolation, stabilize sediment, and reduce flux of dissolved contaminants). The design must also be compatible with available construction and placement techniques.

k. Caps composed of multiple layers of granular materials as well as other materials such as armor stone or geotextiles are often considered for ISC projects, and the in-situ cap design cannot always be developed in terms of cap material thickness alone.

l. Monitoring of capped sites is required during and following placement of the contaminated and capping material to insure that an effective cap has been constructed and to insure that the cap as constructed is effective in isolating the contaminants and that long term integrity of the cap is maintained. Design of monitoring programs must be logically developed, prospective in nature, and tiered with each tier having its own thresholds, null hypotheses, sampling design, and management responses based on exceedance of predetermined thresholds.

m. Management of an ISC requires the routine maintenance of the cap, protecting cap integrity through enforcement of waterway use restrictions, repair and modification of the cap as needed to address changing conditions or design deficiencies indicated by monitoring data.

Recommendations

As more designs are completed and additional field experience is gained, the technical guidelines in this report should be refined and expanded. Additional research is also recommended to develop improved tools for capping evaluations. Specific recommendations for further research are summarized as follows:

a. Refine and verify models that predict long-term erosion of caps.

b. Refine existing estimates of resuspension of contaminated material during cap placement. This work will assist in determining the costs vs. benefits of "sprinkling" cap material versus conventional bottom dumping of cap material.

c. Develop engineering guidance on acceptable rates and methods of application of capping material over contaminated material of varying density and shear strength. These techniques should consider the geotechnical behavior related to displacement and mixing of contaminated and capping sediments and resistance of the sediments to bearing failure. Extend the investigation to include penetration of dense (e.g., rock) cap material into contaminated material or other cap layers.

d. Refine existing models for prediction of cap and sediment consolidation. This effort will likely require developing or refining instrumentation for in situ geotechnical measurements.

e. Develop predictive tools for evaluation of long term cap integrity, considering chemical migration via advection, bioturbation, and diffusion. Both analytical and modeling approaches should be considered.

f. Conduct laboratory and field verification studies of long-term cap integrity. Laboratory approaches should include refinement of existing cap effectiveness tests. Field studies should include periodic monitoring and sampling of capped sites to include analysis of core samples.

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Guidance for In-Situ Subaqueous Capping of Contaminated Sediments: Appendix A: Armor Layer Design

by

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Appendix A: Armor Layer Design

If an evaluation of cap erosion indicates that the capping material will not be sufficiently resistant to erosion, an armor layer can be considered. Such an armor layer would be incorporated into the cap design and would replace any previously determined cap sediment thickness component for erosion.

A design of capping armor layers has been developed as a part of the EPA ARCS program and is presented in this Appendix. This section provides guidance for the design of armoring to ensure the long term stability or integrity of the cap. Caps might be subjected to a variety of physical stresses such as river or tidal currents, wind wave generated currents, ice and debris scour, or propeller wash in navigation channels. Preliminary technical guidance is provided on the hydraulic design of in-situ capping/armoring of contaminated sediments with riprap. Factors pertinent to flood flows, navigation effects, and wind wave induced currents are presented and then formulas and sample calculations are provided. Less predictable forces on ISC such as scouring from ice and debris, flow from velocities generated by channel blockages such as ice dams, or massive bank failure are not evaluated by this analysis. Designers of ISC should consider the significance of these forces and potential effects in the evaluation of the feasibility of ISC.

Filter Design

Filters provide an interface between the riprap layer and the protected material and are an essential element for protecting contaminated sediments, particularly poorly consolidated sediments. Filters prevent turbulence and groundwater from moving sediments through the revetment. Filters serve as foundations or load distributors for the riprap for poorly consolidated material which is typical of many contaminated sediments. Filters can be either geotextile, granular, or a combination of the two. Granular filters are generally more expensive but have been shown to provide long term performance. Geotextile filters are less expensive but have not been around long enough to completely evaluate the potential for clogging of the geotextile over long time periods. Problems can occur with geotextiles if the permeability factor is too low. Gas and advective ground water may displace a cap that has too low a permeability. Uncertainty in design should err on the side of providing too large a permeability. A sand layer on top of fine-grained sediments may be required prior to placement of either a granular or geotextile filter. A bedding layer of granular material (sand or gravel) may be placed on top of the geotextile to prevent damage during placement of the riprap. Guidance on design of geotextile filters can be found in Pilarczyk (1984) and PIANC (1987). In determining the stability of intermediate granular layers subjected to velocity forces, the Worman (1989) equation is

$$\frac{V^2}{gS} = C\,\frac{d_{85}}{D_{15}} \tag{1}$$

Where V is the mean flow velocity above the granular layer, g is gravity, S is the granular layer thickness, C is a coefficient that varies with the uniformity of the granular layer, d_{85} is the 85 percent passing size of the base material, and D_{15} is the 15 percent passing size of the granular material. Based on experimental work by Manamperi (1952), the coefficient for uniform riprap having D_{85}/D_{15} = 1.3 is C = 24 and for Manamperi's graded riprap having D_{85}/D_{15} = 6.7, C = 10. D_{85} is the 85 percent passing size of the riprap. For relatively uniform riprap having D_{85}/D_{15} = 1.3, V = 7 ft/sec, S = 1.0 ft, and D_{15} = 5 in., the required d_{85} of the intermediate granular layer is 0.32" or 8.1 mm. Additional guidance on design of granular filters can be found in Pilarczyk (1984), EM 1110-2-1901 (USACE 1986), and EM 1110-2-2300 (USACE 1982).

Gradation and layer thickness considerations

Both riprap gradation and layer thickness play a significant role in defining the stability of the armor layer. The gradation of rock produced by quarries across the country varies widely and standardized gradations have not been widely adopted in the U.S. The gradations shown in Table A1 are taken from EM 1110-2-1601 and give a maximum or upper limit and a minimum or lower limit at the 100, 50, and 15 percent sizes. Any gradation falling between the maximum and minimum limits is acceptable.

Minimum layer thickness requirements vary depending on the type of attack on the revetment. For flood flows, the minimum layer thickness is $1D_{100}$(max) or $1.5D_{50}$(max), whichever is greater. D_{100} is the riprap size of which 100 percent is smaller, i.e. the largest riprap size. The (max) refers to the upper or maximum limit curve. For propeller wash where turbulence is much greater than flood flows, the minimum layer thickness is $1.5D_{100}$(max) or $2D_{50}$(max), whichever is greater.

Placement and Limits of Coverage

Placement of riprap and filters in dry conditions generally presents no problems and the minimum layer thickness given above is applicable. Underwater placement presents uncertainties with even coverage of stone and a 50 percent increase in granular filter and riprap volume is required. Placement of geotextiles in shallow depths and low velocity can be accomplished as described in the Appendix C case studies, by the method shown in the main body of this report or by attaching the fabric to a framework and lowering the framework into position prior to stone placement. Underwater placement in moderate to high velocity (> 2 ft/sec) would present significant problems with geotextile placement. With a granular filter, a diver may be required to insure adequate coverage in deep placement conditions.

Table A1. Gradations For Specific Stone Weight of 165 LB/FT^3,[a] From USACE (1994)

D_{100}	Limits of Stone Weight (lb) for Percentage Lighter by Weight[b]						D_{50}
(Max)	100		50		15		(Min)
(in)	Max	Min	Max	Min	Max	Min	(ft)
9	36	15	11	7	5	2	0.43
12	86	35	26	17	13	5	0.58
15	169	67	50	34	25	11	0.73
18	292	117	86	58	43	18	0.88
21	463	185	137	93	69	29	1.02
24	691	276	205	135	102	43	1.07

[a] 1 lb/ft^3 = 16.018kg/m^3

[b] Stone weight limit data from USACE (1994). Relationship between diameter and weight is based on shape of a sphere.

The limits of protection and a typical cross-section are shown in Figure A1. Riprap protection should extend 5 times the thickness of the riprap protection beyond the edge of the contaminated material. The thickness of the edge extension should be 1.5 times the riprap thickness to allow for scour along the edges of the protection. On the outer bank of channel bendways, significant scour can be expected at the toe of the bank during flood flows. For contaminated sites on the outer bank of bendways, refer to EM 1110-2-1601 (USACE 1994) for design of toe scour protection. If contaminated sediments on the bed are adjacent to the toe of the bank, protection should not only cover the bed sediments, but should also extend partially up the side slope.

Stone Sizing for Flood Flows

Waterways that do not experience significant navigation may require protection for the maximum flood flow or storm velocities near the capped sediments for the required life of the project. At sites without navigation having flow velocities typically found in flood control channels, the riprap protection requirements should follow the guidance provided in Chapter 3 of the EM 1110-2-1601 entitled "Hydraulic Design of Flood Control Channels" (USACE 1994). The procedures for riprap protection in EM 1110-2-1601 should be used for design guidance and revised as deemed necessary to provide an adequate but practical protection for specific project conditions. Both the guidance presented herein and EM 1110-2-1601 will be useful in evaluating design specifications of riprap protection for capping projects.

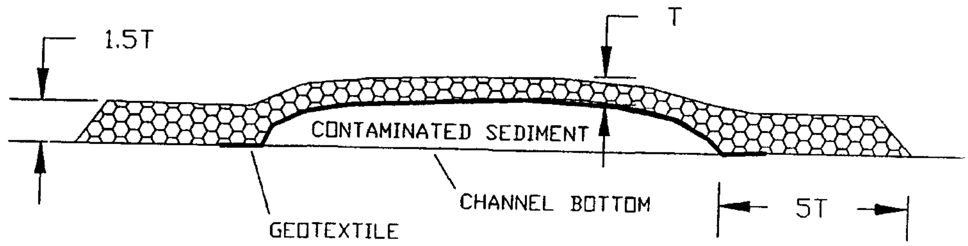


Figure A-1. Cross section of riprap and edge protection.

Stone Size Equations

Velocity and flow depth are the two basic factors used in design of riprap protection. The method of determining the stone size in EM 1110-2-1601 uses depth-averaged local velocity. Stone size computations should be conducted for flow conditions that produce the maximum velocities at the riprap boundary.

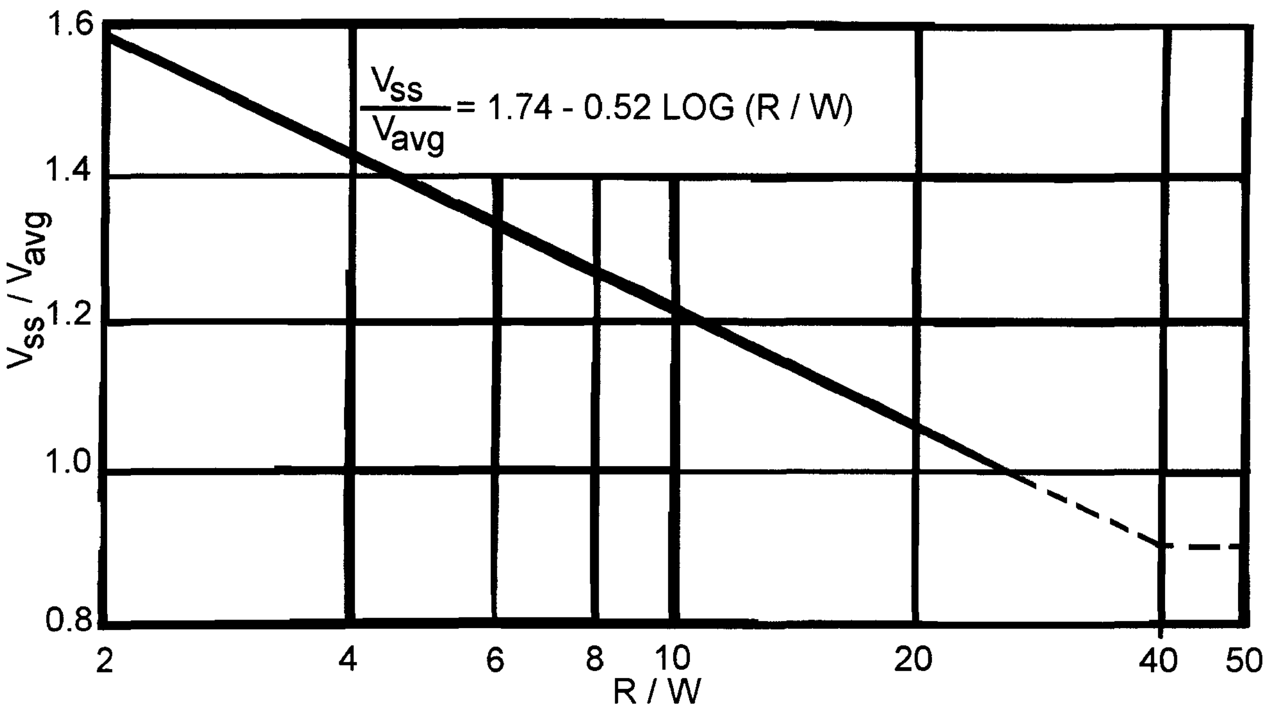
The following equation, modified from EM 1110-2-1601, relates velocity to stone size and is applicable to any location in the channel. The changes from the EM include the use of the gradation factor and basing stone size on D_{50} instead of D_{30}. This was done to use the same characteristic riprap size as in the navigation sizing presented subsequently.

