PDHonline Course C806 (4 PDH)

In-Situ Capping of Contaminated Sediments

Instructor: Michael J. Dickey, P.E.

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PDH Online | PDH Center

5272 Meadow Estates Drive
Fairfax, VA 22030-6658
Phone: 703-988-0088
www.PDHonline.com

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Contaminated Sediment Remediation Guidance for Hazardous Waste Sites

5.0 IN-SITU CAPPING

5.1 INTRODUCTION

For purposes of this guidance, in-situ capping refers to the placement of a subaqueous covering or cap of clean material over contaminated sediment that remains in place. Caps are generally constructed of granular material, such as clean sediment, sand, or gravel. A more complex cap design can include geotextiles, liners, and other permeable or impermeable elements in multiple layers that may include additions of material to attenuate the flux of contaminants (e.g., organic carbon). Depending on the contaminants and sediment environment, a cap is designed to reduce risk through the following primary functions:

- Physical isolation of the contaminated sediment sufficient to reduce exposure due to direct contact and to reduce the ability of burrowing organisms to move contaminants to the surface;
- Stabilization of contaminated sediment and erosion protection of sediment and cap, sufficient to reduce resuspension and transport to other sites; and/or
- Chemical isolation of contaminated sediment sufficient to reduce exposure from dissolved and colloidally bound contaminants transported into the water column.

Caps may be designed with different layers to serve these primary functions or in some cases a single layer may serve multiple functions.

As of 2004, In-situ capping has been selected as a component of the remedy for contaminated sediment at approximately fifteen Superfund sites. At some sites, in-situ capping has served as the primary approach for sediment, and at other sites it has been combined with sediment removal (i.e., dredging or excavation) and/or monitored natural recovery (MNR) of other sediment areas. In-situ capping has been successfully used at a number of sites in the Pacific Northwest, several of which were constructed over a decade ago (see site list at http://www.epa.gov/superfund/resources/sediment/sites.htm). When hazardous substances left in place are above levels allowing for unlimited use and unrestricted exposure, a five-year review pursuant to the Comprehensive Environmental Response, Compensation and Liability Act (CERCLA) §121(c) may be required [U.S. Environmental Protection Agency (U.S. EPA 2001i)].

Variations of in-situ capping include installation of a cap after partial removal of contaminated sediment and innovative caps, which incorporate treatment components. Capping is sometimes considered following partial sediment removal where capping alone is not feasible due to a need to preserve a minimum water body depth for navigation or flood control, or where it is desirable to leave deeper contaminated sediment in place to preserve bank or shoreline stability following removal. There are pilot studies underway to investigate the effectiveness of in-situ caps that incorporate various forms of treatment (see Chapter 3, Section 3.1.3, In-Situ Treatment and Other Innovative Alternatives). Application of thin layers of clean material may be used to enhance natural recovery through burial and mixing with clean sediment when natural sedimentation rates are not sufficient (see Chapter 4, Section 4.5, Enhanced Natural Recovery). Placement of a thin layer of clean material is also sometimes used to backfill dredged areas, where it mixes with dredging residuals and further reduces risk from contamination that remains after dredging. In this application, the material is not often designed to act as an engineered cap to isolate buried contaminants and is, therefore, not considered in-situ capping in this guidance.

Much has been written about subaqueous capping of contaminated sediment. The majority of this work has been performed by, or in cooperation with, the U.S. Army Corps of Engineers (USACE). Comprehensive technical guidance on in-situ capping of contaminated sediment can be found in the EPA's *Assessment and Remediation of Contaminated Sediment (ARCS) Program Guidance for In-Situ Subaqueous Capping of Contaminated Sediments* (U.S. EPA 1998d) and the *Assessment and Remediation of Contaminated Sediments (ARCS) Program Remediation Guidance Document* (U.S. EPA 1994d), available through EPA's Web site at http://www.epa.gov/glnpo/sediment/iscmain. Additional technical guidance is available from the USACE's *Guidance for Subaqueous Dredged Material Capping* (Palermo et al. 1998a)

Although each of the three potential remedy approaches (MNR, in-situ capping, and removal) should be considered at every site at which they might be appropriate, capping should receive detailed consideration where the site conditions listed in Highlight 5-1 are present.

Highlight 5-1: Some Site Conditions Especially Conducive to In-Situ Capping

- Suitable types and quantities of cap material are readily available
- Anticipated infrastructure needs (e.g., piers, pilings, buried cables) are compatible with cap
- Water depth is adequate to accommodate cap with anticipated uses (e.g., navigation, flood control)
- Incidence of cap-disrupting human behavior, such as large boat anchoring, is low or controllable
- Long-term risk reduction outweighs habitat disruption, and/or habitat improvements are provided by the cap
- Hydrodynamic conditions (e.g., floods, ice scour) are not likely to compromise cap or can be accommodated in design
- Rates of ground water flow in cap area are low and not likely to create unacceptable contaminant releases
- Sediment has sufficient strength to support cap (e.g., higher density/lower water content, depending on placement method)
- Contaminants have low rates of flux through cap
- Contamination covers contiguous areas (e.g., to simplify capping)

5.2 POTENTIAL ADVANTAGES AND LIMITATIONS

Two advantages of in-situ capping are that it can quickly reduce exposure to contaminants and that, unlike dredging or excavation, it requires less infrastructure in terms of material handling, dewatering, treatment, and disposal. A well-designed and well-placed cap should more quickly reduce the exposure of fish and other biota to contaminated sediment as compared to dredging, as there should be no or very little contaminant residual on the surface of the cap. Also, the cap often provides a clean substrate for recolonization by bottom-dwelling organisms. Changes in bottom elevation caused by a cap may create more desirable habitat, or specific cap design elements may enhance or improve habitat substrate. Another possible advantage is that the potential for contaminant resuspension and the risks associated with dispersion and volatilization of contaminated materials during construction are typically lower for in-situ capping than for dredging operations and risks associated with transport and disposal of contaminated sediment are avoided. Most capping projects use conventional equipment and locally available materials, and may be implemented more quickly and may be less expensive than remedies involving removal and disposal or treatment of sediment.

In-situ capping may be less disruptive of local communities than dredging or excavation. Although some local land-based facilities are often needed for materials handling, usually no dewatering, treatment, or disposal facilities need to be located and no contaminated materials are transported through communities. Where clean dredged material is used for capping, a much smaller area of land-based facilities is needed.

The major limitation of in-situ capping is the contaminated sediment remains in the aquatic environment where contaminants could become exposed or be dispersed if the cap is significantly disturbed or if contaminants move through the cap in significant amounts. In addition, in some environments, it can be difficult to place a cap without significant contaminant losses from compaction and disruption of the underlying sediment. If the water body is shallow, it may be necessary to develop institutional controls (ICs), which can be limited in terms of effectiveness and reliability, to protect the cap from disturbances such as boat anchoring and keel drag.

