Swedish Geotechnical Institute

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Preface

Contaminated sediments occur to some extent in almost all countries, both in fresh waters and marine environments. Sediment contamination in most countries results from historical releases, when regulatory controls were lacking or minimal, although releases occur to some extent also today. Therefore, the problem of contaminated sediments and risks they can pose to the environment and humans is not unique to Sweden.

Globally-accepted technologies for sediment remediation generally rely on either removing the contaminated sediment then managing it *ex-situ*, or remediating sediment contamination in-place, *in-situ*. *In-situ* capping is an internationally recognized and accepted technology for remediating contaminated sediments. The technique is well established in other countries like the USA, Norway and Canada, in contrast to Sweden, where capping has been very limited to-date.

The Swedish Geotechnical Institute (SGI) has the national responsibility for research, technological development and knowledge building for remediation and restoration of contaminated sites. The aim is to raise the level of knowledge and increase the rate of remediation action, in order for Sweden to achieve the national environmental quality objectives. As part of this, knowledge should be mediated to others, such as regulators, consultants, laboratories, problem owners, contractors, etc. by (among other things) issuing publications.

This publication is intended to serve as a basis for the design and assessment of remediation alternatives to dredging. The publication aims to provide a technology overview of various capping-based techniques and to describe possibilities and limitations. The overall aim is to establish a basis for capping as a viable *in-situ* remediation alternative for managing contaminated sediments.

This publication includes a state-of-the-art review of the remedial practices of *in-situ* capping of contaminated sediments. The publication comprises a main text plus several supporting, but standalone, appendices. These supporting appendices include: a preliminary review of contaminated sediments in Sweden; a general overview of established *ex-situ* and *in-situ* sediment remediation technologies; a preliminary overview of remedial sediment capping projects worldwide; a short discussion on anticipated challenges with capping Sweden’s fiberbank sediments; and an extensive, up-to-date collection of relevant technical and other international references.

The publication is a result of a co-operation between the Swedish Geotechnical Institute (SGI) and SAO Environmental Consulting AB (SAO). The main author is Dr. Joseph Jersak (SAO).) and co-authors are Dr. Gunnel Göransson, Dr. Yvonne Ohlsson, M.Sc. Lennart Larsson, Dr. Peter Flyhammar and Dr. Per Lindh at SGI. Professor Danny D. Reible, Texas Tech University, has reviewed selected parts of the publication and submitted valuable comments. In addition, comments on the publication have also been sought through an external reviewing process, and comments were submitted by the Swedish Environmental Protection Agency and the County Administrative Board of Gävleborg.

SGI and SAO would like to give special thanks to the following people for their valuable contribution to the publication: John Collins, AquaBlok, Ltd. (U.S.A.), Pär Elander, Elander Miljöteknik AB, Henrik Eriksson, Golder Associates AB, Tore Hjartland as a representative for BioBlok Solutions AS (Norge), John Hull, AquaBlok, Ltd. (U.S.A.), Ludvig Landen, Stadsbyggnadsförvaltningen, Helsingborg, Dr. Jens Laugesen, DNV GL AS (Norge), Prof. Danny D. Reible, Texas Tech University (U.S.A.), Kevin Russell, Anchor QEA (U.S.A.), and Prof. Ian Snowball, Uppsala University.

A decision to publish this publication has been taken by Mikael Stark. Linköping, December 2016.

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Abbreviations for key terms used herein are as follows:

AC	Activated carbon
BAZ	Biologically active zone
EMNR	Enhanced monitored natural recovery
GAC	Granular activated carbon
MNR	Monitored natural recovery
NAPLs	Non-aqueous phase liquids
PAC	Powdered activated carbon
TOC	Total organic carbon
USEPA	United States Environmental Protection Agency
USACE	United States Army Corps of Engineers

The entire SGI Publication 30 set includes the following independent parts:

SGI Publication 30-1, Huvuddokument. *In-situ* övertäckning av förorenade sediment. Metodöversikt. (In Swedish)

SGI Publication 30-1E, Main text. *In-situ* capping of contaminated sediments. Method overview.

SGI Publication 30-2E. *In-situ* capping of contaminated sediments. Contaminated sediments in Sweden: A preliminary review.

SGI Publication 30-3E. *In-situ* capping of contaminated sediments. Established *ex-situ* and *in-situ* sediment remediation technologies: A general overview.

SGI Publication 30-4E. *In-situ* capping of contaminated sediments. Remedial sediment capping projects, worldwide: A preliminary overview.

SGI Publication 30-5E. *In-situ* capping of contaminated sediments. Capping Sweden's contaminated fiberbank sediments: A unique challenge.

SGI Publication 30-6E. *In-situ* capping of contaminated sediments. An extensive, up-to-date collection of relevant technical and other international references.