$$D_{50} = S_f C_s C_V C_T C_G d \left[\left(\frac{\gamma_w}{\gamma_s - \gamma_w} \right)^{1/2} \frac{V}{\sqrt{K_1 g d}} \right]^{2.5} \qquad (2)$$

Where,
D_{50} = characteristic riprap size of which 50 percent is finer by weight.
S_f = safety factor, minimum = 1.1
C_s = stability coefficient for incipient failure,
thickness = $1D_{100}$(max) or $1.5D_{50}$(max), whichever is greater,
D_{85}/D_{15} = 1.7 to 5.2
= 0.30 for angular rock
= 0.375 for rounded rock
D_{85}/D_{15} = gradation uniformity coefficient(typical range= 1.8 to 3.5)
CV = velocity distribution coefficient
= 1.0 for straight channels, inside of bends
= 1.283-.2log(R/W) for outside of bends (1 for R/W > 26)
= 1.25 downstream of concrete channels
= 1.25 at end of dikes
R = centerline radius of bend
W = water surface width at upstream end of bend
C_T = blanket thickness coefficient(typically 1.0 for flood flows)
C_G = gradation coefficient = $(D_{85}/D_{15})^{1/3}$
K_1 = side slope correction factor(see EM 1110-2-1601 for other slopes
d = local depth, use depth at 20 percent upslope from toe for side slopes
V = local depth averaged velocity, use velocity at 20 percent upslope from toe for side slope riprap
γ_w = unit weight of water
γ_s = unit weight of stone (typical value of 165 lb/ft^3)
g = gravitational constant

A key element in any riprap design problem is the estimation of local depth-averaged velocity at the protection location. The EM primarily addresses velocity estimation in areas where erosion is expected which is normally the outer bank of channel bendways. Plate B-33 in the EM (Figure A2) provides an estimate of the maximum velocity that will occur in a bend on the outer bank. For sites where flow velocities are the predominate force, contaminated sediments needing protection may be located on either the bed or bank at any position along the length of the channel. Bernard and Schneider (1992) have developed a PC based depth-averaged numerical model that includes secondary current effects that occur in channel bends. This model has been shown to give good results in trapezoidal channels. This model will provide a velocity estimate at any position across the channel and along the bend.

Normally the minimum safety factor for riprap design is 1.1; however, if the consequences of failure are extremely hazardous, the designer should increase the safety factor accordingly. A computer program incorporating the EM 1110-2-1601 procedures is available from the Hydraulics Laboratory of the Waterways Experiment Station.



NOTE: V ss IS DEPTH-AVERAGED VELOCITY AT 20 PERCENT OF SLOPE LENGTH UP FROM TOE

Figure A-2. Riprap design velocites.

Examples of Design for Flood Flows

Consider the Sheboygan River which has contaminated sites along the upper non-navigable reach. The two-year average discharge is 3140 cfs, the five-year is 5000 cfs, and the ten-year is 6150 cfs. For the purpose of this example design, assume design average channel velocity of 6 ft/sec, the channel plan view in Figure 3, and design depths shown in the following table.

AREA	DEPTH
1,5	9 Ft
8,10,11	6 Ft

The following analysis uses a unit stone weight of 165 #/ft^3, minimum S_f = 1.1, angular rock (Cs = 0.30), blanket thickness = 1 D_{100} (C_T = 1.0), 1V:2H side slope (K_1 = 0.88) for all areas, and a gradation having D_{85}/D_{15} of 2.0.

Areas 1 and 5 in Figure 3 are on the outside of bendways where velocities are the highest. From Figure 2, an assumed R/W = 3 gives a ratio between the outer bank velocity and the average channel velocity of about 1.5, so the local velocity is 1.5(6) =9.0 ft/sec. Using equation (2) results in D_{50} = 0.57 ft. From Table A1, a gradation having D_{50}(min) greater than or equal to the computed value would have a D_{100}(max) of 12 in. and if placed in the dry, a thickness of 12 in.

Areas 8, 10, and 11 in Figure 3 are in a relatively straight reach of channel not strongly affected by upstream channel curvature. In these areas the right part of the natural channel curve (Figure 2) is applicable and bank velocity/average channel velocity = 1.0. This leads to a bank velocity of 1.0 (6.0) = 6.0 ft/sec and equation (2) yields a D_{50} = 0.19 ft.

In these examples, rock from a nearby source having D_{50} greater than the computed D_{50} would have to be specified. In practice the largest rock size required is often specified for both areas due to economics. It is assumed that the risk to human health and the environment is greater for a failure of a contaminated sediment cap than for a failure of a bank erosion control riprap layer. Therefore, additional margins of safety in stone sizing may be warranted for a ISC to protect the cap from localized very high velocities resulting.

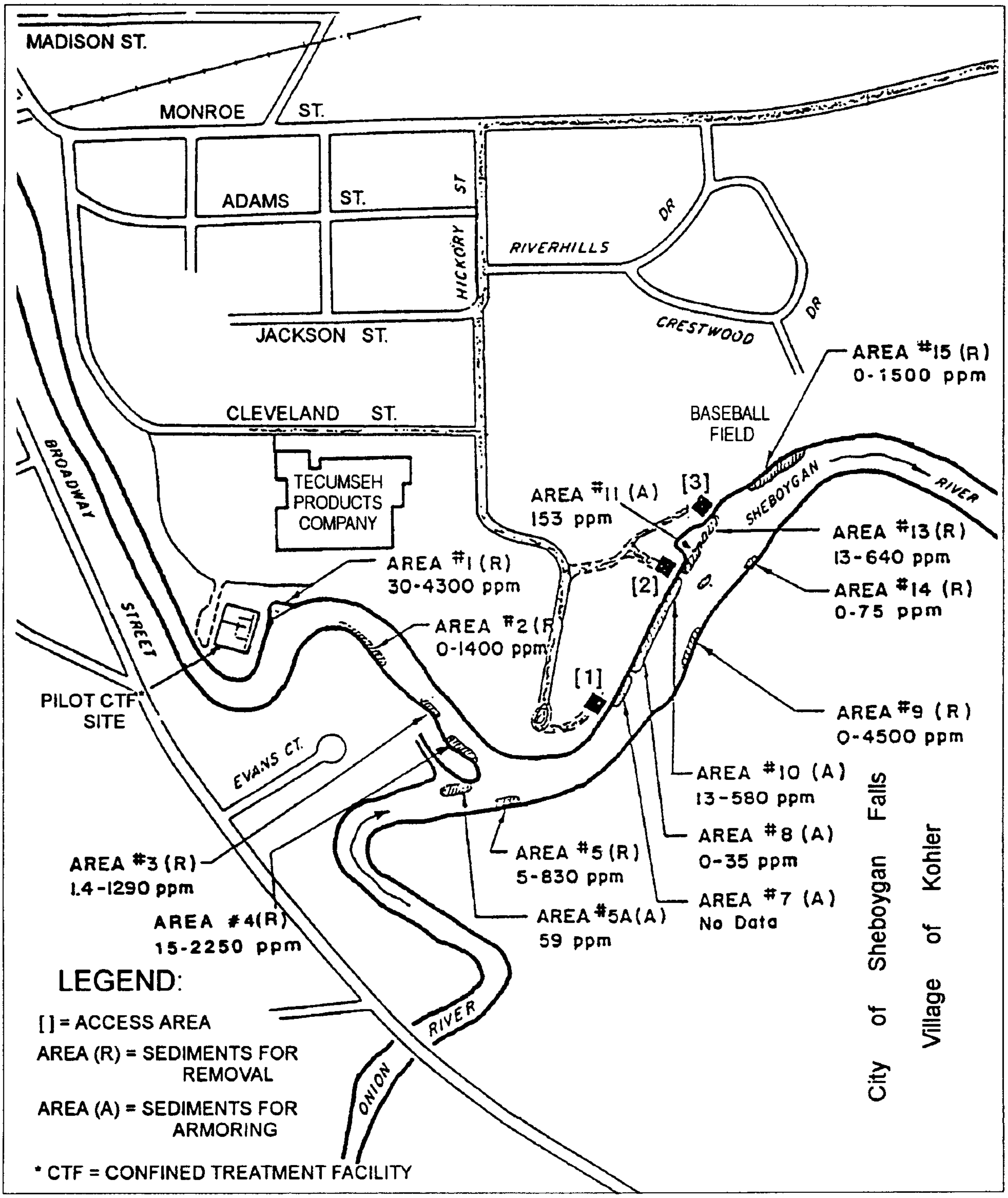


Figure A-3. Sheboygan River and Harbor site.

Stone sizing for navigation effects

Navigation can generally be divided into two categories, underway and maneuvering. For large commercial vessels underway in relatively small channels, the vessel creates a variety of erosion producing forces that are primarily water-level drawdown, return velocity acting opposite to the direction of travel, transverse stern waves, and a limited attack of the propeller jet. For underway vessels, these forces tend to increase with increasing speed and with decreasing channel size. In harbor areas, typical underway speeds tend to be low and erosion producing forces will also be low.

The second category of navigation, maneuvering vessels, produces erosion generating forces that are primarily caused by the propeller jet and can be large. Rock sizing guidance that follows will address the protection requirements for the propeller jet of maneuvering vessels.

Propeller Jet Stone Sizing Equations

The basic equations used in the analysis of riprap size are presented in Blaauw and van de Kaa (1978). The equation for the maximum bottom velocities in the propeller wash of a maneuvering vessel is

$$V_b(\max) = C_1 U_o D_p / H_p \tag{3}$$

where

$V_b(\max)$ = maximum bottom velocity
C_1 = 0.22 for non-ducted propeller
= 0.30 for ducted propeller
U_o = jet velocity exiting propeller
D_p = propeller diameter
H_p = distance from propeller shaft to channel bottom

The ratio D_p/H_p is a measure of the clearance of the propeller above the channel bottom. High values indicate the propeller is close to the channel bottom. Values of $D_p/H_p > 1.2$ are outside the range of data used in developing Equation 3 and should be used with caution.

The jet velocity exiting a propeller is given by Blaauw and van de Kaa (1978) as

$$U_o = C_2 \left(\frac{P_d}{D_p^2} \right)^{1/3} \tag{4}$$

where
U_0 = jet velocity exiting propeller in ft/sec
P_d = applied engine power/propeller in Hp
D_p = Propeller diameter in ft
C_2 = 9.72 for non-ducted propellers
= 7.68 for ducted propellers

The applied engine power used in equation 4 is the most difficult question to answer and one of the most important parameters in determining stone size. Blaauw et al (1984) gives the following equation for rock size

$$V_b(max) = C_3*(g*\Delta*D_{50})^{1/2} \tag{5}$$

where
C_3 = coefficient
Δ = $(\gamma_s - \gamma_w)/\gamma_w$

Blaauw et al. (1984) found C_3=0.55 for no movement and C_3=0.70 for small transport. Data from Maynord (1984) using equations 3-5 show that C_3 = 0.55 provides good agreement with experimental results for no transport and should be used in harbor areas where repeated attack can be expected and no movement can be allowed. For channel protection where infrequent attack can be expected, C_3 = 0.6-0.7 should be used in design.

Thrusters

Bow and stern thrusters are often used in deep draft vessels to permit maneuvering in navigation channels. Thrusters are ducted propellers and, depending on the position of the vessel relative to the bank, the maximum attack may be on either the channel bottom or channel bank. Due to the uncertainty of the location of maximum attack, the general equation from which equation 3 was derived must be used to determine velocity along the bed and bank. The general form of equation 3 from Blaauw and van de Kaa(1978) provides the distribution of jet velocity and is

$$\frac{V_x}{U_o} = 2.78\frac{D_o}{x}\exp[-15.43(\frac{z}{x})^2] \tag{6}$$

where V_x = velocity at coordinates x,z
$D_o = 0.71 D_p$ for non-ducted propeller
$= D_p$ for ducted propeller
x = horizontal distance from propeller
z = radial distance from axis of propeller

Thrusters generally operate at full power and a typical class 8 lake vessel has a bow thruster which is 6.8 ft in diameter and 850 hp. Typical stern thrusters are the same diameter and 1000 hp. Thruster centerlines are about 6.2 ft above the keel. Riprap sizing for thrusters would use equation 6 and solve for V_x at various point along the bottom and up the bank until the maximum V_x is found. This maximum V_x will be the $V_b(max)$ to use in equation 5.