Another potential limitation of in-situ capping may be in some situations, a preferred habitat may not be provided by the surficial cap materials. To provide erosion protection, it may be necessary to use coarse cap materials that are different from native soft bottom materials, which may alter the biological community. In some cases, it may be desirable to select capping materials that discourage colonization by native deep-burrowing organisms to limit bioturbation and release of underlying contaminants.

5.3 EVALUATING SITE CONDITIONS

A good understanding of site-specific conditions typically is critical to predicting the expected feasibility and effectiveness of in-situ capping. Site conditions can affect all aspects of a capping project, including design, equipment and cap material selection, and monitoring and management programs. Some limitations in site conditions can be accommodated in the cap design. General aspects of site characterization are discussed in Chapter 2, Remedial Investigation Considerations. Some specific aspects of site characterization important for in-situ capping are introduced briefly in the following sections.

5.3.1 Physical Environment

Aspects of the physical environment that should be considered include water body dimensions, depth and slope (bathymetry) of sediment bed, and flow patterns, including tides, currents, and other potential disturbances in cold climates, such as an ice scour. Existing infrastructure such as bridges, utility crossings, and other marine structures are discussed in Section 5.3.3.

The bathymetry of the site influences how far cap material will spread during placement and the cap's stability. Flat bottoms and shallow slopes should allow material to be placed more accurately, especially if capping material is to be placed hydraulically. Water depth also can influence the amount of spread during cap placement. Generally, the longer the descent of the cap material through the water column, the more water is entrained in the plume, resulting in a thinner layer of cap material over a larger area.

The energy of flowing water is also an important consideration. Capping projects are easier to design in low energy environments (e.g., protected harbors, slow-flowing rivers, or micro-tidal estuarine systems). In open water, deeper sites are generally less influenced by wind or wave generated currents and less prone to erosion than shallow, near-shore environments. However, armoring techniques or selection of erosion-resistant capping materials can make capping technically feasible in some high energy environments. Currents within the water column can affect dispersion during cap placement and can influence the selection of the equipment to be used for cap placement. Bottom currents can generate shear stresses that can act on the cap surface and may potentially erode the cap. In addition to ambient currents due to normal riverine or tidal flows, the project manager should consider the effects of storm-induced waves and other episodic events (e.g., floods, ice scour).

The placement of an in-situ cap can alter existing hydrodynamic conditions. In harbor areas or estuaries, the decrease in depth or change in bottom geometry can affect the near-bed current patterns, and thus the flow-induced bed shear stresses. In a riverine environment, the placement of a cap generally reduces depth and restricts flow and may alter the sediment and flood-carrying capacity of the channel. Modeling studies may be useful to assess these changes in site conditions where they are likely to be significant. Project managers are encouraged to draft decision documents that include some flexibility in requirements for how a cap affects carrying capacity of a water body, while still meeting applicable or relevant and appropriate requirements (ARARs). For example, in some water bodies, a cap may be appropriate even though it decreases, but not significantly, the flood-carrying capacity. In depositional areas, the effect of new sediment likely to be deposited on the cap should be considered in predicting future flood-carrying capacity. Clean sediment accumulating on the cap can increase the isolation effectiveness of the cap over the long term and may also increase consolidation of the underlying sediment bed.

5.3.2 Sediment Characteristics

The project manager should determine the physical, chemical, and biological characteristics of the contaminated sediment pursuant to using the data quality objective (DQO) process during the remedial investigation. The results of the characterization, in combination with the remediation goals and remedial action objectives (RAOs), should determine the areal extent or boundaries of the area to be capped.

Shear strength, especially undrained shear strength, of contaminated sediment deposits is of particular importance in determining the feasibility of in-situ capping. Most contaminated sediment is fine-grained, and is usually high in water content and relatively low in shear strength. Although a cap can be constructed on sediment with low shear strengths, the ability of the sediment to support a cap and the need to construct the cap using appropriate methods to avoid displacement of the contaminated sediment should be carefully considered. The presence of other materials within the sediment bed, such as debris, wood chips, high sludge fractions, or other non-mineral-based sediment fractions, can also present special problems when interpreting grain size and other geotechnical properties of the sediment, but their presence can also improve sediment stability under a cap. It could be necessary to remove large debris prior to placing a cap, for example, if it will extend beyond the cap surface and cause scouring. Side-scan sonar can be an effective tool to identify debris.

The chemical characteristics of the contaminated sediment are an important factor that may affect design or selection of a cap, especially if capping highly mobile or highly toxic sediment. Capping may change the uppermost layer of contaminated sediment from an oxidizing to an anoxic condition, which may change the solubility of metal contaminants and the susceptibility of organic contaminants to microbial decomposition in this upper zone. For example, many of the divalent metal cations (e.g., lead, nickel, zinc) become less soluble in anaerobic conditions, while other metal ions (e.g., arsenic) become more soluble. Mercury, in the presence of pore water sulfate concentrations and organic matter, can become methylated through the action of anaerobic bacteria, and highly chlorinated, polychlorinated biphenyls (PCBs) may degrade to less chlorinated forms in an anaerobic environment. These issues are also discussed in Chapter 4, Section 4.3.2, Biological and Chemical Processes.

When contaminated sediment is capped, chemical conditions in the contaminated zone change. Mercury methylation is generally reduced as organic matter deposition and biological processes are reduced. Organic matter remaining beneath a cap may be decomposed by anaerobic microorganisms and release methane and hydrogen sulfide gases. As these dissolved gases accumulate, they could percolate through the cap by convective or diffusive transport. This process has the potential to solubilize some contaminants and carry them upward, dissolved in the gaseous bubbles. The grain size of the capping material controls in part how these avenues are developed. Finer grained caps may develop fissures whereas coarser grained caps such as sands allow gas to pass through. However, a compensating factor in some cases is caused by the caps' insulation ability, which can cause underlying sediment to stay cooler and thus reduce expected decomposition rates. Where gas generation is expected to be significant, these factors should be considered during cap design.

5.3.3 Waterway Uses and Infrastructure

If the site under consideration is adjacent to or within a water body used for navigation, recreation or flood control, the effect of cap placement on those uses should be evaluated. As described in Section 5.3.1, the flood-carrying capacity of a water body could be reduced by a cap. If water depths are reduced in a harbor or river channel, some commercial and recreational vessels may have to be restricted or banned. The acceptable draft of vessels allowed to navigate over a capped area depends on water level fluctuations (e.g., seasonal, tidal, and wave) and the potential effects of vessel groundings on the cap. Potential cap erosion caused by propeller wash should be evaluated. Where circumstances dictate, an analysis should be conducted for activities that may affect cap integrity such as the potential for routine anchoring of large vessels. Anchoring by recreational vessels may or may not compromise the integrity of a cap, depending on its design. Such activities may indicate the need for restrictions (see Chapter 3, Section 3.6, Institutional Controls) or a modification of the cap design to accommodate certain activities. It may be necessary to restrict fishing and swimming to prevent recreational boaters from dragging anchors across a cap. In some situations, partial dredging prior to cap placement may minimize these limitations of capping.