SGI Publication 30-7. *In-situ* övertäckning av förorenade sediment. Övergripande sammanfattning. (In Swedish)

SGI Publication 30-7E. *In-situ* capping of contaminated sediments. Overall summary.

Fact sheet. *In-situ* capping of contaminated sediments. Method overview.

Abstract

The main objective for this project was to conduct a technically detailed, state-of-the-art review of the remedial practice of *in-situ* capping of contaminated sediments. Another objective was to develop several supporting appendices intended to collectively explain how and why such a state-of-the-art review is important and relevant to a wide variety of Swedish stakeholders.

***In-situ* capping: A state-of-the-art review.** As discussed in detail in the current document, capping in-place (*in-situ*) is an internationally accepted technology for remediating contaminated sediments. It generally involves placing cap material overtop the sediment surface to create a new bottom and to meet certain performance objectives. Capping offers advantages and limitations compared to other sediment remediation technologies, like dredging or natural recovery. Two different types of capping are recognized – isolation and thin-layer capping – and they differ in many ways, but mainly in terms of specific objectives for cap performance. Various natural and man-made materials are used in isolation and thin-layer capping, including conventional (non-reactive) and reactive (e.g. sorptive) materials. Numerous factors are considered and evaluated when selecting and designing a capping remedy that is most appropriate for meeting site- and project-specific goals for sediment remediation. Once a cap is designed, it should be constructed in a controlled and geotechnically stable manner, and with minimal sediment re-suspension. Subaqueous caps can be constructed using many different types of equipment and approaches. Monitoring should occur both during cap construction (to insure the cap is constructed as designed) and long after cap-construction is completed (to confirm the cap is functioning as intended over the long-term).

How big is Sweden's contaminated sediment problem? SGI Publication 30-2E presents a preliminary review of the type and occurrence of contaminated sediments identified in each of Sweden's 21 counties. Contaminated mineral-based (minerogenic) and/or cellulose-bearing ("fiberbank") sediments occur in at least 19 counties and, at many sites, likely pose unacceptable risks that require effective management (remediation).

What technologies are available for remediating contaminated sediments? A general understanding of established sediment remediation technologies is essential to more fully appreciate capping-based remedies in particular. SGI Publication 30-3E introduces, describes, and generally compares proven-effective and internationally accepted *ex-situ* (removal-based) and *in-situ* technologies for remediating contaminated sediments. Each technology has relative advantages and limitations, and there is no "one-size-fits-all" technology for all situations. Remedy selection is a site and project-specific process.

How well-established is *in-situ* capping as a sediment remedy? SGI Publication 30-4E collectively present a preliminary overview of capping projects, worldwide. To-date, over 180 capping projects (isolation, thin-layer, conventional or active) have been completed, initiated or planned worldwide over the last several decades, most in the U.S. and many in Norway. Six capping projects have been conducted in Sweden. Virtually all projects involve contaminated minerogenic sediments. Capping is a versatile and internationally-established sediment remediation technology – at least for minerogenic sediments. Thus, *in-situ* capping, in its various forms, is one proven technology that can be an option in many cases.

What about Sweden's fiberbank sediments? Can they be remediated by *in-situ* capping? Fiberbank sediments result from past discharges from pulp and papermill industries and typically contain multiple contaminants. They represent a significant national problem both in terms of their broad distribution (identified in at least 10 counties) and because of the unacceptable risks they likely pose at many sites. Theoretically, one or more types of capping should be appropriate for

remediating many fiberbank sediment sites. However, there is very little global experience to-date in capping fiberbank sediments. Because of this – coupled with their unique characteristics – there are many unknowns related to how fiberbank sediments will respond to different types of capping remedies. SGI Publication 30-5E outlines some of these unknowns.

1. Introduction

The problem of contaminated sediments and risks they can pose to the environment and humans is not unique to Sweden. Contaminated sediments occur in nearly all countries to some extent, in both inland and coastal aquatic environments. And, like Sweden, most sediment contamination in most countries results from historical releases, when regulatory controls were lacking or minimal.

There is no single national inventory currently available for contaminated sediments, as there is for contaminated land[1]. However, information does exist on contaminated sediments in Sweden. Such information is distributed throughout various published documents, including in: regional programs summarizing contaminated sites, regional and national environmental monitoring programs, and risk assessments related to land-based point-sources for contaminant inputs into surface waters.

The true scale and severity of the contaminated sediment problem in Sweden is unclear. Regardless, a preliminary review of available information indicates that contaminated sediments occur in 19 of Sweden's 21 counties. Sediment-related risks at some portion of the identified sites are no-doubt at unacceptable levels, thus requiring remediation now or in the near future.