Example designs for navigation

Two examples are presented in this subsection, one based on commercial vessel traffic and another on recreational vessel traffic. On the Ashtabula River in Ohio, the possible areas for capping are located in the Federal Navigation Channel where depths in this area vary from 2 to 16 ft. Small recreational craft normally use this reach with an infrequent commercial vessel. Contacts with the U.S. Coast Guard led to the following findings regarding the largest commercial vessels using this reach:

Table A2. Largest Commercial Vessels on the Ashtabula River

		PROPELLER		SHAFT	
LENGTH	WIDTH	DIA-INCHES	DRAFT	BELOW W.S.	HP
FT	FT	INCHES	FT	FT	
42	12.5	40	6	4.5	300
72	22.5	60	9.4	6.5	1100
59	14.0	60	8	6.0	680

Using the 1100 hp vessel at 1/4 throttle which is typical of this vessel, the applied engine power is P_d = 1100(0.25) = 275 hp, and with the propeller diameter D_p = 5 ft, equation (4) results in U_O = 21.6 ft/sec for a non-ducted propeller. With a 16 ft depth, H_p = 9.5 ft and from Equation (3), $V_b(max)$ = 0.22(21.6)5/9.5 = 2.50 ft/sec. From Equation (5) with C_3 = 0.60, D_{50} = 0.33 ft. A blanket thickness of 9 in. from Table A1 has a $D_{50}(min)$ greater than or equal to 0.33 ft.

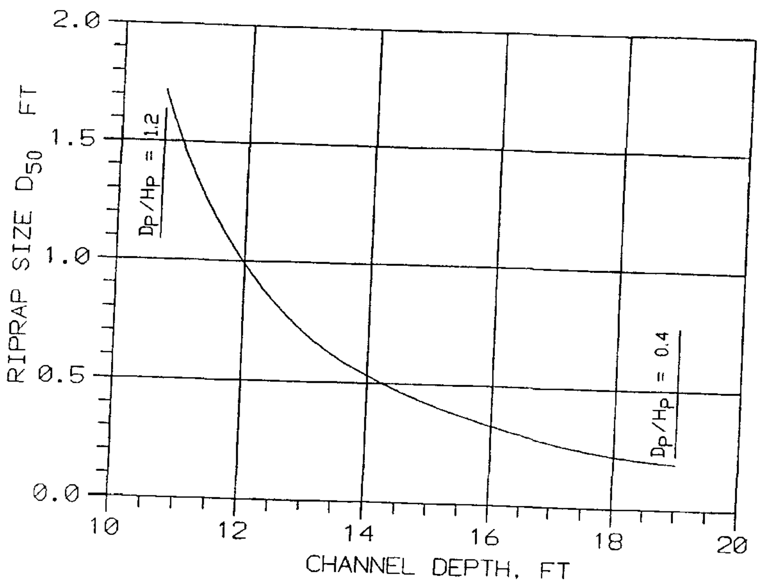


Figure A-4. Influence of channel depth on stone size, Astabula River, 1100 hp vessel, 25 percent power.

Two of the significant variables in the propeller jet stone sizing equations are the channel depth and the applied power. Figure 4 demonstrates the change in rock size D_{50} for changing channel depth with all other parameters as above for the 1100 hp vessel on the Ashtabula River. Rock size becomes large as the propeller approaches the bottom. Figure 5 demonstrates the change in rock size for changing percent of total power applied for a depth of 13 ft and all other parameters as above. Rock size becomes large for significant power increases.

In the second example, the largest vessels in a contaminated reach adjacent to a towing basin are 300 HP recreational craft with maximum draft of 3.5 ft. These vessels are twin propeller boats with maximum propeller diameter of 1.44 ft with the centerline of the shaft 2 ft below the water level. The maximum throttle is about 25 percent. Water depth varies from 4-11 ft. Based upon the basic equations 3-5 and a water depth of 5 ft, the jet velocity for the maximum vessels would be based on 150 hp per propeller. The applied power is P_d = 0.25(150) = 37.5 hp. From Equation (4),U_o = 25.5 ft/sec. For a 5 ft depth, H_p = 3 ft. From Equation (3), V_b(max) = 2.7 ft/sec. From Equation (5), D_{50} = 0.38 ft and a blanket thickness of 9" from Table A1 (EM1110-2-1601) provides D_{50}(min) greater than or equal to 0.38 ft. If depth were 10 ft., Hp = 10-2 = 8 ft. From equation (3), V_b(max) = 1.0 ft/sec and Equation (5) gives D_{50} = 0.053 ft which would be equivalent to a large gravel covering.

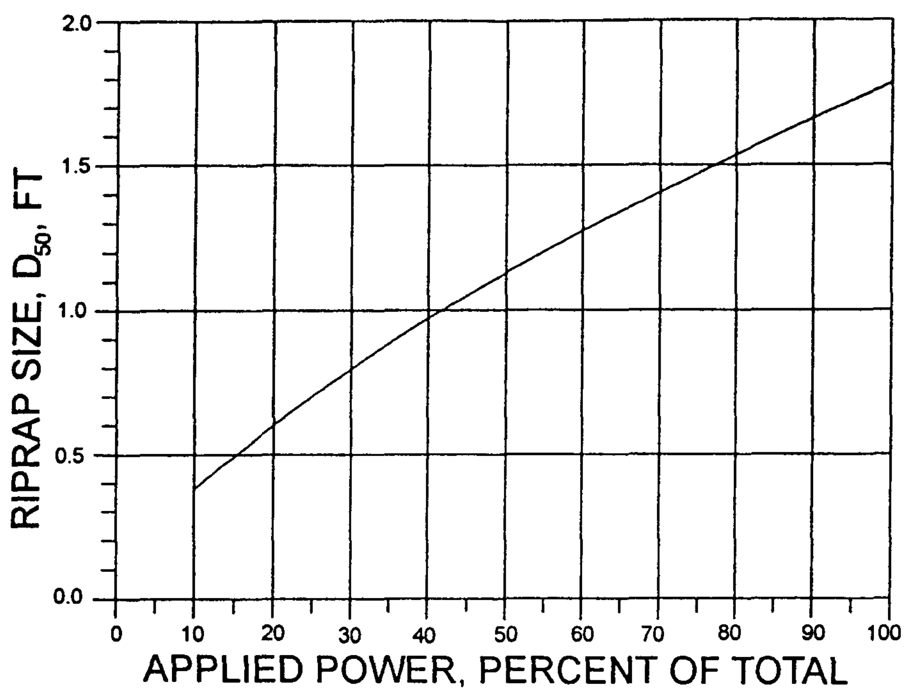


Figure A-5. Influence of applied power on sstone size, Ashtabula river, 1100 HP vessel, 13 ft depth.

Stone sizing for wave induced currents

Significant wind wave activity can create large bottom velocities that can erode an unprotected sand cap. To define the required armor layer size to prevent scour, Equation 5 should be used with with the maximum horizontal bottom velocity from the wave. For orbital velocities beneath waves, a C_3 = 1.7 is recommended.

Example Design for wave induced currents

Wave induced bottom velocities are calculated to be 7 fps for the design wave. Using equation 5 with C_3 = 1.7 results in D_{50} = 3.8" for unit stone weight of 165 lb/cf. A maximum/minimum stone size of about 2 is recommended to reduce attack of underlying layers and the resulting stone gradation is 2.5" to 5.0".

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Guidance for In-Situ Subaqueous Capping of Contaminated Sediments: Appendix B: Model for Chemical Containment by a Cap

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Introduction

This Appendix describes a model for evaluation of chemical flux through a cap. Through use of this model the effectiveness of chemical containment of a cap can be assessed. This model should be applied once cap design objectives with respect to flux are determined, a specific capping material has been selected and characterized, and a minimum cap thickness has been determined based on components for isolation, bioturbation, erosion, consolidation, and operational considerations. If an objective of the cap is attainment of a given contaminant flux, the model can be used to estimate the required cap thickness.

The effective thickness, L_{eff} , of a cap can be defined as the thickness available for long term chemical containment. This thickness is reduced by consolidation of the cap, ΔL_{cap}, the thickness affected by short term pore water migration due to consolidation in the underlying sediment, ΔL_{sed}, and by bioturbation over a thickness, L_{bio}. Bioturbation, the normal life-cycle activities of benthic organisms, leads to mixing and redistribution of contaminants and sediments in the upper layer. The chemical migration rate within the bioturbated zone is typically much faster than in other portions of a cap. In addition, consolidation typically occurs on a time scale that is rapid compared to the design lifetime of a cap. Consolidation of the cap directly reduces the thickness of a cap and the separation between contaminants and the overlying water and benthic organisms while consolidation of the underlying sediment results in the expression of potentially contaminated porewater. Note, however, that in addition to reducing the thickness of a cap, consolidation serves to reduce both the porosity and permeability of a cap causing reductions in chemical migration rates by both advection and diffusion.

Using $\Delta L_{sed,A}$ to represent the thickness of a cap affected by a contaminant A during consolidation of the underlying sediment, the effective cap thickness remaining for chemical containment is given by

$$L_{eff} = L_0 - L_{bio} - \Delta L_{cap} - \Delta L_{sed,\,A} \qquad (1)$$

where L_0 is the initial thickness of the cap immediately after placement.

The depth of bioturbation can be assessed through an evaluation of the capping material and recognition of the type, size and density of organisms expected to populate this material. Because of the uncertainty in this evaluation, the bioturbed zone is generally chosen conservatively, that is considered to be as large as the deepest penetrating organism likely to be present in significant numbers. Due to the action of bioturbating organisms, this layer is also generally assumed to pose no resistance to mass transfer between the contaminated sediment layer and the overlying water.

The consolidation of the underlying contaminated sediment can be estimated through consolidation models. The resulting movement of the chemical contaminants must be estimated, however, and a model is described below. The effective cap thickness estimated by Equation (1) is still subject to chemical migration by advection and diffusion processes. The long term chemical flux to the water via these processes can also be modeled.

The complete model of chemical movement must be composed of two components:

- An advective component considering the short term consolidation of the contaminated sediment underlying the cap, and,
- A diffusive or advective-dispersive component considering contaminant movement as a result of porewater movement after the cap has stabilized.

The first component is operative for all caps in which the underlying contaminated sediment layer is compressible but only for a short period of time. The first component allows completion of the determination of the effective cap thickness through Equation (1). The resulting effective cap thickness can then be used to assess long term losses through the cap by advective and/or diffusive processes. For simplicity and conservatism, the sediment underlying a cap could be assumed to remain uniformly contaminated at the concentration levels prior to cap placement. In reality, migration of contaminants into the cap reduce the sediment concentration and the long term flux to the overlying water. The consideration of this situation, however, greatly complicates the analysis and the models used to describe contaminant flux. Both of the model components will be considered separately. Due to the different mechanisms operative in a system with porewater motion present or absent, the second model component will be subdivided into submodels appropriate for each.

Model for Short Term Cap Losses - Advection during Cap Consolidation

After placement of capping materials, consolidation of both the cap and the underlying sediment occurs. Consolidation of the cap results in no contaminant release since the cap is initially free of contamination. Furthermore, the consolidation of the cap serves to reduce the permeability and, to a lesser extent, the porosity of a cap. Both serve to reduce contaminant migration through the cap by both diffusive and advective processes.

Consolidation of the underlying sediment due to the weight of the capping material, however, tends to result in expression of porewater and the contaminants associated with that water. The ultimate amount of consolidation may be estimated using standard methods or computer models. The consolidation of the underlying sediment is likely to occur over a very short period (e.g. months) compared to the lifetime of the cap. It is appropriate, therefore, to assume that the consolidation occurs essentially instantaneously and estimate the resulting contaminant migration solely on the basis of the total depth of consolidation and the porewater expressed. For a nonsorbing contaminant, the penetration depth of the chemical is identical to that of the expressed porewater. For a sorbing contaminant, the penetration depth is less as a result of the accumulation of chemical on the sediment. Mathematically, if ΔL_{sed} represents the ultimate depth of consolidation of the underlying contaminated sediment due to cap placement, the depth of cap affected by this porewater (or nonsorbing contaminant), $\Delta L_{sed,pw}$, is given by

$$\Delta L_{sed,pw} \approx \frac{\Delta L_{sed}}{\epsilon} \qquad (2)$$

where ϵ is the porosity of the cap materials. The division by the cap porosity recognizes that the expressed porewater moves only through the void volume formed by the spaces between the grains of the capping material. Equation (2) assumes that the capping material is spatially uniform and that porewater is not preferentially forced through an area a fraction of the total cap area.

Although the depth of cap affected by the expressed porewater is given by Equation (2), the migration distance of a sorbing contaminant is less due to accumulation in the cap. The quantity of contaminant that can be rapidly adsorbed by the cap material, ω_c (mg/kg), is generally assumed to be proportional to the concentration in the porewater (C_{pw}, mg/L),

$$\omega_c = K_d^{obs} C_{pw} \qquad (3)$$

where the constant of proportionality is the observed sediment-water partition coefficient. Note that the observed partition coefficient is measured during sorption onto clean cap material. The value of K_d^{obs} may be predicted or measured as described in a subsequent section. Use of a measured value, however, does not require linearity or reversibility of the sorption isotherm, nor does it require specification of the form of the contaminant in the porewater (e.g. dissolved or bound to particles). For a compound that sorbs to soil with an observed partition coefficient of K_d^{obs} (L/kg), the ratio of the total concentration in the soil to that in the porewater is given by the retardation factor, R_f,

$$R_f = \epsilon + \rho_b K_d^{obs} \qquad (4)$$

The distance that the contaminant migrates during underlying sediment consolidation of a distance ΔL_{sed} is then given by

$$\Delta L_{sedA} \approx \frac{\Delta L_{sed}}{R_f} \approx \frac{\Delta L_{sed}}{\epsilon + \rho_b K_d^{obs}} \qquad (5)$$

This distance must be subtracted from the actual cap thickness to estimate effective cap thickness.