Other activities in and around the water body may also impact cap integrity and maintenance needs and should be evaluated. These include the following:

- Water supply intakes;
- Storm water or effluent discharge outfalls;
- Utilities crossings;
- Construction of bulkheads, piers, docks, and other waterfront structures;
- Navigational dredging adjacent to the cap area; and
- Future development of commercial navigation channels in the vicinity of the cap.

Utilities (e.g., storm drains) and utility crossings (e.g., water, sewer, gas, oil, telephone, cable, and electric lines) are commonly located in urban waterways. It may be necessary to relocate existing utility crossings under portions of water bodies if their deterioration or failure might impact cap integrity. More commonly however, pipes or utilities are left in place under caps, and long-term operation and maintenance (O&M) plans include repair of cap damage caused by the need to remove, replace, or repair the pipes or utilities. Future construction or maintenance of utility crossings would have to consider the cap, and it may be necessary to consider limiting those activities through institutional controls (ICs) if cap repair cannot be assured. The presence of the cap can also place constraints on future waterfront development if dredging would be needed as part of the development activity.

In designing caps to be placed within federal navigation channels, horizontal and vertical separation distances may be developed by USACE based on considerations of normal dredging accuracy and depth allowances. This can provide a factor of safety to protect the cap surface from damage during potential future maintenance dredging.

To date, environmental agencies have little experience with 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.), although experience is growing. Generally, a state or local enforcement mechanism is necessary to implement specific use restrictions. Project managers should consider mechanisms for compliance assurance, enforcement, and the consequences of non-compliance, on use restrictions when evaluating in-situ capping.

5.3.4 Habitat Alterations

In-situ capping alters the aquatic environment and, therefore, can affect aquatic organisms in a variety of ways. As is discussed further in Chapter 6, Dredging and Excavation, while a project may be designed to minimize habitat loss or degradation, or even to enhance habitat, both sediment capping and sediment removal do alter the environment. Where baseline risks are relatively low, it is important to determine whether the potential loss of a contaminated habitat is a greater impact than the benefit of providing a new, modified but less contaminated habitat. Habitat considerations are especially important when evaluating materials for the uppermost layers of a cap. Sandy sediment and stone armor layers are often used to cap areas with existing fine-grained sediment. Through time, sedimentation and other natural processes will change the uppermost layer of the cap. At least initially, changes in organic carbon content of the capping material may change the feeding behavior of bottom-dwelling organisms in the capped area. Generally, the uppermost cap layers become a substrate for recolonization. Where possible, caps should be designed to provide habitat for desirable organisms. In some cases it is possible to provide a habitat layer over an erosion protection layer by filling the interstices of armor stones with materials such as crushed gravel. In some cases, natural sedimentation processes after cap placement can create desirable habitat characteristics. For example, placement of a rock cap in some riverine systems can result in a final cap surface that is similar to the previously existing surface because the rock may become embedded with sands/silts through natural sedimentation.

Desirable habitat characteristics for cap surfaces vary by location. Providing a layer of appropriately sized rubble that can serve as hard substrate for attached molluscs (e.g., oysters, mussels) can greatly enhance the ecological value at some sites. Material suitable for colonization by foraging organisms, such as bottom-dwelling fish, can also be appropriate. A mix of cobbles and boulders may be desirable for aquatic environments in areas with substantial flow. In addition, the potential for attracting burrowing organisms incompatible with the cap design or ability to withstand additional physical disturbances should be considered. Habitat enhancements should not impair the function of the cap or its ability to withstand the shear stresses of storms, floods, propeller wash, or other disturbances. Project managers should consult with local resource managers and natural resource trustee agencies to determine what types of modifications to the cap surface would provide suitable substrate for local organisms.

Habitat considerations are also important when evaluating post-capping bottom elevations. Capping often increases bottom elevations, which in itself can alter the pre-existing habitat. For example, a remediated subtidal habitat can become intertidal, or lake habitat can become a wetland (Cowardin et al. 1979). Changes in bottom elevation may either enhance or degrade desirable habitat, depending on the site.

Project managers should consult EPA staff familiar with implementing the Clean Water Act, as well as natural resource trustees and USACE, where Section 404 of the Clean Water Act is either applicable or relevant and appropriate [see Chapter 3, Section 3.3, Applicable or Relevant and Appropriate Requirements (ARARs) for Sediment Alternatives]. Where remedies under consideration degrade aquatic habitat, substantive requirements may include minimizing the permanent loss of habitat and mitigating it by creation or restoration of a similar habitat elsewhere. However, it should not be assumed that in-situ caps result in a permanent loss of habitat; this is a site-specific decision. In addition, project managers should be aware that any mitigation related to meeting the substantive requirements of ARARs for the site, such as the Clean Water Act, may be independent of the Natural Resource Trustees' natural resource damage assessment process.

5.4 FUNCTIONAL COMPONENTS OF A CAP

As introduced in Section 5.1 of this chapter, caps are generally designed to fulfill three primary functions: physical isolation, stabilization/erosion protection, and chemical isolation. In some cases, multiple layers of different materials are used to fulfill these function and in some cases, a single layer may serve multiple functions. Project managers are encouraged to consider the use of performance-based measures for caps in remedy decisions to preserve flexibility in how the cap may be designed to fulfill these functions.

5.4.1 Physical Isolation Component

The cap should be designed to isolate contaminated sediment from the aquatic environment order to reduce exposure to protective levels. The physical isolation component of the cap should also include a component to account for consolidation of cap materials.

To provide long-term protection, a cap should be sufficiently thick to effectively separate contaminated sediment from most aquatic organisms that dwell or feed on, above, or within the cap. This serves two purposes: 1) to decrease exposure of aquatic organisms to contaminants, and 2) to decrease the ability of burrowing organisms to move buried contaminants to the surface (i.e., bioturbation). To design a cap component for this second purpose, the depth of the effective mixing zone (i.e., the depth of effective sediment mixing due to bioturbation and/or frequent sediment disturbance) and the population density of organisms within the sediment profile should be estimated and considered in selecting cap thickness. Especially in marine environments, the potential for colonization by deep burrowing organisms (e.g., certain species of mud shrimp) could lead to a decision to design a thicker cap. Measures to prevent colonization or disturbance of the cap by deep burrowing bottom-dwelling organisms can be considered in cap design, and in developing biological monitoring requirements for the project. Project managers should refer to Chapter 2, Section 2.8.3 and consult with aquatic biologists with knowledge of local conditions for evaluation of the bioturbation potential. In some cases, a site-specific biological survey of bioturbators would be appropriate. In addition, the USACE Technical Note *Subaqueous Cap Design: Selection of Bioturbation Profiles, Depths and Process Rates* [Clarke et al. 2001, (Dredging Operations and Environmental Research (DOER)-C21 at http://el.erdc.usace.army.mil/dots/doer/technote.html], provides information on designing in-situ caps and also provides many useful references on bioturbation. Although not usually a major pathway for contaminant release, project managers should also be aware of the potential for wetland/aquatic plants to penetrate a cap and create pathways for some contaminant migration.