Globally-accepted technologies for sediment remediation generally rely on either removing the contaminated sediment then managing it *ex-situ*, or remediating sediment contamination in-place (*in-situ*). Between 2007 and 2013, the Baltic Sea Region programme financed a project referred to as SMOCS (Sustainable Management of Contaminated Sediments in the Baltic Sea). A guideline was released from the SMOCS project focusing on sustainable management of contaminated sediments dredged in the Baltic Sea region, as well as *ex-situ* management of contaminated sediments. Motivations for conducting the SMOCS project included: *i)* increasing costs for disposal of dredged contaminated sediments, *ii)* challenges in locating new and adequate disposal sites, and *iii)* the possibility for beneficial use of dredged sediments for different purposes, e.g. land improvement, port constructions/extension, etc.

In-situ capping is an internationally recognized and accepted technology for remediating contaminated sediments, and is extensively used in other countries like the USA, Norway and Canada. In contrast, use of capping-based remedies in Sweden has been very limited to-date. There are likely multiple reasons for this, including (but not limited to): *a)* the Swedish branch and relevant Swedish authorities feel they do not have sufficient knowledge on remedial sediment capping, *d)* there is a preference for dredging, which removes contaminants and is considered an already-established and "known to work" technology, and *c)* there may be a perception that capping sediment contaminants in place is simply "covering up the problem", even when a cap can successfully physically and chemically isolate the contamination. The third reason may, however, be related to the first, i.e. a lack of knowledge on and experience of the method. Nevertheless, in recognition of capping, the Swedish EPA released a guidance document in 2003 on remediation of contaminated sediments (Efterbehandling av förorenade sediment – en vägledning, Rapport 5254). The guidance document summarizes several *in-situ* and *ex-situ* remediation technologies and capping is mentioned as a remedial technology that has become important, worldwide.

The primary goal of this publication is to establish a basis for capping as a viable *in-situ* remediation alternative for managing contaminated sediments by compiling a technology overview and

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[1] For clarification, Sweden's national inventory of contaminated land does not contain information on contaminated sediments.

effectively disseminating overview results. This publication is also intended to serve more-or-less as a “companion” document to the SMOCS guideline focused on *ex-situ* sediment management, and as a more in-depth and up-to-date expansion of the Swedish EPA’s earlier discussions on capping.

As descried in detail in Section 2 below, this publication comprises a main text (the current document) plus several supporting publications appendices.

To underscore: This is not intended to function as a guidance document for remedial sediment capping. However, this document can serve as a basis for such guidance.

2. Objectives

The main objective for this project was to conduct a technically detailed, state-of-the-art review of the remedial practice of *in-situ* capping of contaminated sediments. The current document comprises this review. Another objective for this project was to develop several publications to collectively support and help “make the case” for why the state-of-the-art review is important and relevant to a wide variety of Swedish stakeholders (government authorities and institutes, university researchers, engineering and environmental consultants, site owners, and the public). These supporting publications – which are intended to be stand-alone references on their own – include:

- Contaminated sediments in Sweden: A preliminary review (SGI Publication 30-2E).
- Established *ex-situ* and *in-situ* sediment remediation technologies: A general overview (SGI Publication 30-3E).
- Remedial sediment capping projects, worldwide: A preliminary overview (SGI Publication 30-4E).
- Capping Sweden’s contaminated fiberbank sediments: A unique challenge (SGI Publication 30-5E).
- 265 technical and other international references (SGI Publication 30-6E).

Additionally provided are an overall summary (SGI Publication 30-7E) which summarizes the review document and the supporting documents mentioned above, and a fact sheet on *in-situ* remedial sediment capping.

3. *In-situ* remedial sediment capping: An in-depth focus

3.1 Introduction

To properly place *in-situ* capping into the larger context of sediment remediation, brief summaries of the other major and internationally established, *in-situ* and *ex-situ* sediment remediation technologies are provided in SGI Publication 30-3E. In addition to capping, these technologies include: removal, mainly dredging; monitored natural recovery (MNR); enhanced MNR and *in-situ* treatment.

For completeness, a brief summary of capping is included in SGI Publication 30-3E. It is recommended that the reader review this general summary before reading the current document.

In SGI Publication 30-3E, a distinction is made between the remedial practices of isolation capping and thin-layer capping, and it is around these two major capping "strategies" much of the state-of-the-art review is structured and presented. In practice, project-specific sediment caps are often hybrids which fall somewhere along the isolation ↔ thin-layer spectrum, both in terms of remediation objectives and cap design.

Since the remedial practice of isolation capping was developed and in use before thin-layer capping, isolation capping is discussed first.