Note that this model suggests that the more sorbing a cap, the less important is consolidation in the underlying sediment. Sorption for hydrophobic organics such as polyaromatic hydrocarbons and polychlorinated biphenyls is strongly correlated with the organic carbon content of the sediments. If a cap contains 0.5% organic carbon or more, the K_d^{obs} is typically of the order of hundreds or thousands for these compounds and the loss of effective cap thickness by consolidation is a small fraction of the consolidation distance. Metals also tend to be strongly associated with the solid fraction, again reducing the migration of contaminant out of the sediment as a result of consolidation.

Estimation of Long-Term Losses
Mechanisms and Driving Force

The effective cap thickness defined by Equation (1) is subject to advection or diffusion or a combination of both throughout the lifetime of the cap. The long term contaminant release or loss requires estimation of the contaminant flux by these processes. Diffusion is always present while advection only occurs if there exists a significant hydraulic gradient in the underlying sediments. The relative magnitude of diffusion to advection in the cap of effective thickness, L_{eff}, can be estimated by the Peclet number.

$$P_e = \frac{UL_{eff}}{D_{eff}} \qquad (6)$$

where U is the advective velocity (Darcy or superficial velocity) in the sediment and D_{eff} is the effective diffusion/dispersion coefficient. If the magnitude or absolute value of the Peclet number is much greater than one, advection dominates over diffusion/dispersion while the opposite is true for absolute values much less than one. Advection directed out of the cap will speed contaminant release while advection directed into the sediment will effectively lengthen the cap.

The average groundwater flow velocity is estimated from the sediment conductivity (K, cm/sec) or permeability (k, cm^2) and the local hydraulic gradient.

$$U = K\frac{\partial h}{\partial z} = \frac{k\rho g}{\mu}\frac{\partial h}{\partial z} \qquad (7)$$

Here, ρ is the density of water (~1 gm/cm^3), g is the acceleration of gravity (980 cm·sec^{-2}) and μ is the viscosity of water (~0.01 gm·cm^{-1}·sec^{-1}). $\frac{\partial h}{\partial z}$ is the local gradient in hydraulic head or elevation with distance into the sediment. The average groundwater flow is also the volumetric seepage rate divided by the sediment-water interfacial area. Thus lakes, with large sediment-water interfacial areas tend to exhibit less potential for advective influences than small streams. Estuarine systems subject to significant tidal fluctuations may also exhibit significant advective transport. Losing streams, in which the advective transport is into the sediment may exhibit advection but may not be important since the direction of transport is away from the sediment-water interface and long travel distances may be required to impact groundwater of significance. Similarly, advection may be less important in wetlands subject to frequent cycles of flooding followed by infiltration due to the downward vector of advection. The presence of a cap will tend to reduce any advective transport by preferentially channeling flow to uncapped sediment. The permeability of the cap materials may also be selected to minimize advection.

The effect of advection includes both transport by the porewater flow and that by diffusion and dispersion. Dispersion is the additional "diffusion-like" mixing relative to the average porewater velocity that occurs as a result of heterogeneities in the sediments. Thus the description of advection is more complicated than diffusion and the model for long term cap losses will be subdivided into models appropriate when advection is important and a model appropriate only when diffusion dominates.

Both processes, however, are operative only for that portion of the contaminant present in the porewater. This might include contaminant dissolved in the porewater as well as contaminant sorbed to fine particulate or colloidal matter suspended in the porewater. The pore-water concentration in the underlying sediment, assuming linear partitioning between the sediment and porewater, is given by

$$C_{pw} = \begin{cases} \dfrac{\omega_{sed}}{K_d} & if\ \dfrac{\omega_{sed}}{K_d} \leq C^* \\ C^* & if\ \dfrac{\omega_{sed}}{K_d} \geq C^* \end{cases} \tag{8}$$

where C^* is the equilibrium solubility of the chemical in water and ω_{sed} is the sediment loading (mg chemical/ kg (dry) sediment). The Equation indicates that the porewater concentration increases linearly with the sediment loading until the water is saturated, that is, until the solubility limit is reached. Loading above that critical value cannot increase the sediment porewater concentration or the driving force for diffusion. The porewater concentration can exceed this value, however, if colloidal organic matter, typically measured by dissolved organic carbon, is present in large quantities in the porewater. Sorption onto this colloidal matter can increase the total fraction of contaminant present in the porewater. If the partitioning to the organic colloidal matter is assumed to be given by $K_{oc,}$ the organic carbon to water partition coefficient, and if ρ_{oc} represents the colloidal organic carbon concentration, then the porewater concentration calculated above must be corrected by the factor $(1+ K_{oc}\rho_{oc})$. This approximately accounts for the enhanced chemical solubility due to the presence of sorbing colloids. A similar correction for metal species could be adopted, however, it is difficult to predict the partitioning of metals to soils and colloidal particles.

Degradation of contaminants over the long time of expected confinement is a significant benefit of capping which should be incorporated into the design of a cap. If simple first order degradation kinetics is employed the sediment loading changes with time according to

$$\omega_{sed} = \omega^0_{sed}e^{-k_r t} \tag{9}$$

where ω^0_{sec} is the sediment loading at the time of cap placement and k_r the exponential time constant is given by $0.693/t_{0.5}$, with $t_{0.5}$ the chemical half life in the sediment.

In the subsequent sections, the sediment porewater concentration estimated by Equation (5) is used to evaluate diffusive and advective-dispersive transport.

Diffusion

Diffusion is a process that occurs at significant rates only within the pores of the sediment and is driven by the difference in porewater concentration between the sediment and the cap. The initial concentration of the contaminant in the cap porewater is generally 0 while the concentration in the sediment is given by Equation(8), modified if appropriate by Equation (9). Even without degradation, however, migration of contaminants into the cap will deplete the underlying sediments as a result of the loss of mass by diffusion through the cap.

Thoma et al. (1993) developed a model of diffusion through a cap that explicitly accounts for depletion in the underlying sediment. A simpler model of diffusion through the cap, however, assumes that the contaminant concentration in the underlying sediment is essentially constant. This would be most appropriate if the contaminant concentration in the sediment far exceeds the critical concentration defined by Equation (8). Because the assumption of no depletion in the underlying sediment overpredicts the driving force for diffusion, however, it also represents a conservative assumption of the effectiveness of the cap. We will therefore employ it in the description that follows.

Let us first estimate the steady long term flux of contaminants through the cap via diffusion. This is the maximum flux that can occur through the cap by the diffusive mechanism.

Maximum Flux Estimation (Steady State) If diffusion is the only operative transport process through the cap, the pseudo steady-state flux through the cap (assuming constant contaminated sediment porewater concentration and no sorption effects in the cap layer) is given by

$$F = \frac{D_w \epsilon^{4/3}}{L_{eff}} C_{pw} \approx K_{cap} C_{pw} \qquad (10)$$

where	F	=	chemical flux ($ng \cdot cm^{-2} \cdot sec^{-1}$)
	D_W	=	the binary diffusivity of the chemical in water, (cm^2/sec)
	ε	=	the sediment porosity (void volume/ total volume),
	L_{eff}	=	effective cap thickness
	C_{pw}	=	pore-water concentration (ng/cm^3)
	K_{cap}	=	effective mass transfer coefficient through cap (cm/sec)

Millington and Quirk (1961) suggest the factor $\varepsilon^{4/3}$ to correct for the reduced area and tortuous path of diffusion in porous media. The overlying water concentration is assumed very much less than the sediment porewater concentration.

In general, the chemical flux is influenced by bioturbation and a variety of water column processes. Figure 1 shows the idealized concentration profile in a capped system at this pseudo steady state. The flux of chemical through each layer is equal to the sum of the rate of evaporation and flushing.

Mathematically, in terms of mass transfer coefficients, we have:

$$\begin{aligned} M = K_{ov} A_s C_{pw} = K_{cap} A_s (C_{pw} - C_{bio}) = \\ K_{bio} A_s (C_{bio} - C_{sw}) = K_{bl} A_s (C_{sw} - C_w) = (K_e A_e + Q) C_w \end{aligned} \qquad (11)$$

where

M	=	rate of chemical loss from the system (mg/day) = $F^* A_s$
K_{ov}	=	overall mass transfer coefficient (cm/day)
A_S	=	contaminated sediment area (m^2)
A_e	=	evaporative surface area (m^2)
K_{cap}	=	cap mass transfer coefficient = $D_w \epsilon^{4/3} / L_{eff}$ (cm/day)
C_{pw}	=	porewater concentration within the contaminated sediment Including dissolved and any sorbed to colloidal material

C_{blo} = porewater concentration at the top of the cap (ng/cm^3)

C_{sw} = porewater concentration at the sediment water interface (ng/cm^3)

K_{blo} = bioturbation mass transfer coefficient = $\frac{\eta D_{blo} R_f}{L_{blo}}$ (cm/day)

η = desorption efficiency of contaminant from sediment particles (0.1-0.2)

D_{blo} = biodiffusion coefficient (cm^2/day)

R_f = retardation factor = $\epsilon + \rho_B K_d^{obs}$

L_{blo} = depth of bioturbation (cm)

K_{bl} = benthic boundary layer mass transfer coefficient (cm/day)

K_e = evaporation mass transfer coefficient (cm/day)

D_e = effective diffusivity = $D_w \cdot \epsilon^{4/3}$ (cm^3/day)

Q = basin flushing rate (cm^3/day).

C_w = chemical concentration in the basin water (ng/cm^3).

K_d = sediment water partition coefficient for the chemical = $K_{oc} f_{oc}$ (cm^3/g)

K_{oc} = organic carbon-water coefficient for the chemical (cm^3/g)

f_{oc} = sediment fractional organic carbon content.

ρ_B = sediment bulk density.

The overall mass transfer coefficient, K_{ov}, can be obtained from the following:

$$\frac{1}{K_{ov}} = \frac{1}{K_{cap}} + \frac{1}{K_{blo}} + \frac{1}{K_{bl}} + \frac{A_s}{K_e A_e + Q} \tag{12}$$

An analysis of this relationship for reasonable values of L_{eff} suggests that $1/K_{ov} \cong 1/K_{cap}$ and therefore the cap controls the flux to the overlying water and Equation ((10)) is valid.

This flux can be used to estimate water concentrations in the water (C_W) or at the sediment water interface (C_{SW}) or multiplied by the capped area to determine total release rate. For hydrophobic organics, the concentration in the overlying water at steady-state is defined by a balance between the flux through the cap, the rate of evaporation to the air and the rate of flushing of the water column. For metals and elemental species not associated with volatile compounds, the flux through the cap is balanced only with the flushing of the water column. The overlying water concentration of the contaminant is given by:

$$C_w = \left(\frac{K_{ov} A_s}{K_e A_f + Q} \right) C_{sed} \tag{13}$$

The concentration at the sediment-water interface, which would be indicative of the level of exposure of bottom surface dwelling organisms, is defined by the balance of the flux through the cap with the flux through the benthic boundary layer. The contaminant concentration at the sediment-water interface is:

$$C_{Sw} = \frac{K_{ov} C_{sed}}{K_{b\ell}} + C_w \tag{14}$$

Either of these concentrations or the estimated fluxes may be compared to applicable criteria for the chemical in question to determine if a specified cap thickness is adequate. A sample calculation is presented below.

Transient Diffusion - Breakthrough time estimation The simple steady state analysis we have presented above is not capable of predicting the time required for the contaminant(s) to migrate through the cap layer. Until sorption and migration in the cap is complete, the flux to the water column will be less than predicted by Equation (10). Time must be explicitly incorporated in the differential mass balance to address this problem. The following partial differential equation represents a differential mass balance on the contaminant in the pore-water of the cap as it diffuses from the contaminated sediment below.

$$R_f \frac{\partial C_{pw}}{\partial t} = D_w \varepsilon^{4/3} \frac{\partial^2 C_{pw}}{\partial z^2} \tag{15}$$

We apply the conditions of a constant concentration at the sediment-cap interface as specified by Equation (8) and effectively zero concentration at the height L_{eff} in the cap. Carslaw and Jaeger (1959) present a solution to the equivalent heat transfer problem which in terms of concentration and mass diffusion is given by:

$$F_{diff} = \frac{C_{pw} D_{eff}}{L_{eff}} \left[1 + 2 \sum_{n=1}^{\infty} (-1)^n \exp\left(- \frac{D_{eff} (n \pi)^2 t}{R_f L_{eff}^2} \right) \right] \tag{16}$$

where D_{eff} represents $D_w \varepsilon^{4/3}$. Note that as $t \rightarrow \infty$ the expontential term in square brackets approaches zero and the flux approaches the value obtained by the approximation $K_{ov} \approx D_{eff}/L_{eff}$ as indicated by Equation (10). From Equation (16) we can obtain relations for the breakthrough time and the time required to approach the steady state flux.