The project manager should consider consolidation when designing the cap. Fine-grained granular capping materials can undergo consolidation due to their own weight. The thickness of granular cap material should have an allowance for consolidation so that the minimum required cap thickness is maintained following consolidation. 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 erosion.

Even if the cap material is not compressible, most contaminated sediment is compressible and some may be highly compressible. Underlying contaminated sediment will almost always undergo some consolidation due to the added weight of the capping material or armor stone. The degree of consolidation should provide an indication of the volume of pore water expelled through the contaminated layer and capping layer to the water column due to consolidation. The consolidation-driven advection of pore water should be considered in the evaluation of short-term contaminant flux. Also, consolidation may decrease the vertical permeability of the capped sediment and thus reduce long-term flux. Methods used to define and quantify consolidation characteristics of sediment and capping materials, such as standard laboratory tests and computerized models, are available (U.S. EPA 1998d, Palermo et al. 1998a, Liu and Znidarcic 1991).

5.4.2 Stabilization/Erosion Protection Component

This functional component of the cap is intended to stabilize both the contaminated sediment and the cap itself to prevent either from being resuspended and transported from the capping location. The potential for erosion generally depends on the magnitude of the applied bed shear stresses due to river, tidal, and wave-induced currents, turbulence generated by ships/vessels (due to propeller action and vessel draft), and sediment properties such as particle size, mineralogy and bed bulk density. At some sites, there is also the potential for seismic disturbance, especially where contaminated sediment and/or cap material are of low shear strength. These and other aspects of investigating sediment stability are discussed in Chapter 2, Section 2.8, Sediment Stability and Contaminant Fate and Transport. Conventional methods for analysis of sediment transport are available to evaluate erosion potential of caps, ranging from simple analytical methods to complex numerical models (U.S. EPA 1998d, Palermo et al. 1998a). Uncertainty in the estimate of erosion potential should be evaluated as well.

The design of the erosion protection features of an in-situ cap (i.e., armor layers) should be based on the magnitude and probability of occurrence of relatively extreme erosive forces estimated at the capping site. Generally, in-situ caps should be designed to withstand forces with a probability of 0.01 per year, for example, the 100-year storm. As is discussed further in Chapter 2 (Section 2.8, Sediment Stability and Contaminant Fate and Transport), in some circumstances, higher or lower probability events should also be considered.

Another consideration for capping, especially capping of contaminated sediment with high organic content is whether significant gas generation due to anaerobic degradation will occur. Gas generation in sediment beneath caps, especially those constructed of low permeable materials, could either generate significant uplift forces and threaten the physical stability of the overlying capping material, or carry some contaminants through the cap. Little has been documented in this area to date, but the possible influence of this process on cap effectiveness presents an uncertainty the project manager should consider in the analysis of remedial alternatives.

5.4.3 Chemical Isolation Component

If a cap has a properly designed physical isolation component, contaminant migration associated with the movement of sediment particles should be controlled. However, the vertical movement of dissolved contaminants by advection (flow of ground water or pore water) through the cap is possible, while some movement of contaminants by molecular diffusion (movement across a concentration gradient) over long periods usually is inevitable. However, in assessing these processes, it is important to also assess the sorptive capacity of the cap material, which will act to retard contaminant flux through the cap, and the long-term fate of capped contaminants that may transform through time. Slow releases of dissolved contaminants through a cap at low levels will generally not create unacceptable exposures. If reduction of contaminant flux is necessary to meet remedial action objectives, however, a more involved analysis to include capping effectiveness testing and modeling should be conducted as a part of cap design. Because of the uncertainties involved in predicting future flux rates over very long time periods, this guidance does not advocate a particular minimum rule of thumb for the appropriate time frame for design with respect to chemical isolation. In general, it is reasonable for the physical isolation component (i.e., physical stability) of a cap design to be based on a shorter time frame (e.g., a disruptive event with a more frequent recurrence interval) than the much longer time frames considered in design for chemical isolation (e.g., the time required for accumulation of contaminants in the cap material or that required to attain the maximum chemical flux through the cap), in part because erosion of small areas of a cap is easier to repair.

Nevertheless, both advective and diffusive processes should be considered in cap design. If a ground water/surface water interaction study indicates that advection is not significant over the area to be capped (e.g., migration of ground water upward through the cap would not prevent attaining the RAOs), the cap design may need to address only diffusion and the physical isolation and stabilization of the contaminated sediment. In this case, it may not be necessary to design for control of dissolved and/or colloidally facilitated transport due to advection (Ryan et al. 1995).

In contrast, where ground water flow upward through the cap is expected to be significant, the hydraulic properties of the cap should also be determined and factored into the cap design. These properties should include the hydraulic conductivity of the cap materials, the contaminated sediment, and underlying clean sediment or bedrock. According to a USACE laboratory study, ground water flow velocities exceeding 10^{-5} cm/sec potentially result in conditions in which equilibrium partitioning processes important to cap effectiveness could not be maintained (Myers et al. 1991). Such conditions should be carefully considered in the cap design. High rates of ground water flow through contaminated sediment may cause unacceptable exposures. In these areas, in-situ capping may not be an effective remedial approach without additional protective measures. Use of amended caps (caps containing reactive or sorptive material to sequester organic or inorganic contaminants) is one potential measure undergoing pilot studies. Project managers should refer to the Remediation Technologies Development Forum (RTDF) Web site at http://www.rtdf.org for the latest in-situ cleanup developments. More information on the interactions of ground water and in-situ caps can be found in the USACE Technical Note, *Subaqueous Capping and Natural Recovery: Understanding the Hydrogeologic Setting at Contaminated Sediment Sites* (Winter 2002).

Where non-aqueous phase liquids (NAPL) are present in part of an area to be capped, the process for potential contamination migration should be carefully considered. NAPL may be mobilized by consolidation-induced or ground water-induced advective forces. Field sampling and bench-scale tests such as the Seepage Induced Consolidation Test can be designed to test these issues (e.g., Hedblom et al. 2003). In situations where conventional cap designs are not likely to be effective, it may be possible to consider impervious materials (e.g., geomembranes, clay, concrete, steel, or plastic) or reactive materials for the cap design. Where this is done, however, care must be taken such that head increases along the edges of the impervious area do not lead to additional NAPL migration. Project managers are encouraged to draw on the experience of others who have conducted pilot or full scale caps in the presence of NAPL.