3.2 Isolation capping

3.2.1 General description

Isolation sediment caps are engineered and designed structures, like land-based permeable reactive barriers, landfill liners, and slurry cutoff walls. Isolation capping involves placing one or more layers of cap material of one or more types overtop the surface of contaminated sediments. Isolation caps are intended to effectively eliminate exposure of organisms colonizing the cap to sediment contaminants in two different ways: by cutting off direct physical contact of burrowing benthic organisms with the underlying contaminated sediment and by significantly minimizing long-term migration of dissolved-phase, sediment-borne contaminants up into the cap's biologically active zone (BAZ).

3.2.2 Objectives for isolation-cap performance

Various cap-performance objectives can be considered for isolation capping. The objectives are dictated by site-specific needs for risk reduction, that is, reductions in organism exposure to and bioaccumulation of sediment contaminants.

Cap-performance objectives typically listed in international guidance documents and considered in isolation-capping projects worldwide include the following (e.g. USEPA, 2005; ITRC, 2014; SFT, 2002; Palermo et al., 1998a, 1998b; COWI, 2013):

- **Physical isolation** of burrowing benthic organisms from direct contact with contaminated sediments.
- **Chemical isolation** of benthic organisms from exposure to dissolved-phase sediment contaminants migrating up into and through the cap, including into the cap's BAZ, over time.
- **Stabilization** and protection of contaminated sediment masses against erosion and transport away from the site. Note, this is not the same as treatment of contaminated sediments using Solidification/Stabilization (S/S) processes.

The cap-performance objectives of physical and chemical isolation are implicit to the general description of isolation capping. Furthermore, the cap-performance objectives of physical isolation and stabilization are relatively self-explanatory. In contrast, the objective of chemical isolation can be defined in different ways, depending on whether temporary (transient) or permanent (steady-state) conditions of the capped sediment system are considered (Reible and Lampert, 2014; Parsons and Anchor QEA, 2012b; Russell et al., 2013).

Under transient conditions*:* As dissolved-phase sediment contaminants migrate upwards over time through saturated and connected pore spaces in a cap, a typical transient cap-performance objective can be to maximize the time to contaminant "breakthrough" into the cap's BAZ (e.g. at least 100 years). The goal is often to ensure the design lifetime for the cap is long enough such that other processes may render contaminants harmless or of minimal subsequent impact (e.g. slow degradation).

Under steady-state conditions*:* Typical cap-performance objectives can include establishing and maintaining: (a) total contaminant concentrations in the BAZ at some protective level; (b) contaminant concentrations in BAZ porewaters at some protective level; and/or (c) contaminant flux from the cap surface into the overlying water column at some target rate, often relative to that from uncapped sediment surfaces.

Additional discussions on chemical isolation of contaminants when capping with particular types of capping materials are provided in Sections 3.2.4 and 3.2.5.

3.2.3 Approach to isolation-cap design

The internationally accepted approach to designing isolation caps is based on the "layer-cake" concept, which was first developed by the U.S. Army Corps of Engineers (Palermo et al., 1998a, 1998b; Palermo and Reible; 2007; DNV GL, 2014; Mohan et al., 2000; Naturvårdsverket, 2003).

The layer-cake design concept involves including different capping layers at pre-defined thicknesses, each of which is intended to address or counter-act one or more site-specific processes. These function-specific capping layers include the:

- **Bioturbation layer** – to accommodate activity of benthic burrowing organisms down to some depth in the cap's surface.
- **Erosion-protection layer** – to counter-act natural and/or human-related erosive forces acting on the cap over time. Natural forces include river and tidal currents, wind-driven waves, and ice scour. Human-related forces include propeller wash (propwash) from ships and boats as well as vessel-generated waves.

- **Chemical isolation layer** – to achieve long-term chemical isolation of dissolved-phase sediment contaminants migrating upwards in cap porewaters.
- **Consolidation layer** – to account for sediment (and cap) settlement or consolidation upon cap loading.
- **Mixing layer** – to account for physical mixing of cap material with sediment during cap construction.
- **Operational layer** – to account for expected thickness variability during cap construction.

A conceptual illustration of an isolation cap showing function-specific capping layers is shown as Figure 3.1.

Isolation caps can either be monolayer or composite caps. A monolayer cap is when all function-specific layers are comprised of the same material, like sand. A composite cap is when function-specific layers comprise a combination of different materials, like sand + larger stone + a basal geotextile.

Total cap thickness could theoretically be determined by simply summing up thicknesses of all function-specific capping layers (Figure 3.1). However, it is recognized such a summing-up approach is usually too conservative. Instead, total cap thickness can often be reduced by assuming particular capping layers may serve multiple functions, e.g. benthic habitat + erosion protection, or erosion protection + chemical isolation (Palermo and Reible, 2007; Russell, 2015; Parsons and Anchor QEA, 2012a; Palermo, 2015).