We define breakthrough time, τ_b, as the time at which the flux of contaminant from the contaminated sediment layer has reached 5% of its steady state value, and we define the time to reach steady state, τ_{ss}, as the time when the flux is 95% of its steady state value. It is easily shown that

$$\tau_b = \frac{0.54 L_{eff}^2 R_f}{D_w \varepsilon^{4/3} \pi^2} \tag{17}$$

and

$$\tau_{ss} = \frac{3.69\, L_{eff}^{2} R_f}{D_w \varepsilon^{4/3} \pi^2} \tag{18}$$

Advective-Dispersive Models

When advection cannot be neglected during the operation of a cap, the basic equation governing contaminant movement is

$$R_f \frac{\partial C_{pw}}{\partial t} + U \frac{\partial C_{pw}}{\partial z} = D_{eff} \frac{\partial^2 C_{pw}}{\partial z^2} \tag{19}$$

where C_{pw} is the contaminant concentration in the porewater. U is again the Darcy velocity and D_{eff} is the effective diffusion/dispersion coefficient. The effective diffusion/dispersion coefficient is often modeled by a relationship of the form

$$D_{eff} = D_w \epsilon^n + \alpha U \tag{20}$$

The first term in this relation is associated with molecular diffusion and is identical to the effective diffusivity used above.

The second term is mechanical dispersion associated with the additional mixing due to flow variations and channeling. α is the dispersivity and is typically taken to be related to the sediment grain size (uniform sandy sediments) or travel distance (heterogeneous sediments). Very little guidance exists for the estimation of field dispersivities for vertical flow in sediments. In uniform sandy sediments, the dispersivity is approximately one-half the grain diameter. Dispersion in heterogeneous sediments would be expected to be larger.

If the effective dispersivity can be estimated, the contaminant concentration and flux through the cap can be estimated by solutions to Equation (19). Let us first consider the long time behavior of Equation (19) when the sediment originally exhibits a contaminant porewater concentration C_0. If the contaminant is not subject to depletion by either degradation or migration through the cap, the flux through the cap, at infinitely long time periods, ultimately reaches that given by

$$F_{adv} \rightarrow U\, C_0 \qquad as\ t \rightarrow \infty \tag{21}$$

That is, once the adsorbing capacity of the cap is exhausted, the contaminant flux due to advection is identical to that which would be observed if no cap were placed over the sediment. Recognize that any sorption in the cap must deplete the reservoir of contaminants in the contaminated layer. The assumption of no depletion is therfore very conservative.

In the advection dominated case, therefore, it is important to examine the transient release of the contaminant. The conditions on Equation (10) that are appropriate for a cap include

$$\begin{array}{l} cap-sed \\ \quad cap \\ \quad\; ini \end{array} \qquad (22)$$

Available solutions, however, do not satisfy the cap-water interface condition. Instead there are two solutions that are commonly applied.

$$\begin{aligned} \frac{\partial C_{pw}}{\partial z} &= 0 \qquad at\ z = L \qquad (finite\ cap) \\ \frac{\partial C_{pw}}{\partial z} &= 0 \qquad as\ z \to \infty \qquad (infinite\ cap) \end{aligned} \qquad (23)$$

The first explicity recognizes the finite thickness of the cap while the second assumes that it is infinitely thick. For Pe>1, however, the solution to Equation (10) subject to either condition is essentially identical. Moreover, for Pe<1 when diffusion dominates, the finite cap condition is inappropriate and causes the solution to underpredict the contaminant flux through the cap. The solution for the infinite cap is also simpler to use. For these reasons, only the infinite cap thickness model will be described here.

The solution to Equation(19) subject to the infinite cap condition is given by

$$C_{pw}(z,t) = \frac{C_0}{2}\left[erfc\left(\frac{R_f z - Ut}{2\sqrt{R_f D t}}\right) + \exp\left(\frac{Uz}{D}\right) erfc\left(\frac{R_f z + Ut}{2\sqrt{R_f D t}}\right)\right] \qquad (24)$$

Here erfc represents the complementary error function which is given by 1- erf, the error function. The error function is a tabulated function (e.g.,Thibodeaux, 1979) and is commonly available in spreadsheets and computer languages. It ranges from 0 at a value of the argument equal to zero to 1 at a value of the argument equal to infinity. The model is most useful in predicting the penetration of the contaminant into the cap and the time until the sediment-water interface begins to be significantly influenced by the cap, the breakthrough time. The breakthrough time can be estimated by evaluating Equation (24) for $z=L_{eff}$ and determining the time required until $C_{pw}(L_{eff},t)$ is equal to some fixed fraction of the concentration in the underlying sediment, for example until $C_{pw}(L_{eff},t)=0.05\ C_0$. The flux at any time could also be evaluated by computing

$$F_{adv/disp} = U\, C_{pw}(L_{eff},t) - D_{eff}\frac{\partial C_{pw}}{\partial t} \qquad (25)$$

The equation for the flux is lengthy, however, and, as indicated earlier, Equation(24) is most useful to calculate the breakthrough time or the concentration profile within the cap at any given time.

Parameter Estimation

Use of any of the equations presented above requires estimation of a variety of model parameters. The most important of these parameters and an example calcuation are presented below.

These include the porosity(ϵ), bulk density(ρ_b) and organic carbon content (f_{oc}) of the cap material, the partition coefficient(K_d) for the chemical(s) between the pore-water and the cap material, the diffusivity of the chemical(s) in water(D_W), the depth of bioturbation(b) and a biodiffusion coefficient(D_{bio}), benthic boundary layer(k_{bbl}) and evaporation(K_e) mass transfer coefficients, and for flowing systems the water depth(H) and current velocity(v). Information should be obtained on the degradadion half-life or reaction rate of chemicals of concern in the specific project if such information is available.

$$K_d^{obs} = \frac{K_d}{1 + \rho_{oc} K_{oc}} \qquad (26)$$

Contaminant properties These include water diffusivity and sediment-water or cap-water partition coefficient. The water diffusivity of most compounds varies less than a factor of two from 1×10^{-5} cm^2/sec. Higher molecular weight compounds such as PAH's tend to have a water diffusivity of the order of 5×10^{-6} cm^2/sec. Estimation techniques can be found in Lyman et al. (1990). The preferred means of determining the partition coefficient is through experimental measurement of sediment and porewater concentration in the sediment or cap. In this manner, any sorption of contaminant onto suspended particulate or colloidal matter is implicitly incorporated. If such measurements are unavailable, it is possible to predict values of the partition coefficient, at least for hydrophobic organic compounds. For other contaminants, including metals, very little predictive guidance exists. For hydrophobic organics, the partition coefficient between the pore-water and sediment for a given chemical can be estimated from the organic carbon-water partition coefficient through the relation $K_d = f_{oc}K_{oc}$. K_{oc} values are tabulated (e.g. Montgomery and Welkom, 1990) or may be estimated from solubility or the octanol-water partition coefficient using the methods in Lyman et al. (1990). If colloidal material in the porewater influences the partition coefficient, an apparent or effective partition coefficient can be estimated from the dissolved organic carbon concentration, ρ_{oc}, in the porewater and the relationThe porewater concentration to be used in this case is then not the truly dissolved concentration but that corrected for the amount sorbed on the colloidal matter. This is the same correction for the presence of colloidal matter referred to in the discussion of Equation (8).

Physical characteristics The long term average current velocity and water depth should be evaluated for the site to determine water side mass transfer resistances. Cap material properties are dependent on the specific materials available and should be measured using standard analytical methods. The water diffusivity can be estimated using the Wilke-Chang method (Bird *et al.,* 1960). Compilations of diffusivities are also available (Thibodeaux, 1979; Montgomery and Welkom, 1990).

Mass transfer coefficients A turbulent mass transfer correlation (Thibodeaux, 1979) can be used to estimate the value of K_{bl} in the water above the cap:

$$Sh = 0.036\ Re^{0.8}\ Sc^{1/3} \qquad (27)$$

where Sh = Sherwood number = $\frac{K_{bl} \cdot x}{D_w}$

Re = Reynolds number = $\frac{x \cdot u}{\nu}$

Sc = Schmidt number = $\frac{\nu}{D_w}$

ν = kinematic viscosity of water, (0.01 cm^2/sec at 20°C)

u = benthic boundary layer water velocity (cm/s)

x = length scale for the contaminated region - here we take $x = \sqrt{A_s}$ (cm), where A_s is the surface area of the contaminated region

As indicated previously, however, the benthic boundary layer mass transfer coefficient is rarely significant in the estimation of contaminant flux through the cap.

Transport by bioturbation has often been quantified by an effective diffusion coefficient based on particle reworking rates. A bioturbation mass transfer coefficient can then be estimated from the following relation assuming linear partitioning between the sediment and water in the bioturbation layer

$$K_{bio} = \frac{D_{bio}\rho_b K_d \eta}{L_{bio}} \tag{28}$$

where η is a desorption efficiency of the chemical once the particle carrying it has been reworked to the sediment-water interface. η would tend to be small for more hydrophobic compounds thattend to desorb slowly at the surface and large for compounds that are more soluble. In the absence of experimental information to the contrary, η is assumed to be 1. The biodiffusion coefficient and the depth of bioturbation are important factors in the determination of the required cap thickness, and thus the best possible estimates should be used. The ranges for D_{bio} and L_{bio} are quite large, and an extensive tabulation is presented by Matisoff (1982). An examination of this data suggests that a depth of bioturbation of 2-10 cm is typical and that biodiffusion coefficients are generally in the range of 0.3-30 cm^2/yr. As indicated previously, however, the contaminant flux is controlled by transport through the cap and is essentially insensitive to the bioturbation mass transfer coefficient.

Evaporation mass transfer coefficient Evaporation from natural, unagitated surfaces is normally water side controlled for sparingly soluble compounds such as those of interest in this discussion. We will take the overall evaporation mass transfer coefficient as equal to the water-side mass transfer coefficient. A water-side mass transfer coefficient for evaporative losses is given by Lunny (1983) as

$$K_e = 19.6\, U_x^{2.23} D_w^{2/3}$$

where U_x is the wind speed at 10m (miles/hr), D_w has units of cm^2/sec, and K_e has units of cm/hr.

Cap technical design Several design criteria are possible for specifying the physico-chemical containment afforded by a cap. There are at least five quantities which may be of interest to the cap designer and for which models were presented here. These are the breakthrough time, the pollutant release rate (as an source term input to other fate and effects models), concentrations at the sediment-water interface or in the overlying water column and the time to approach steady state. The two physico-chemical properties of the cap material which have the largest effect on the efficacy of the cap are the organic carbon content and the cap thickness. We will illustrate the design procedure for choosing the proper cap thickness and estimating the breakthrough time in the following example.

Example calculation of cap thickness Table 1 presents parameter values used for estimating polychlorinated biphenyl release from New Bedford Harbor sediments (Thibodeaux and Bosworth, 1990).