Laboratory tests can be used to calculate sediment- and capping material-specific diffusion and chemical partitioning coefficients. Several numerical models are available to predict long-term movement of contaminants due to advection and diffusion processes into or through caps, including caps with engineered components. The models can evaluate the effectiveness of varying thicknesses of granular cap materials with differing properties [grain size and total organic carbon (TOC)]. The results generated by such models include flux rates to overlying water and sediment and pore water concentrations in the entire sediment and cap profile as a function of time. These results can be compared to sediment remediation goals or applicable water quality criteria in overlying surface water, or interpreted in terms of a mass loss of contaminants as a function of time. Results could also be compared to similar calculations for other remediation technologies.

5.5 OTHER CAPPING CONSIDERATIONS

In preparing a feasibility study to evaluate in-situ capping for a site, project managers should consider the following:

- Identifying candidate capping materials physically and chemically compatible with the environment in which they will be placed;
- Evaluating geotechnical considerations including consolidation of compressible materials and potential interactions and compatibility among cap components;
- Assessing placement methods that will minimize short-term risk from release of contaminated pore water and resuspension of contaminated sediment during cap placement; and
- Identifying performance objectives and monitoring methods for cap placement and long-term assessment of cap integrity and biota effects.

In addition to evaluation during the feasibility study, these aspects should be addressed in more detail during design. These topics are discussed briefly below. In addition, project managers should refer to Chapter 8, Section 8.4.2 for a discussion of general monitoring considerations for in-situ capping, and to Chapter 3, Section 3.6 for a discussion of ICs that may relate to caps.

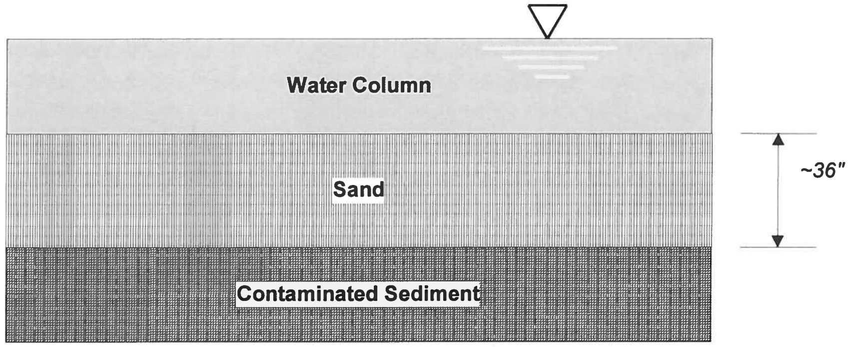
5.5.1 Identification of Capping Materials

Caps are generally composed of clean granular materials, such as upland sand-rich soils or sandy sediment; however, more complex cap designs could be required to meet site-specific RAOs. The project manager should take into consideration the expected effects of bioturbation, consolidation, erosion, and other related processes on the short- and long-term exposure and risk associated with contaminants. For example, if the potential for erosion of the cap is significant, the level of protection could be raised by increasing cap thickness or by engineering the cap to be more erosion-resistant through use of cap material with larger grain size, or by using an armor layer. Porous geotextiles do not contribute to contaminant isolation, but serve to reduce the potential for mixing and displacement of the underlying sediment with the cap material. A cap composed of naturally occurring sand is generally preferred over processed sand because the associated fine fraction and organic carbon content found in natural sands are more effective in providing chemical isolation by sequestering contaminants migrating through the cap. However, sand containing a significant fraction of finer material may also increase turbidity during placement.

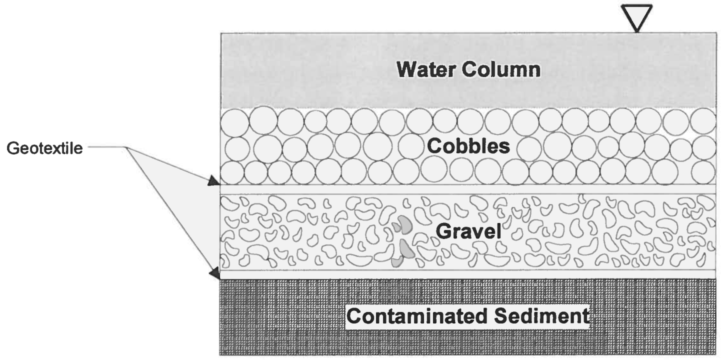
Specialized materials may be used to enhance the chemical isolation capacity or otherwise decrease the thickness of caps compared to sand caps. Examples include engineered clay aggregate materials (e.g., AquaBlok™), and reactive/adsorptive materials such as activated carbon, apatite, coke, organoclay, zero-valent iron and zeolite. Composite geotextile mats containing one or more of these materials (i.e., reactive core mats) are becoming available commercially.

Highlight 5-2 illustrates some examples of cap designs.

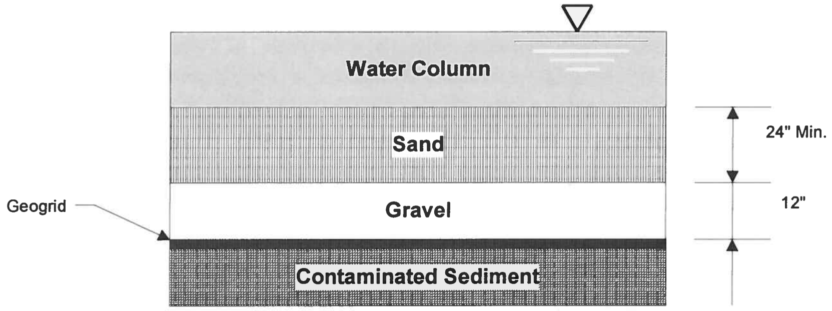
Highlight 5-2: Sample Cap Designs



A. Eagle Harbor, WA



B. Sheboygan, WI



C. Convair Lagoon, CA

Source: Modified from U.S. EPA 1998d

5.5.2 Geotechnical Considerations

Usually, contaminated sediment is predominately fine-grained, and often has high water content and low shear strength. These materials are generally compressible. Unless appropriate controls are implemented, contaminated sediment can be easily displaced or resuspended during cap placement. Following placement, cap stability and settlement due to consolidation can become two additional geotechnical issues that may be important for cap effectiveness.

As with any geotechnical problem of this nature, the shear strength of the underlying sediment will influence its resistance to localized bearing capacity or sliding failures, which could cause localized mixing of capping and contaminated materials. Cap stability immediately after placement is critical, before any excess pore water pressure due to the weight of the cap has dissipated. Usually, gradual placement of capping materials over a large area will reduce the potential for localized failures. Information on the behavior of soft deposits during and after placement of capping materials is limited, although some field monitoring data have shown successful sand capping of contaminated sediment with low shear strength. Conventional geotechnical design approaches should, therefore, be applied with caution (e.g., by building up a cap gradually over the entire area to be capped). Similarly, caps with flatter transition slopes at the edges are not generally subject to a sliding failure normally predicted by conventional slope stability analysis.