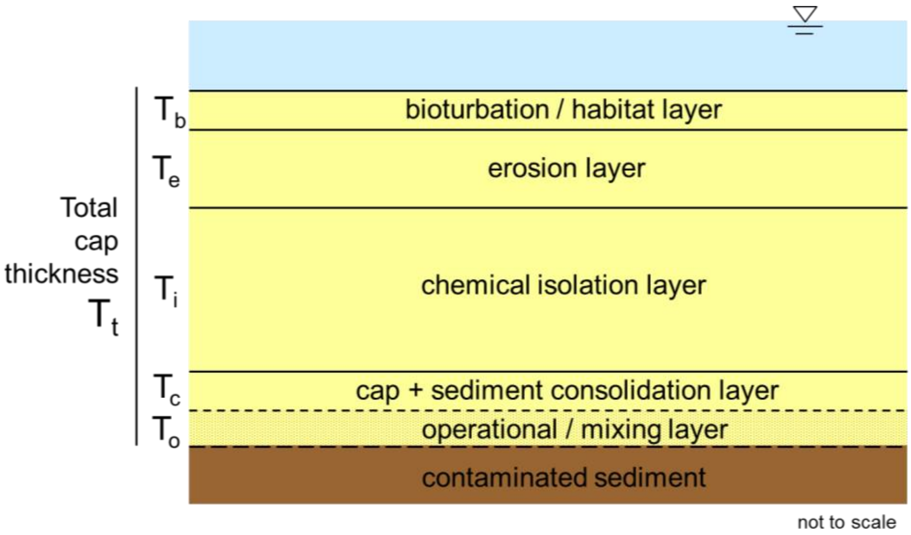

Figure 3.1 Conceptual isolation cap, with emphasis on function-specific capping layers.

A separate evaluation of each site-specific process (bioturbation, erosion potential, chemical isolation, etc.) is typically required to determine the appropriate material type and thickness for each function-specific capping layer.

All function-specific capping layers are integral to isolation capping. Nevertheless, probably the two most critical components to isolation-cap design are the chemical isolation layer and the erosion-protection layer. These two function-specific capping layers are highlighted in Figure 3.2.

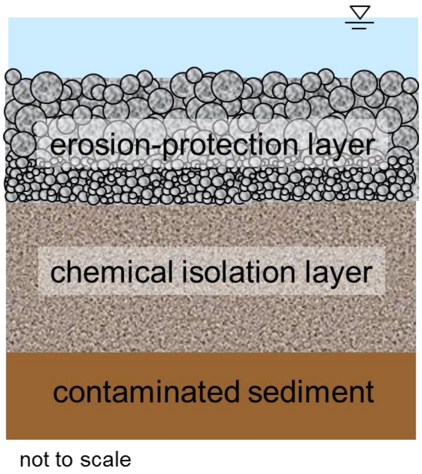

Figure 3.2 Isolation cap, with emphasis on erosion-protection and chemical isolation layers.

The **chemical isolation layer** is usually relatively fine-grained. Its main function is to slow down or retard long-term migration of dissolved-phase sediment contaminants up through the cap in one or more ways (e.g. sorption, extended migration pathways, contaminant transformation or degradation, etc.). An appropriate thickness and particle-sizing for this layer should be determined by site-specific computer-based modeling. Analytical or numerical cap models have been developed specifically for this purpose (Reible, 1998; Lampert and Reible, 2009; Go et al., 2009; Parsons and Anchor QEA, 2012b; Reible and Lampert, 2014; Viana et al., 2008; Russell et al., 2013; Eek et al., 2008; Petrovski et al., 2005; Bessinger et al., 2012; Reible et al., 2009).

The **erosion-protection layer** is usually relatively coarse-grained. Its main function is to prevent exposure and erosion of the underlying chemical isolation layer. The erosion-protection layer, itself, will also obviously need to be resistant to erosive forces. An appropriate particle-sizing and thickness for this layer should be determined by conducting a site-specific erosion analysis, which is usually desktop-based. Erosion analyses require qualitative and quantitative knowledge of prevailing natural and human-related erosional forces, including the dominant force. The analyses may also require use of different types of specialized models (Maynord, 1998; Mohan et al., 2000; Anchor QEA, 2009; SFT, 2002; DNV, 2008).

A “filter layer” is also often included in isolation-cap design (e.g. Wright et al., 2001; Maynord, 1998). This layer is positioned directly beneath the erosion-protection layer (as generally shown in Figure 3.2). Filter-layer material is typically medium-grained stone, and is graded to prevent turbulence at the cap’s surface from moving finer-sized isolation and sediment materials up into and through the coarser-grained erosion-protection layer over time. A geotextile could instead be included in cap design to serve as the filter layer.