Table 1. Physico-Chemical Properties of Site Parameters

Cap Properties		
Organic carbon content	(f_{oc})	0.005
Porosity	(ϵ)	0.25
Bulk density	(ρ_b)	2.0 g/cm^3
Colloid concentration	(C_c)	20 mg/L
Effective cap thickness	(L_{eff})	35 cm
Aroclor 1242 Properties		
Solubility (salt water)	(s)	88 μg/L
Diffusivity in Water	(D_w)	4.5 x 10^{-6} cm^2/sec
Organic Carbon Partition Coeff.	(K_{oc})	198000 L/kg
Evaporative Mass Transfer Coeff.	(K_e)	7 cm/hr (Thibodeaux and Bosworth, 1990)
Site Properties		
Bioturbation Depth	(L_{bio})	10 cm
Biodiffusion Coefficient	(D_{bio})	10 cm^2/yr
A1242 sediment loading	(ω_A)	500 mg/kg
Extent of contamination	A_s)	10000 m^2
Evaporative mass transfer area	A_e	10000 m^2
Benthic Boundary Layer Velocity	(u)	10 cm/sec
Basin flushing rate	(Q)	1.7 x 10^{13} cm^3/day
Water Quality Criterion	(C_{WQC})	30 ng/L

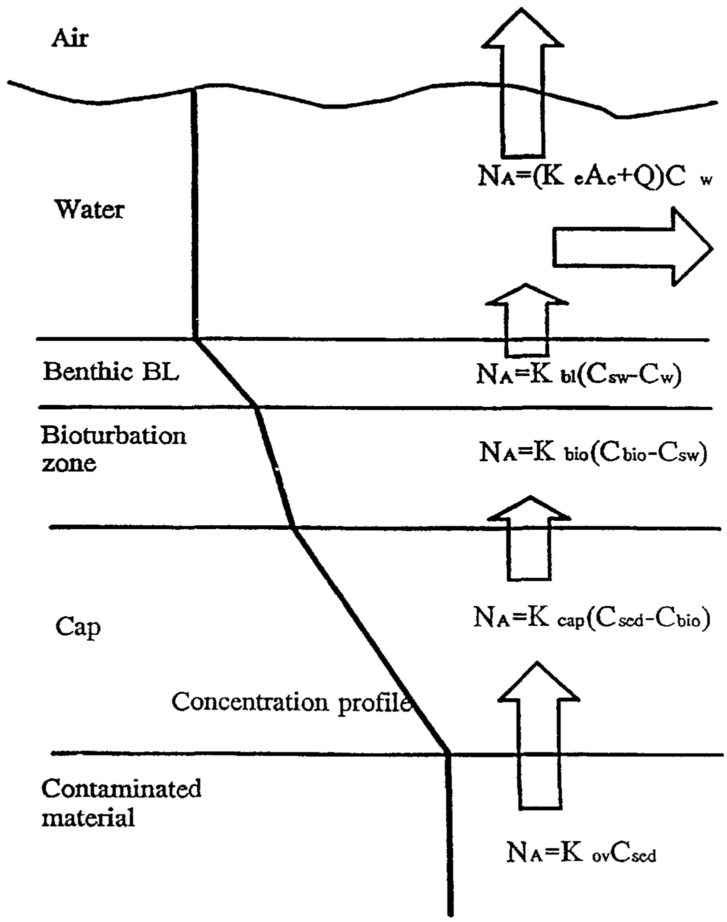

Figure B-1. Idealized contaminant concentration in a cap and sediment profile and flux relationships.

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Guidance for In-Situ Subaqueous Capping of Contaminated Sediments:

Appendix C: Case Studies on Geotechnical Aspects of In-Situ Sand Capping

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Appendix C: Case Studies on Geotechnical Aspects of In-Situ Sand Capping

Introduction

Industrial activities have resulted in significant deposits of contaminated sediments in some US harbors and waterways. Remediation of these contaminated sites can be costly and technically difficult. In-situ sand capping has been identified as a feasible and cost-effective technique for on-site remediation. The extremely low shear strength of these sediments presents unique engineering problems. The geotechnical aspects of successful in-situ sand capping projects conducted in the U.S., Japan, and Norway are reviewed and compiled in this report. Geotechnical assessment of in-situ capping technique, based on bearing capacity and slope stability analyses, is made with reference to these projects. Usage of geosynthetic of adequate strength and hydraulic conductivity is recommended to improve the sand cap stability in case where extremely soft sediments are encountered. Recommendations leading to improvement of sand capping design are included.

Significant deposits of contaminated submarine sediments are found within the U.S., in and around the Great Lakes, typically as a consequence of industrial manufacturing activities. These materials are physically characterized by a low shear strength and high compressibility. They are easily transferred to the water column as a result of disturbance by natural currents and maritime activities. For example, propeller wash from the traffic and movement of powerful vessels at shallow depths are found to be a source of significant disturbance. The Army Corps of Engineers has been involved in developing technical guidelines related to remediation by dredging and capping (Palermo et al., 1993).

The level-bottom capping and contained aquatic disposal are two of the most common methods of isolating dredged contaminants in the U.S. Clean materials, such as sand, have been used to cap the contaminated sediments. The Army Corps of Engineers, New England Division, initiated the first sand capping project on dredged sediments in Central Long Island Sound (CLIS) Disposal Site at Connecticut in 1979, as part of Disposal Area Monitoring System (DAMOS). This is referred to as Stamford/New Haven Project in which contaminated sediments were dredged from Stamford and New Haven Harbor. The Stamford sediments were deposited as two mounds, one capped with sand (2.1-3 m thick) and the other with silt (3.9 m thick). A successful sand capping project was also reported for the Mud Dump Site in New York Bright in 1980 (O'Connor and O'Connor, 1983).

The contaminated dredge material was capped with fine sediments from the Bronx River and Westchester Creek, then followed by sand from the Ambrose Channel. The cap was 1 m thick.

A comprehensive monitoring program was conducted when the Black Rock and New Haven Habors were dredged in 1983. Black Rock Harbor sediments were reported to be composed of organic silt and clay that were highly contaminated with oil, grease, heavy metals and PCB's. The dredged sediments from this site were placed in two mounds in CLIS Disposal Site and capped with silt from New Haven Harbor and sand from the nearby channel, respectively. A Field Verification Program (FVP) was also conducted on the uncapped sediments at the northeastern corner of CLIS site in order to evaluate the effectiveness of capping. A monitoring program was established for these sites and documented by SAIC (1984). Additional cases of sand capping projects may be found in Palermo et al. (1993).

Remediation of contaminated sediments by first dredging followed by disposal and capping at a site different from the source may not be the most economical solution. As the volume of contaminated material increases, an appropriate disposal site becomes limited. Risk of resuspension of contaminants into the water column increases by disturbance during dredging and disposal. Due to the extremely low shear strength of sediments immediately after dredging, cap placement is technically very difficult. This has led to use of different technology in Japan in which sand caps are placed directly over contaminated sediments without involving dredging (hereafter known as **in-situ capping**). The purpose of this report is to document the geotechnical aspects of several in-situ capping projects conducted in Japan, U.S. and other countries. The report also highlights cases in which geotextiles were used to improve stability of the sand caps placed on extremely soft sediments. Geotechnical evaluation of sand cap and foundation stability are made with reference to these case histories.

In-Situ Capping: Case Histories

Successful Japanese sand capping projects were conducted primarily on fishery grounds near the Seto Inland Sea (Figure C-1). This area has poor current circulation and is affected by heavy industrial discharges carried by several major rivers. **The red and blue tides have seriously affected the fisheries.** An experimental in-situ sand capping project was conducted in 1979 by the Port Construction Bureau of the Ministry of Transport. Since then, several other projects were conducted (see Table 1). Figure C-1 gives the individual location of these sites. Earlier studies related to in-situ sand capping projects tend to focus on the chemical and biochemical aspects of the sand-sediment-water column environment. It has, however, been recognized that success of this technique depends also on geotechnical considerations. The following is a description of a few of the well-documented cases with insight on geotechnical properties. Later, these cases are utilized for geotechnical evaluation.

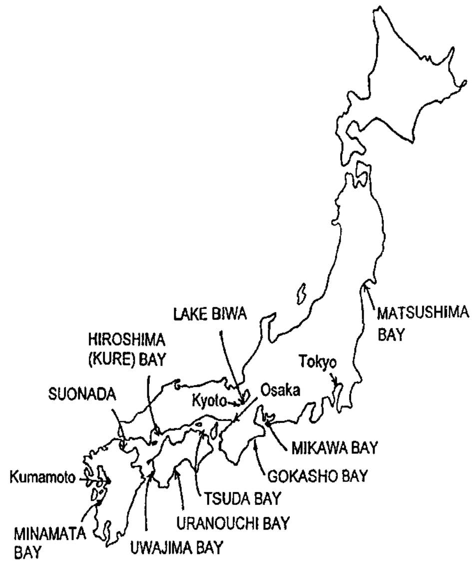

Figure C-1. Sand capping sites in Japan.

Table 1. Detail of Sand Capping Sites

SITE	YEAR	DEPTH BELOW SEA LEVEL (m)	CAP THICKNESS (cm)	AREA (10^3 m^2)	MAIN REFERENCE
Hiroshima Bay	1979	21	50	19.2	Horie
(Japan)	1980	21	30	44.8	(1991)
	1979		15	1.2	P.C.B.
Uranouchi Bay		13-14	15	10.0	(1994)
(Japan)		6-9	20	7.4	
Suonada Bay					P.C.B.
(Japan)	1986	1	30	0.9	(1994)
	1987	5	50	15.0	P.C.B.
Mikawa Bay			40-100	9.6	(1994)
(Japan)			40-100	4.5	
Minamata Bay[1] (Japan)	1988	2-10	80	324.7	Namba (1994)
	1991	10-15	50	212.8	P.C.B.
Tsuda bay	1992	10-15	50	114.0	(1994)
(Japan)	1993	10-15	50	91.2	
Lake Biwa[2]					Gomyoh et
(Japan)	1992	1.5	20	24.2	al.
Matsushima					(1994)
Bay[2] (Japan)	1993	3	30	19.2	
Gokasho Bay					P.C.B.
(Japan)			20	106.9	(1994)
Uwajima Bay					P.C.B.
(Japan)			20	46.8	(1994)
Soerfjorden[1] (Norway)	1991	10	30-60	100	Instanes (1994)
Eagle Harbor	1993	17	100	99.1	Gilbert
(US)		13	100	117.4	(1994)

1: Geotextile was installed

2: Sand capping after dredging

Hiroshima/Kure Site

The chemical and biochemical aspects of this site are found in Kuroda and Fujita (1981), Fujita (1980), Ichikawa et al.(1981), and Horie (1991). The sand capping project was conducted in two phases. Phase 1 was conducted in 1979 covering an area of 160 m×120 m. Phase 2 was conducted a year later and covered an area 2.3 times that of Phase 1. Sand dredged from the nearby sea was used as capping material (mean diameter= 0.1-10 mm, G_s=2.62). The cap thickness was 50 cm and 30 cm, respectively, for phase 1 and 2. As shown in Figure C-2, the two sites overlap each other.

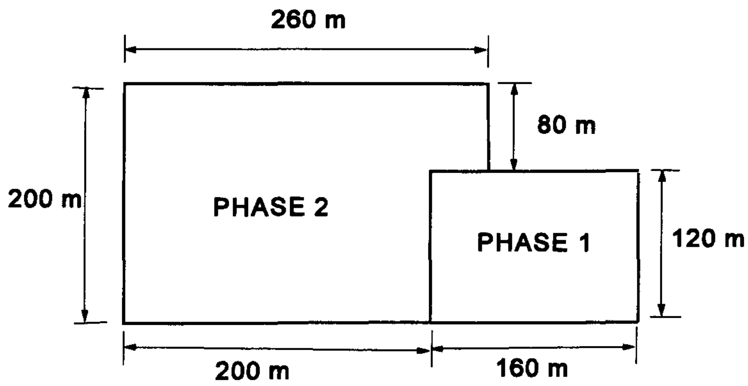

Figure C-2 Configuration of Hiroshima Site

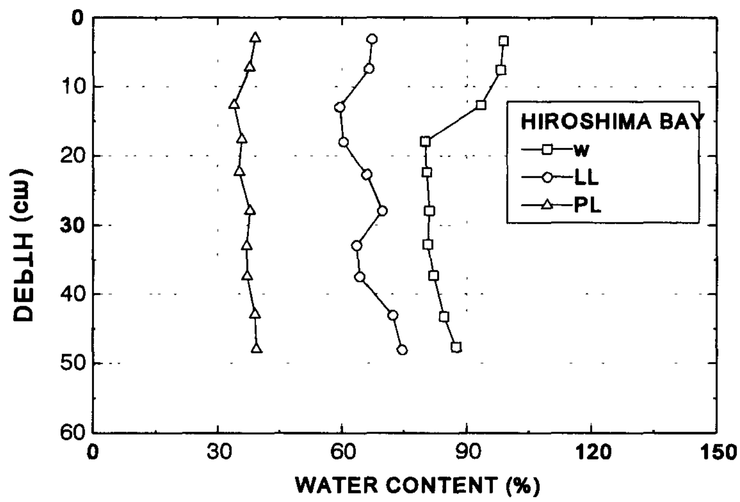

Figure C-3 Index Properties of Hiroshima Bay Sediments
(after Gomyoh et al., 1994)

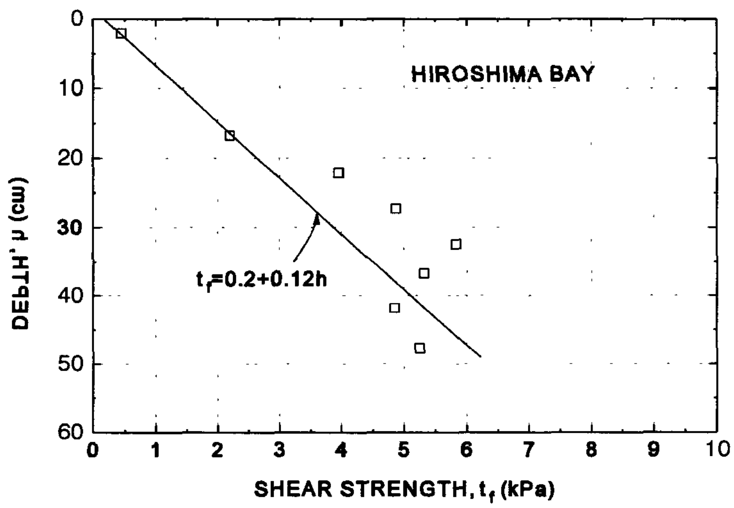

Figure C-4 Vane Shear Strength of Hiroshima Bay Sediments
(after Gomyoh et al., 1994)

The properties of the contaminated sediment were described by Gomyoh et al (1994). The natural water content of the first 10-20 cm of the mud is close to 100% (Figure C-3). The value at greater depths is about 80%, still higher than the liquid limit. Figure C-4 shows the typical value of vane shear strength distribution with depth. The undrained shear strength in the top 20 cm is extremely low, but increases linearly to 5 kPa as the depth increases to 50 cm. The sediments were slightly overconsolidated at the surface.