5.5.3 Placement Methods

Various equipment types and placement methods have been used for capping projects. The use of granular capping materials (i.e., sand, sediment, and soil), geosynthetic fabrics, and armored materials are all in-situ cap considerations discussed in this section. Important considerations in selection of placement methods include the need for controlled, accurate placement of capping materials. Slow, uniform application that allows the capping material to accumulate in layers is often necessary to avoid displacement of or mixing with the underlying contaminated sediment. Uncontrolled placement of the capping material can also result in the resuspension of contaminated material into the water column and the creation of a fluid mud wave that moves outside of the intended cap area.

Granular cap material can be handled and placed in a number of ways. Mechanically excavated materials and soils from an upland site or quarry usually have relatively little free water. Normally, these materials can be handled mechanically in a dry state until released into the water over the contaminated site. Mechanical methods (e.g., clamshells or release from a barge) rely on gravitational settling of cap materials in the water column, and could be limited by depth in their application. Granular cap materials can also be entrained in a water slurry and carried to the contaminated site wet, where they can be discharged by pipe into the water column at the water surface or at depth. These hydraulic methods offer the potential for a more precise placement, although the energy required for slurry transport could require dissipation to prevent resuspension of contaminated sediment. Armor layer materials can be placed from barges or from the shoreline using conventional equipment, such as clamshells. Placement of some cap components, such as geotextiles, could require special equipment. Examples of equipment types used for cap placement are shown in Highlight 5-3. The *Guidance for In-Situ Subaqueous Capping of Contaminated Sediments* (U.S. EPA 1998d) contains more detailed information about cap placement techniques.

Monitoring sediment resuspension and contaminant releases during cap placement is important. Cap placement can resuspend some contaminated sediment. Contaminants can also be released to the water column from compaction or disruption of underlying sediment during cap placement. Both can lead to increased risks during and following cap placement. Applying cap material slowly and uniformly can minimize the amount of sediment disruption and resuspension. Therefore, designs should include plans to minimize and monitor impacts during and after construction.

5.5.4 Performance Monitoring

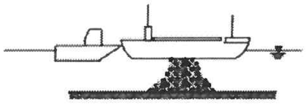
Performance objectives for an in-situ cap relate to its ability to provide sufficient physical and chemical isolation and stabilization of contaminated sediment to reduce exposure and risk to protective levels. Broader RAOs for the site such as decreases in contaminant concentrations in biota or reduced toxicity should be monitored when applicable. The following processes should be considered when evaluating the performance of a cap, and in developing a cap monitoring program:

- Erosion or other physical disturbance of cap;
- Contaminant flux into cap material and into the surface water from underlying contaminated sediment (e.g., ground water advection, molecular diffusion); and
- Recolonization of cap surface and resulting bioturbation.

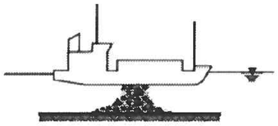
General considerations related to monitoring caps and an example of cap monitoring elements are presented in Chapter 8, Remedial Action and Long-Term Monitoring.

Performance monitoring of a cap should be related to the design standards and remedial action objectives related to the site. Generally, physical monitoring is initially conducted on a more frequent schedule than chemical or biological monitoring because it is less expensive to perform. Some processes (i.e., contaminant flux) are not generally assessed directly because they are very difficult to measure, but are assessed by measuring contaminant concentrations in bulk samples from the cap surface, in shallow cores into the surface layer of a cap, and by bathymetric surveys and various photographic techniques. It is often desirable to establish several permanent locational benchmarks so that repeated surveys can be accurately compared. In some cases, contaminant flux and the resulting contaminant concentration in surface sediment, cap pore water, or overlying surface water can be compared to site-specific sediment cleanup levels or water quality standards (e.g., federal water quality criteria or state promulgated standards). In addition, the concentration of contaminants accumulating in the cap material as a function of time can be compared to site-specific target cleanup levels during long-term cap performance monitoring. Both analytical and numerical models exist to predict cap performance and have been compared and validated with laboratory tests and field results (e.g., Ruiz et al. 2000). However, project managers should be aware that representative chemical monitoring of caps is difficult, in part because of the need to distinguish between vertical migration into the cap and the mixing that occurs at the cap/sediment interface during placement. In some cases, physical measurement of cap integrity and water column chemical measurement may be sufficient for routine monitoring.

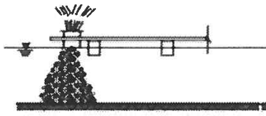
Highlight 5-3: Sample Capping Equipment and Placement Techniques



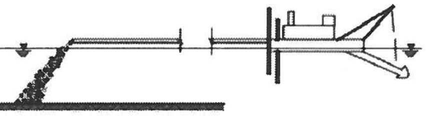
SURFACE RELEASE FROM BARGE



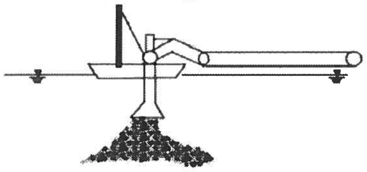
SURFACE RELEASE FROM HOPPER DREDGE



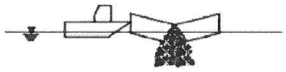
SPREADING WITH PIPELINE AND BAFFLE PLATE OR BOX



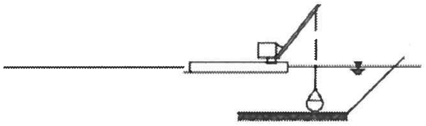
SURFACE DISCHARGE WITH PIPELINE



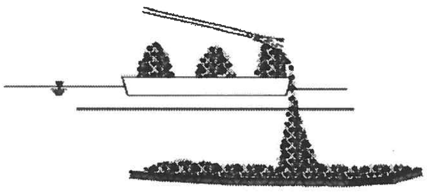
SUBMERGED DIFFUSER WITH PIPELINE



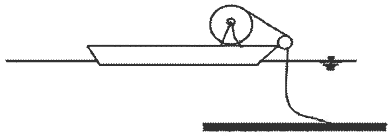
SPREADING BY CONTROLLED BARGE RELEASE



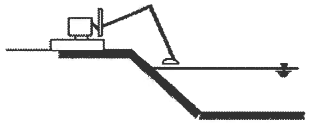
DIRECT MECHANICAL PLACEMENT



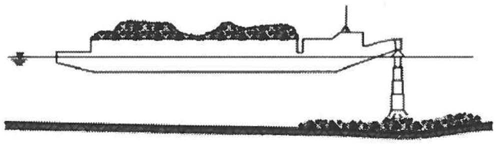
JETTING FROM BARGE



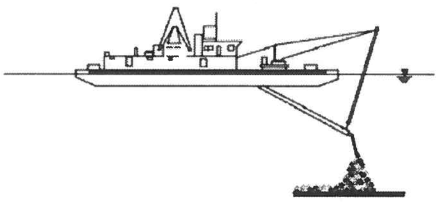
BARGE EQUIPPED FOR GEOTEXTILE PLACEMENT



LAND-BASED DIRECT PLACEMENT



BARGE WITH TREMIE



SAND SPREADER BARGE

Source: U.S. EPA 1998d

Highlight 5-4 presents some general points to remember from this chapter.