3.2.4 Use of conventional capping materials

As defined herein, conventional isolation capping involves the exclusive use of conventional materials in cap design.

“Conventional” capping materials are relatively inert or passive. That is, they are neither chemically reactive (e.g. have minimal contaminant binding capacity) nor biologically reactive (e.g. do not promote or enhance microbial degradation of organic contaminants). Conventional materials can be natural earthen materials, e.g. sediment, natural sand or gravel, crushed stone of different gradations, etc. (Figure 3.4). Glacial moraine material, which is abundant in many locations in Sweden, could also be used. Conventional capping materials can also be man-made, e.g. geofabrics, like permeable geotextiles or low-permeability geomembranes.

Most conventional materials used in isolation capping (except for geomembranes) are relatively permeable (on the order of 10^{-6} m/s or higher). Sometimes this is intentional (by design), and sometimes not. The type(s) of conventional material(s) included in cap design will depend on a wide variety of factors, including: specific objectives for cap performance; physical sediment conditions, including bearing capacity; availability and relative cost of capping materials; approach used for cap construction; and cap-construction costs.

For some projects, a separate “habitat layer” (e.g. topsoil) may also be incorporated into the cap design to serve as habitat for benthic fauna and/or flora. The Onondaga Lake capping project in the U.S. is one such example (Parsons and Anchor QEA, 2012a). Even without including a designated habitat layer, initial colonization of cap surfaces by benthic fauna can occur relatively rapidly in marine and freshwater riverine environments, often within as short as one year. Development of a more evolved and stable faunal community takes longer, typically several years (SAO, 2013).

Nearly all the earlier isolation capping projects involved exclusive use of conventional materials – often clean sediment, sand, or coarser stone (SGI Publication 30-4E) – mainly because these were materials most readily available for use at the time. Regardless, even with the more recent development of active capping materials (next section), conventional materials continue today to be extensively used in isolation capping, worldwide (Reible and Lampert, 2014; Eek et al., 2013; ITRC, 2014; SGI Publication 30-4E).

3.2.5 Use of active capping materials, including active-capping products

There are conditions when conventional materials may not provide adequate long-term chemical isolation and risk reduction, even when such materials are properly incorporated into a well-constructed isolation cap (ITRC, 2014; Reible and Lampert, 2014). Such conditions include if/when:

- Sediment contaminants do not bind (sorb) strongly to the sediment’s solid phase.
- Significant groundwater upwelling or tidal influences occur.
- Sediments are contaminated by non-aqueous phase liquids (NAPLs), like oil or creosote.
- There is the need or desire for in-place treatment of unavoidable yet ongoing contaminant inputs to an already-remediated (e.g. capped) sediment surface.

Under such conditions, there may be a need for – and nowadays an opportunity for – incorporating “alternative” materials or amendments into an isolation-cap design. Such materials make the cap more efficient or effective in different ways, and allows for adequately meeting the cap-performance objective of chemical isolation when conventional materials cannot. Alternative capping materials or amendments are collectively referred to herein as “active” materials, and their use in remedial sediment capping is referred to as “active capping”.

Many different materials with unique properties or attributes have been evaluated as possible active capping materials at laboratory bench-scale and some at field pilot-scale. These materials have generally been organic carbon-based or inorganic materials, naturally occurring minerals or substances, and processed or manufactured materials. As expected, they have shown varying degrees of effectiveness.

Naturally occurring materials and substances or manufactured products that have been evaluated as active capping materials include the following: metal (Al, Fe) oxides, hydroxides and ores (e.g. bauxite); zeolites (natural and modified); calcium phosphate-based minerals (e.g. apatite and hydroxyapatite); activated carbon; phyllosilicate clays; biopolymers (e.g. chitosan); zero valent iron; organoclays; Ambersorb®; XAD-2; Bion Soil; and nutrients (to encourage microbial activity and contaminant degradation) (e.g. Gavaskar et al., 2005; Dixon and Knox, 2012; Jacobs and Förstner, 1999; Knox et al., 2007; USEPA, 2013; Thomaszewski et al., 2005; Ghosh et al., 2008; Jersak and Eek, 2009).