Matsushima Bay and Lake Biwa Sites

Toa Corporation conducted experimental projects at these two sites (Toa Corporation, 1994; Gomyoh et al., 1994). Sand capping at Lake Biwa covered an area of 110 m × 200 m. At Matsushima Bay, the project was composed of three areas, each 15 m×15 m. At Lake Biwa site, the upper 20 cm of sediment and then the area was covered with sand 20 cm thick. At Matsushima site, a 1.9 m thick sediment deposit was first dredged followed by a sand cap of 30 cm. The index properties of the bottom sediments at the sites are shown in Figures C-5 and C-6. Matsushima Bay mud has a natural water content as high as 250% The vane shear strength of these sites are given in Figures C-7 and C-8. The sediments at both sites show slight overconsolidated behavior. Piezocone penetration tests were conducted before and after dredging at Lake Biwa. It was reported that negligible strength reduction has resulted from dredging. Typical values of strength variation with depth are shown in Figure C-8. The sand used at Lake Biwa has a mean diameter of about 0.8 mm and a unit weight of 15.5 kN/m^3. Two types of sand were used at Matsushima Bay, one has a mean diameter of 0.25 mm and a unit weight of 11.7 kN/m^3 (dredged sand), and the other sand has a mean diameter of 0.45 mm and a unit weight of 15.6 kN/m^3.

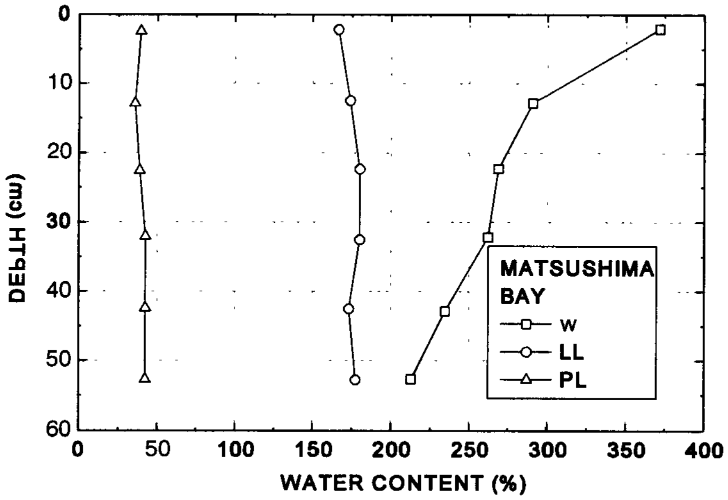

Figure C-5 Index Properties of Matsushima Bay Sediments
(after Gomyoh et al., 1994)

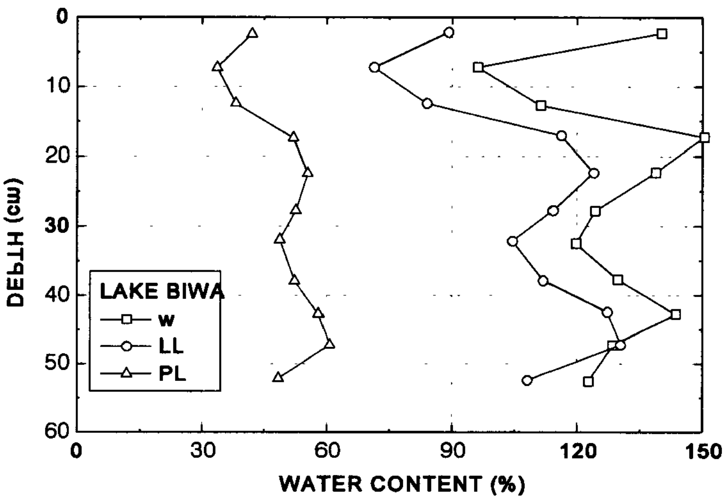

Figure C-6 Index Properties of Lake Biwa Sediments
(after Gomyoh et al., 1994)

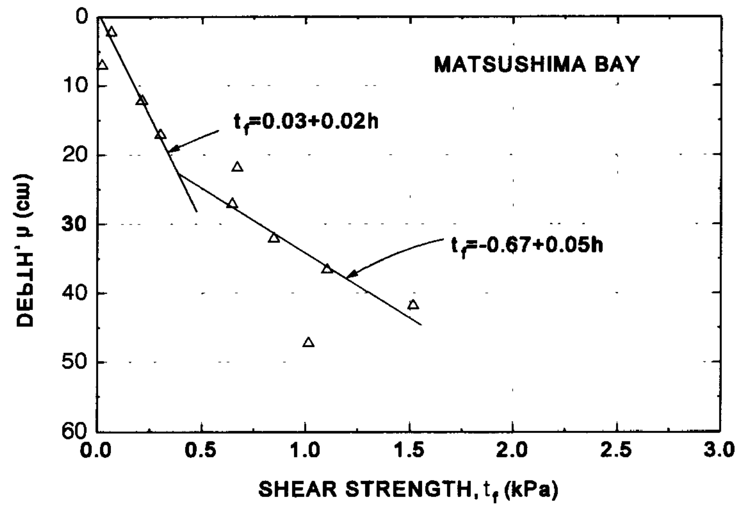

Figure C-7 Shear Strength of Matsushima Bay Sediments (after Gomyoh, et al., 1994)

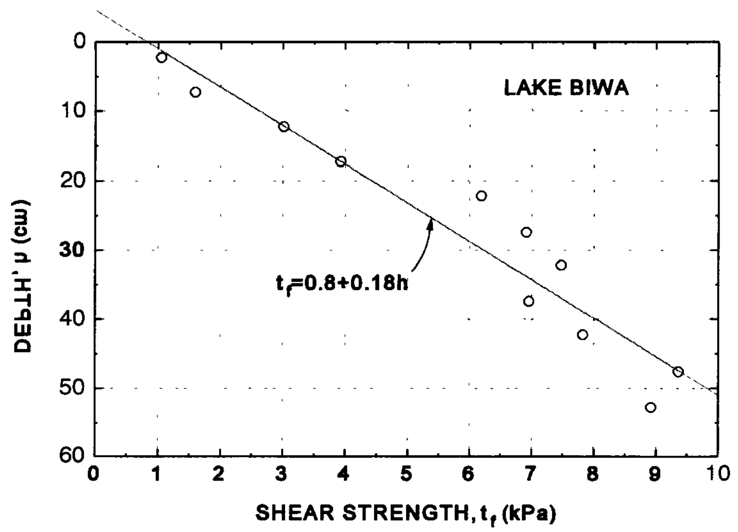

Figure C-8 Shear Strength of Lake Biwa Sediments (after Gomyoh et al., 1994)

Eagle Habor Site

The first in-situ sand capping project conducted in the US was that of the Eagle Harbor at the Wyckoff/Eagle Harbor Superfund Site (Figure C-9). The site was highly contaminated with mercury and polynuclear aromatic hydrocarbons. It was decided to cap two areas at the site with different materials. Areas 1 and 2 are at a water depth of 17 and 13 m, respectively. A split hull barge was used in Area 1 and the water jet washing of material off of a barge was used for Area 2. A sediment sample obtained at a point between Areas 1 and 2 shows that the sediments are comprised of 80% silt and 20% clay. Sediment properties were reported by Nelson, Vanerberden and Schuldt (1994) as LL= 40-50%, PL= 30%, G_s=2.65. The average unit weight of the sand cap was 16.4 kN/m^3. The targeted cap thickness was 1 m, but post construction surveying indicated slight variation of the final cap thickness over the site. Vane shear strengths obtained shortly after placement of the cap is shown in Figure C-10. These values are considerably higher than most Japanese sites. The measured in-situ shear strength indicated that the sediment is overconsolidated.

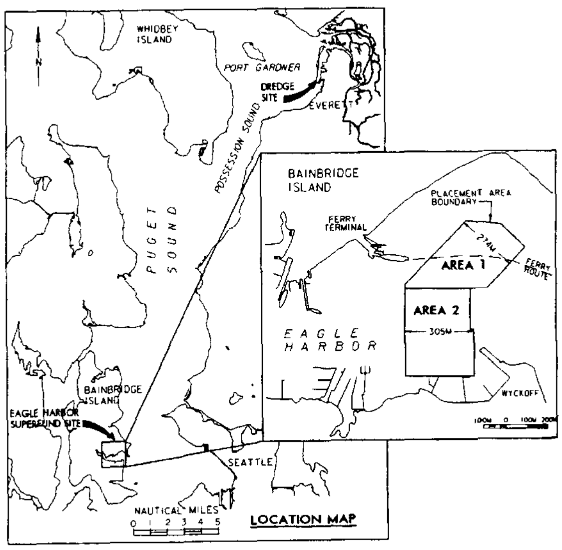

Figure C-9 Eagle Harbor Site (U.S.A.)

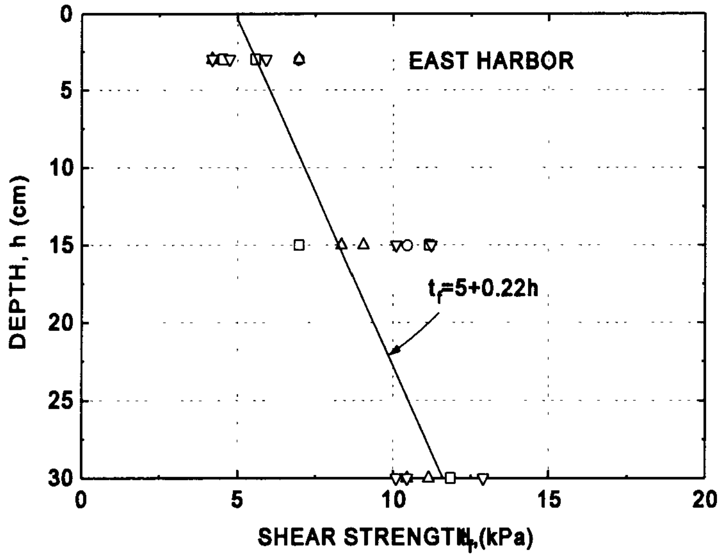

Figure C-10 Shear Strength of Eagle Harbor Site Sediments (after Gilbert, 1994)

In-situ Sand Capping Utilizing Geosynthetic: Case Histories

In-situ sand capping may not be feasible if the submarine sediment is extremely soft to the point where the sediment is not capable of supporting a cap. The geosynthetic sheet, placed between the cap and the soft sediment, allows the sand cap to be constructed over the soft foundation. With the geosynthetic in place, sediments may consolidate under the sand cap load and gain strength. The sand cap restrains the geosynthetic sheet and prevents migration of contaminated fines into the water column. Two successful projects, from Japan and Norway, are summarized below.

Minamata Site

Geosynthetics have been used in nearshore reclamation works in Japan since the 1960's (e.g., Fukuzumi and Nishibayashi, 1967; Watari and Higuchi, 1985). This experience led to a successful sand capping at Minamata site. The sediments at this site were highly contaminated with mercury. Human consumption of contaminated fish from this area led to the well known Minamata disease. It was decided that the sediments with mercury concentration greater than 25 ppm were to be dredged and capped. Hirose and Yamaguchi (1990) reported on the general aspects of this project.

A schematic drawing of Minamata site is shown in Figure C-11. It has an extremely soft sediment layer between 4.3 - 6.8 m deep. Some of the index properties are: G_s=2.71, LL=96%, PL=38.5%, PI=57.5% (Umehara and Zen, 1981). Figure C-12 shows the typical variation of strength with depth. The shear strength for this site is considerably lower than other Japanese capping sites. It exhibits normally consolidated behavior. Geotextile sheets, with a tensile strength of 78 kN/m and a hydraulic conductivity of 4.4×10^{-2} cm/s, were used. These geotextile sheets, each 30 m x 51 m, were laid over the dredged sediments with a 1 m overlay along the edges of the sheets to allow for possible differential settlement. Sand ($\phi=25^\circ$, $\gamma=10$ kN/m^3, D_{50}=0.1 mm) was spread in two layers under water. The water table was adjusted so that it was maintained at 50 cm during sand spreading. Water was then removed and the contaminated sediments were capped permanently with another type of sand ($\gamma=14.7$ kN/m^3, D_{50}=0.7 mm), 2 m thick, on top.