Highlight 5-4: Some Key Points to Remember When Considering In-Situ Capping

- Source control generally should be implemented to prevent recontamination
- In-situ caps generally reduce risk through three primary functions: physical isolation, stabilization, and reduction of contaminant transport
- Caps may be most suitable where water depth is adequate, slopes are moderate, ground water flow gradients are low or contaminants are not mobile, substrates are capable of supporting a cap, and an adequate source of cap material is available
- Evaluation of capping alternatives and design of caps should consider buried infrastructure, such as water, sewer, electric and phone lines, and fuel pipelines
- Alteration of substrate and depth from capping should be evaluated for effects on aquatic biota
- Evaluation of a capping project in natural riverine environments, should include consideration of a fluvial system's inherent dynamics, especially the effects of channel migration, flow variability including extreme events, and ice scour
- Evaluation of capping alternatives should include consideration of cap disruption from human and natural sources, including at a minimum, the 100-year flood and other events such as seismic disturbances with a similar probability of occurrence
- Selection of cap placement methods should minimize the resuspension of contaminated sediment and releases of dissolved contaminants from compacted sediment
- Use of experienced contractors skilled in marine construction techniques is very important to placement of an effective cap
- Monitor in-situ caps during and after placement to evaluate long-term integrity of the cap, recolonization by biota, and evidence of recontamination
- Maintenance of in-situ caps is expected periodically

United States
Environmental Protection
Agency

Great Lakes
National Program Office
77 West Jackson Boulevard
Chicago, Illinois 60604

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Assessment and Remediation Of Contaminated Sediments (ARCS) Program

GUIDANCE FOR IN-SITU SUBAQUEOUS CAPPING OF CONTAMINATED SEDIMENTS

Michael R. Palermo and Steve Maynord
U.S. Army Engineer Waterways Experiment Station
Vicksburg, Mississippi

Jan Miller
U.S. Army Engineer Division, Great Lakes and Ohio River
Chicago, Illinois

Danny D. Reible
Louisiana State University
Baton Rouge, Louisiana

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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.

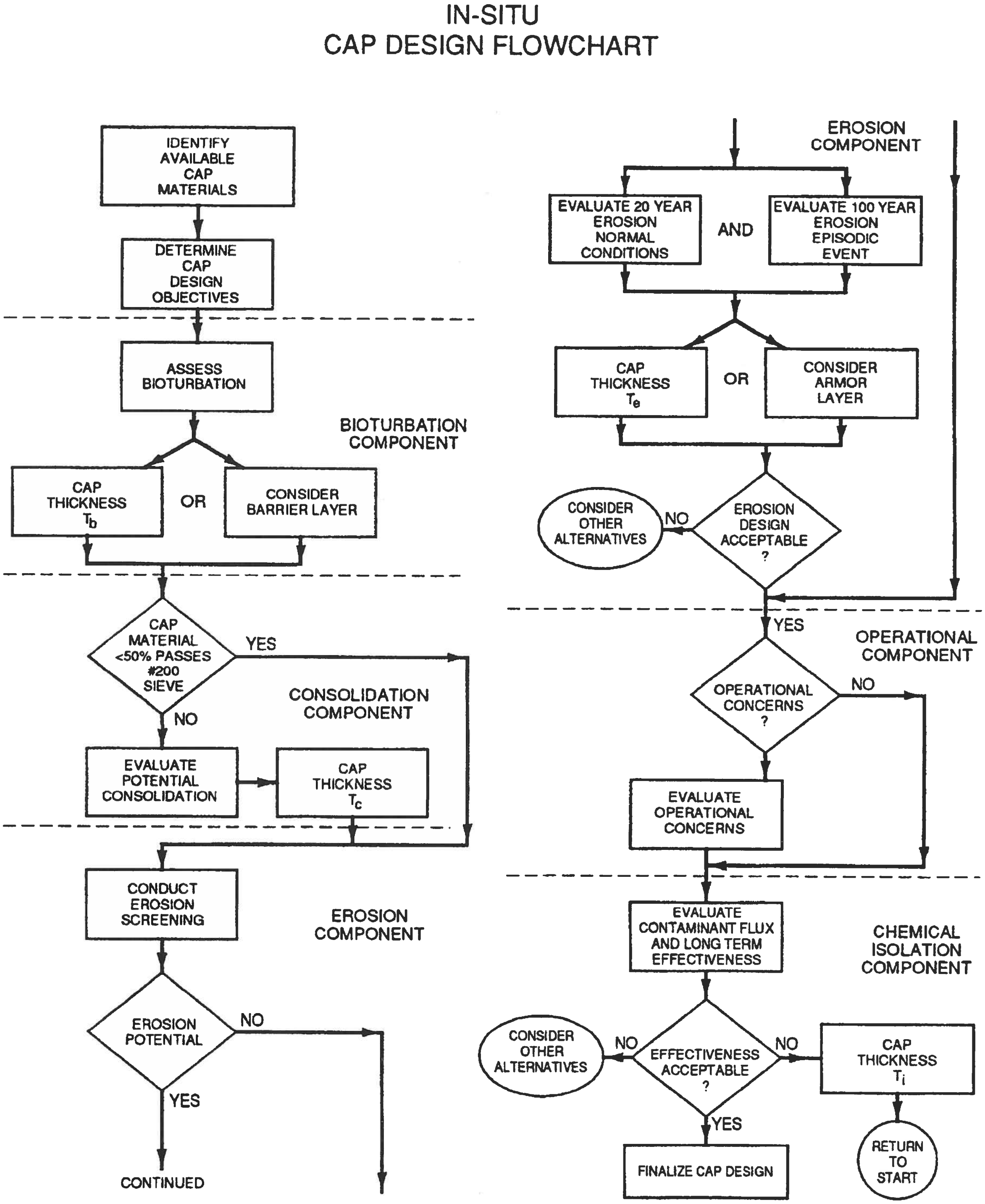
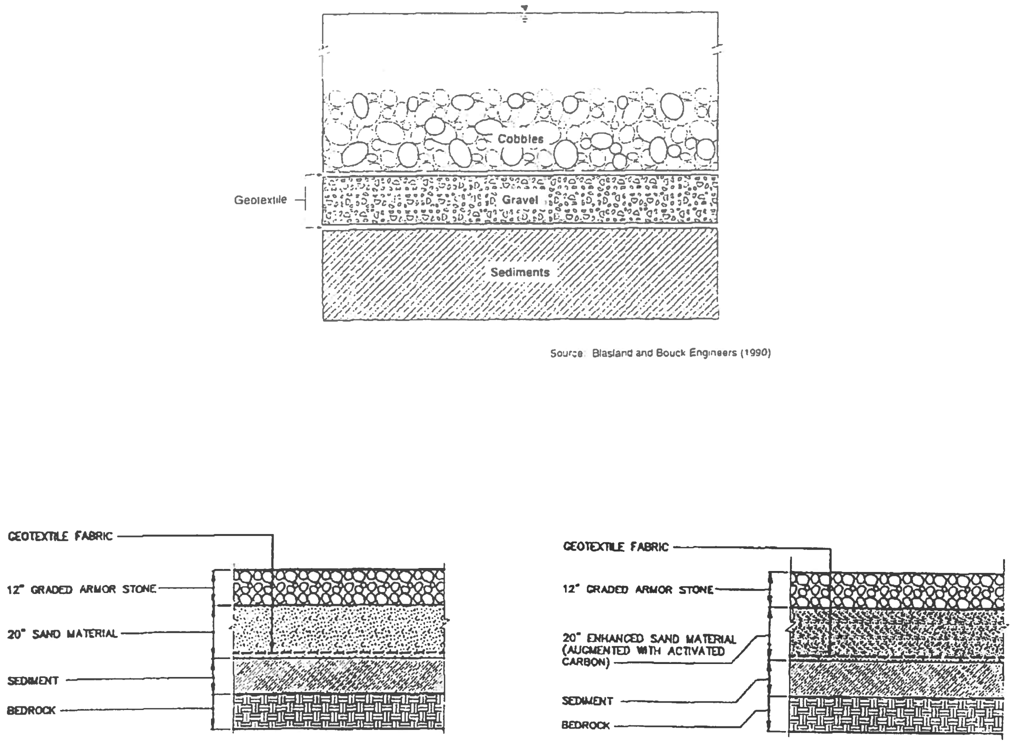