Active capping materials that have, over time, demonstrated the greatest degree of effectiveness and overall relative success include:

- **Sorbent materials:** These materials can sorb (bind) hydrophobic organic contaminants and some metals to the cap material's immobile solid phase much more extensively and strongly than can conventional granular materials, like sand or most types of crushed stone. Prime examples include:
    - **Carbon-based sorbents**, like organic-rich soil, coal, coke breeze, and especially activated carbon (AC). All of these bind hydrophobic organics and some metals (see SGI Publication 30-3E, Section 3.4).
    - **Calcium phosphate minerals**, the apatite mineral family. These bind and/or precipitate a variety of different metals (Crannell et al., 2004; USEPA, 2013; Dixon and Knox, 2012).
    - **Organoclays**, organically modified clays. These bind NAPLs mainly, but also dissolved-phase organic contaminants (USEPA, 2013; Hull et al., 2015; Reible et al., 2007; Oregon DEQ and UT, 2005).
- **Phyllosilicate clays** (clay minerals): Compared to sand, clay minerals are substantially finer-grained and display much lower permeabilities. Some clay minerals also possess significant metal exchange capacities, although often pH-dependent. Prime examples of clay minerals (including clay-rich geologic materials) used in capping include bentonite and palygorskite (attapulgite). Both have well-established track records in the environmental remediation industry, especially bentonite

  Sediment caps incorporating certain clays, like bentonite and/or attapulgite, can: (a) create a hydraulic barrier that can effectively divert flow of contaminated sediment porewaters away from migrating through the cap; (b) reduce the rate of advective transport of dissolved contaminants up into and through the cap; and (c) reduce steady-state contaminant flux through the cap more effectively than can coarser-grained materials, like sand (Reible and Lampert, 2014; USEPA, 2007; USEPA, 2013; Reible, 2008; Anchor QEA and SAO, 2014).

  Bentonite (mainly but not only sodium-rich varieties) is also cohesive, especially in freshwater environments. This characteristic can offer the additional performance attribute of significant resistance to at least some erosional forces (e.g. Gailani et al., 2001; Hull et al., 1998b; Barth et al., 2008; SE, 2006).

Active capping materials are often combined with conventional materials in active isolation-cap designs, with the active material serving as the chemical isolation layer (at least partially).

Conceptual examples of conventional and active isolation caps are shown in Figure 3.3.

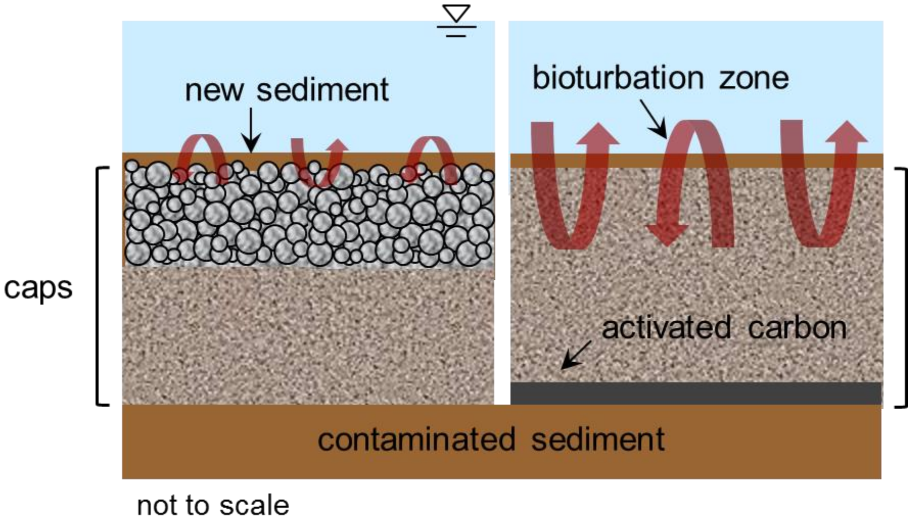

Figure 3.3 Conceptual examples of conventional (left) and active (right) isolation caps.

3.2.5.1 Active-cap performance

Incorporating active materials can significantly increase the time for migrating contaminants to “break through” into the isolation cap’s BAZ. This can effectively lengthen the timespan for cap functioning (Lampert and Reible, 2009; Viana et al., 2008; Lowry et al., 2009). Even if cap modeling predicts contaminant concentrations in the BAZ are above protective levels when steady-state conditions are reached, the greater time to breakthrough for an active cap may give some organic contaminants time to significantly degrade in the sediment and/or capping zone (Lowry et al., 2009; Parsons and Anchor QEA, 2012b; Reible and Lampert, 2014). The extent of this degradation will depend on many factors, including: timeframe, the biotic and/or abiotic degradation or transformation process(es) involved, contaminant type and concentration, oxidation-reduction status, carbon supply, etc.

Active caps are more effective than conventional caps at attenuating migration of sediment contaminants. Consequently, relatively thinner active isolation caps can often provide a level of performance at least equal to that provided by thicker conventional isolation sand caps (USEPA, 2005; Olsta, 2012; Hawkins et al., 2011; Hull et al., 1999a, 1999b; Anchor QEA and SAO, 2014).