Soerfjorden Site

Geosynthetic was used in a sand capping project in Soerfjord, Norway (Instanes, 1994). The site was highly contaminated with heavy metals. The sediments have an undrained shear strength of 5-10 kPa and natural water content of 35%. The geosynthetic used was a composite material manufactured from polyester, density is higher than the water. It is comprised of a nonwoven geomembrane and a woven polyester geotextile which acted as separation/filter function and tensile reinforcement (Colins, 1994). The strength of geosynthetic was 50 kN/m. Polyester is denser than water, and thus, facilitated installation process. Fourteen geosynthetic sheets were placed with a minimum overlay of 2.5 m to allow for settlement. Finally, a sand cap of 30-60 cm was placed.

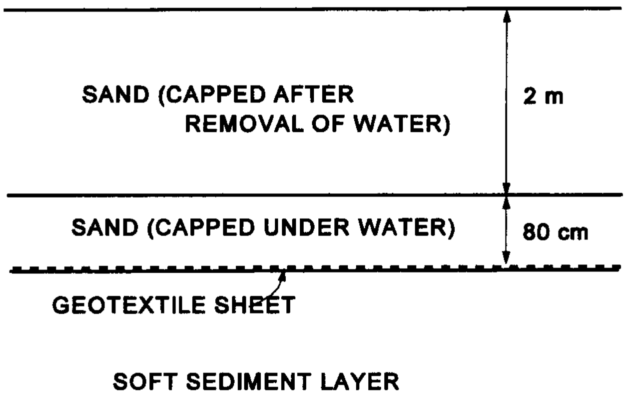

Figure C-11 Configuration of Sand Cap at Minamata Site (after Namba, 1994)

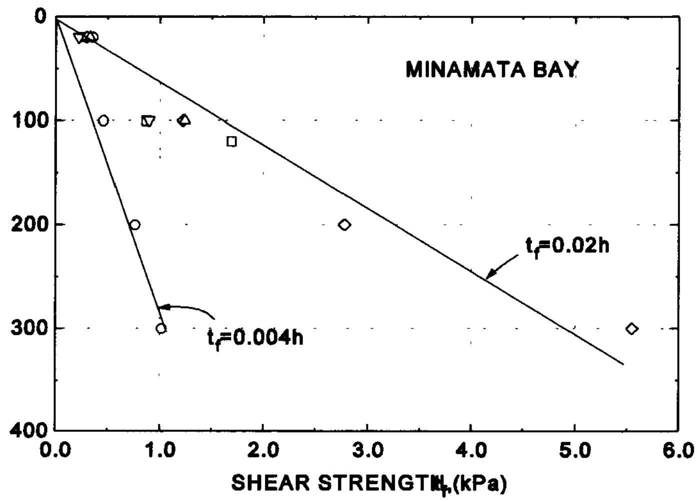

Figure C-12 Shear Strength of Minamata Site Sediments (after Namba, 1994)

Geotechnical Considerations

In a capping project, there are several objectives to be considered regarding the cap thickness. For example, the sand cap should be sufficiently thick to offer chemical isolation, protection from intrusion as the result of bioturbidity, and protection from breach as the result of erosion. From a geotechnical view point, a larger cap thickness may lead to instability if the sediments have very low shear strength.

The cap stability and settlement due to consolidation are two main geotechnical issues. However, the most critical aspect of the cap would be its stability immediately after placement, before any excess pore water pressure due to the weight of the sand layer has dissipated. The settlement is related to long-term performance of the cap as the sediments consolidate simultaneously with the dissipation of excess pore water pressure while gaining additional strength. In this report, *(the (BF))* discussion will be focused on a short term stability analysis (i.e., the most critical state) of the sand cap as viewed from bearing capacity and slope stability analysis.

Bearing Capacity Analysis

In bearing capacity analysis, the sand cap is considered as a footing acting over large area. The footing contact pressure is replaced by an equivalent surcharge, q, due to the cap's effective unit weight, γ', and thickness, h. That is,

$$q = \gamma' h \qquad (1)$$

In undrained analysis, considering local shear failure (i.e., punching mode of failure) and a footing embedded on a purely cohesive soil with zero depth into the foundation, the ultimate bearing capacity, q_{ult}, is determined as (Terzaghi and Peck, 1967):

$$q_{ult} = 2/3\ c_u\ N_c \qquad (2a)$$

and

$$N_c = (2 + \pi) \qquad (2b)$$

where c_u is the undrained shear strength, and N_c is the bearing capacity factor. The usage of local failure is justified in sand capping projects because the bottom sediments are soft, and therefore, do not allow the classical bearing capacity type of failure to occur.

In design, the allowable surcharge is obtained by reducing the ultimate bearing capacity by a safety factor, typically of value 3. Thus, combining Eqs. (1) and (2), the allowable cap thickness, h_{allow}, is determined as

$$h = 1.14\ \ c_u / \gamma' \qquad (3)$$

Assuming a typical value of $\gamma' = 5\ kN/m^3$ and $c_u = 1$ to 2 kPa, the allowable cap thickness is between 20 and 50 cm. This range of value explained reasonably the success of most sand capping projects.

It should be pointed out that traditional bearing capacity analysis (Eq. 3) assumes a constant value of undrained shear strength. However, the review of case histories indicates that soft sediments are having undrained shear strength that increases with depth. Therefore, it is recommended to sing a small value of c_u) and only when limited shear strength data of the foundation are available.

Cap Stability Analysis

Cap slope stability is analyzed using a computer program with the procedure proposed by Leshchinsky (1987) and Leshchinsky and Smith (1989). It is based on a limit equilibrium approach considering a log-spiral and a circular failure mechanisms in the sand cap and soft sediments, respectively. If stability cannot be attained, the analysis will indicate whether geosynthetic reinforcement is needed or whether additional consolidation must be allowed to occur prior to cap placement. The analysis determines the geosynthetic strength required to restore stability if the safety factor falls below a specified value. The notation used is shown in Figure C-13.

Since the in-situ cap is completely submerged, the buoyant unit weight (γ') and the design value of the internal friction angle of the sand (ϕ_d) are specified. The water depth above the cap does not affect its effective stresses (and thus the cap stability) if external forces, such as waves, are not excessive. Different layers of sediments having depth (d_i) and undrained shear strength ($c_m=c_u/F_s$, F_s: safety factor) may be specified. The strength of each layer can be specified as a constant value or varying linearly with depth (Figure C-14).

It should be noted that the water depth affects the falling velocity of sand particles placed in water leading to different impact energy as they reach the sediments. This may result in different penetration depths into the soft sediments and affect the unit weight of sand. The shear strength of sand is also affected by this unit weight. However, since accurate identification of subaqueous material properties is very limited, it seems justified to ignore these effects at this stage. That is, the quantification of properties is not warranted considering the potential uncertainties in design.

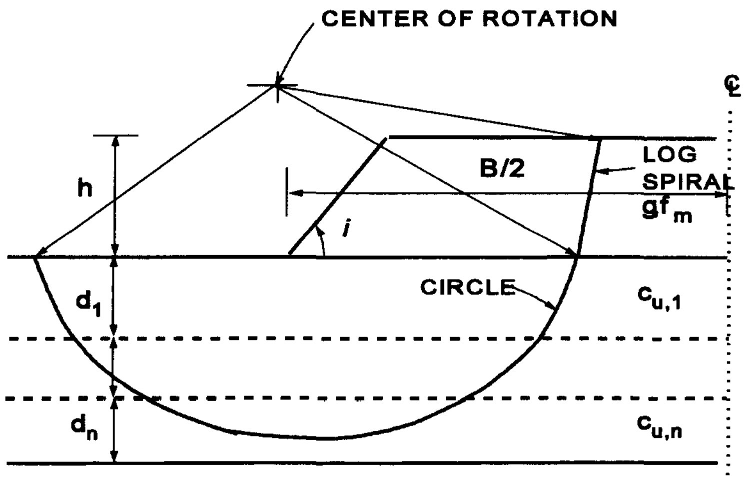

Figure C-13 Cap Stability Analysis

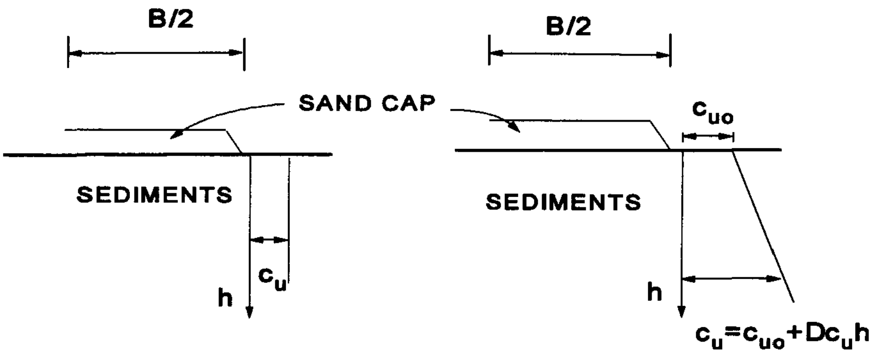

Figure C-14 Variation of Undrained Strength with Depth

Stability analyses were conducted for several of the reported case histories (Hiroshima, Minamata, Lake Biwa, Matsushima, and Eagle Harbor). Sediment properties required for stability analysis are available only at these sites (Table C-2). The internal friction angle of the sand and the slope angle of the cap are assumed as 35° and 30°, respectively. This is by assuming the largest possible angle of repose under water since the actual value was not available. Since the submerged unit weight of sand at the Hiroshima site is not available, it is assumed as 6.0 kN/m^3 in the analysis.

Table C-2 shows the sand cap thickness analyzed using a safety factor of 1.0 applied to the soils. Consequently, the calculated cap thickness signifies the maximum theoretical cap thickness. The analysis shows that Hiroshima site, Lake Biwa and Eagle Habor sites are stable against potential failure. In particular, the Eagle Harbor site has an extremely large safety margin. The analysis indicates that the Minamata site requires the sand cap to be placed with the aid of geosynthetic. The required geosynthetic strength is 7 N/m based on γ'= 0.2 kN/m^3. If γ' is assumed as 6.0 kN/m^3 (i.e., a reasonable design value), the required geosynthetic strength increases significantly to 3.2 kN/m. The analysis also indicates possible instability of the sand cap at the Matsushima site. The required geosynthetic strengths are 4 N/m and 77 N/m for γ'= 1.9 kN/m^3 and 5.8 kN/m^3, respectively. The successful sand cap placement at this site could have been due to dredging away of the top extremely soft sediment layer so that the actual sediments strength was larger than that used in the analysis. That is, dredging the top 20 cm of the sediment exposed the stronger sediment layer as foundation for the sand cap without the use of geosynthetic reinforcement.

Table C-2. Computed and Constructed Sand Cap Thickness

Capping Site	Undrained Strength of Contaminated Sediments $C_u = C_{uo} + \Delta c_u$ x depth		Effective Unit Weight of Cap Material	Constructed Cap Thickness	Computed Cap Thickness (max stable thickness)
	c_{uo} (kPa)	Δc^u(kPa/m)	γ' (kN/m^3)	(cm)	(cm)
Hiroshima	0.2	12	6.0*	50	58
Minamata	0	0.4	0.2	80	**
Lake Biwa	0.8	18	5.7	20	295
Matsushima	0.03	2	1.9	30	22***
			5.8	30	5***
Eagle Harbor	5	22	6.6	100	>17m

*assumed value

**construction is infeasible without reinforcement. In actual construction, geosynthetic reinforcement was used.

***actual sediment strength was likely greater than that before dredging.

Conclusions and Recommendations

Successful case histories related to in-situ sand capping projects are reviewed and presented. This technique has been evaluated and proved feasible from a geotechnical view point. At the sites where the sediments are of extremely low strength, geosynthetics of adequate strength and permeability can improve the stability of the sand cap. Dredging away the top layer (10 - 20 cm) may also be a feasible solution. There are several topics that need to be further studied so that in-situ capping technique and its design procedure may be verified and refined:

1. It appears that construction technique is an important factor in the success of a sand capping projects. Sand dumped in lumps may penetrate the soft sediments and may cause resuspension of contaminants into the water column. Conversely, "raining" the sand in layers will allow gentle spreading and result in a stable sand cap. It is recommended that laboratory model tests be conducted and the performance monitored and quantified. This should lead to an optimized construction procedure which takes the geotechnical properties of the sediments into account.

2. It is suggested to develop an analytical technique which may be used to predict the density of sands pluviated in water. Experimental work should also be conducted to verify the theory. The effect of soil grain size, water depth and foundation compressibility should be considered as the parameters in the analytical and experimental studies.

3. It is recommended that the roles of a geosynthetic (reinforcement, separation, and filtration) in maintaining the cap integrity be considered in future research. This should also be studied and quantified using a well-controlled experimental work, including "control tests" which do not have a geosynthetic layer.

4. A reliable procedure to estimate the in-situ distribution of sediments strength is needed.

5. Potential external forces, in particular waves, need to be included in future studies.

6. Finally, a versatile procedure which considers the deformations, generation and dissipation of excess pore water pressure from the sediments should be developed.

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