Figure 3. Flowchart showing steps involved in design evaluation of various insitu cap components.



Source: Blasland and Bouck Engineers (1990)

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.

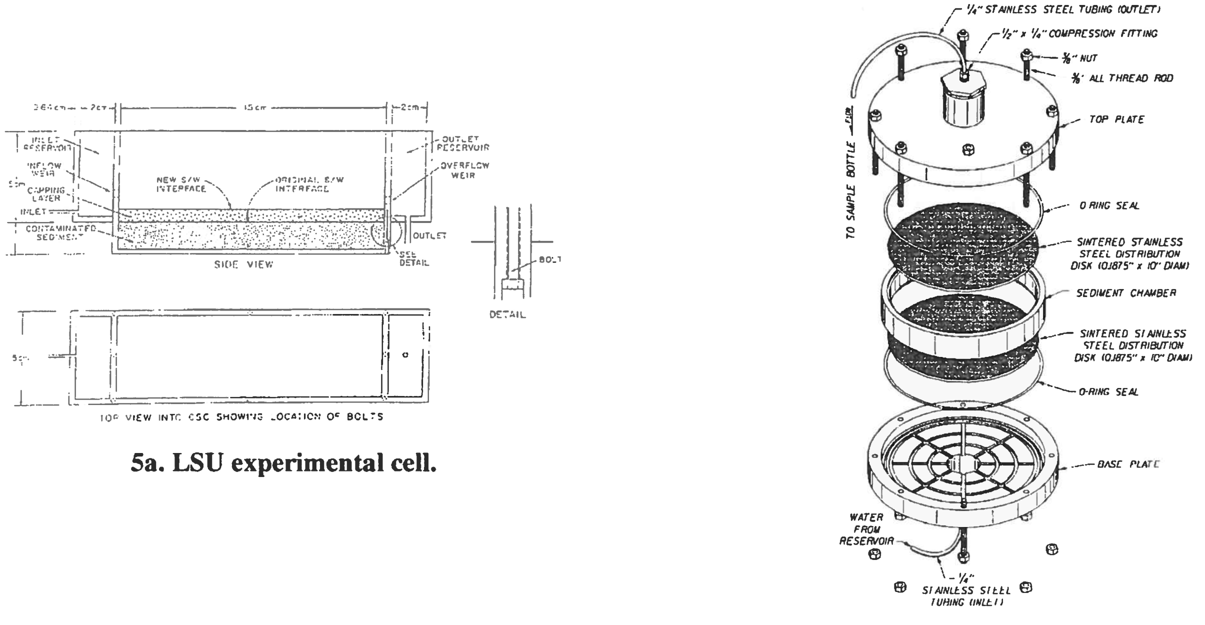
Laboratory Tests for Capping Effectiveness

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

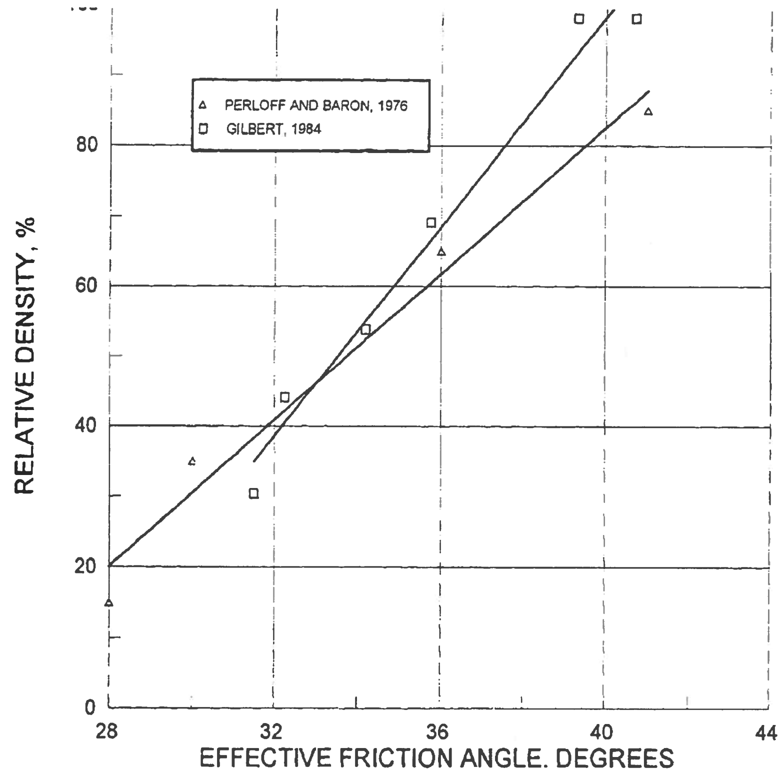


Figure 6. Relationship between relative density and effective friction angle for clean sands.

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 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.

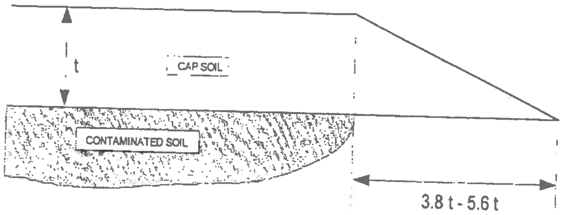


Figure 7. Recommended cap edge overlap.

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.