Thinner yet equally effective active isolation caps can provide a number of advantages over conventional isolation caps, including: (a) fewer restrictions to waterway navigation, (b) fewer effects or modifications to site hydrology and/or ecology (depending on the active material used), (c) less transfer of contaminated sediment porewaters up into the cap during sediment consolidation, due to the cap’s lower submerged weight, and (d) reduced overall project costs, when placement as well as material costs are both taken into account (e.g. Hull et al., 1999a, 1999b).

In cap modeling, it is not uncommon to assume that the contaminant source (sediment) concentration remains constant over time. This is a simplifying and conservative assumption. In contrast to conventional caps, active caps incorporating highly effective sorbents like AC can sorb contaminants from the underlying contaminated sediment. This could lead to depletion of the source concentration, and reduced contaminant flux from the capped sediment. In such cases, the conservative assumption of a constant source concentration need not be made (e.g. Reible, 2016).

Active capping tends to be most appropriate, and necessary, when organic rather than metallic sediment contaminants are involved. This is because for many metals, concentrations in sediment porewaters are often low since most are mainly bound into relatively insoluble metal-sulfide complexes (e.g. Bishop, 1998; NYDEC, 2014; MERAG, 2007). Metal-sulfide complexes often prevail in anoxic freshwater and marine sediments, especially at depth.

Low porewater concentrations may not always be the case for some of the more (bio) geochemically dynamic metals, like Hg, As, and Cr. Furthermore, groundwater upwelling can also affect metal solubility and mobility in sediment environments (Liu et al., 2001). In these cases, active capping may be much more appropriate, and necessary.

One unavoidable reality of active isolation capping should be recognized: Once steady-state conditions are reached (e.g. once reactive sites on and in AC particles are fully occupied by sorbed contaminants), the active cap is no more effective than a conventional cap of equal thickness at reducing contaminant concentrations in the BAZ, and contaminant flux from the capped surface (e.g. Lampert and Reible, 2009). This steady-state reality applies to all relatively permeable active carbon-based sorbents, calcium phosphate minerals, and organoclays. However, it does not apply to physical functioning of fine-grained and low-permeability clay-based capping materials at steady-state.

3.2.5.2 Placing active capping materials through water

If active material cannot be adequately incorporated into an isolation cap during cap construction in the field, it obviously cannot function as intended (regardless of how effective the material is under controlled laboratory conditions). It is particularly challenging to achieve adequate placement and incorporation of active materials into a cap when the sediment surface is underwater, and especially when surface waters are deep and/or flowing.

Particles of some active capping materials – including apatite sand, granular organoclay, and water-soaked granular AC (GAC) – are usually large and dense enough to adequately settle through water and deposit in a relatively controlled manner, and with minimal losses to the water column during descent (Reible et al., 2006; Parsons, 2013; Horne and Sevenson, 2004; USEPA, 2013; Geary, 2012).

In contrast, particles of some other active capping materials – like powdered bentonite and powdered AC (PAC) – are too small to adequately settle through water and deposit in their bulk (as-is) form. In these cases, the active materials are typically incorporated into engineered technologies or products which themselves are easily settleable and thus readily placeable through water in a controlled manner.

The most well-known and widely used active-capping products or technologies, worldwide, are presented and summarized in Table 3.1. Most are also shown in Figure 3.4. Interestingly, despite the rapid international growth in interest and use of active sediment capping, only a few products or technologies for proven-effective delivery of active materials to submerged sediment surfaces are commercially established and currently available.

Note, the OPTICAP method was originally developed for use in active thin-layer capping (e.g. NGI and NIVA, 2012). Regardless, it is likely this method may also be appropriate for use in active isolation capping, depending on site conditions (including bottom slope), cap design, and other factors. The OPTICAP method appears to only be available in Norway.

Table 3.1 Well-known and widely used active-capping products or technologies, worldwide.

Name of product/technology	General description of product/technology	Reactive material(s) delivered to submerged sediment surfaces	Selected references for product/technology
AquaBlok®; AquaGate+™ and BioBlok®	Composite aggregate particles comprised of active plus other materials attached to a dense core with polymers.	Wide variety, including: clay minerals, AC, organoclay, apatite minerals, zeolite minerals, etc.	www.aquablok.com; www.bioblok.no.
SediMite™	Extruded agglomerate particles comprised of a treatment agent, a weighting agent, and an inert binder.	Typically AC.	www.sedimite.com.
Reactive Core Mats, RCM™s	Reactive materials, plus perhaps also inert materials, "sandwiched" between two sewn-together geotextiles.	Generally the same as for AquaBlok® et al.	http://www.cetco.com/en-us/Products/Environmental-Products/Sediment-Capping-Technologies
OPTICAP	A water-based slurry containing active and other materials, which is pumped down through the water column and deposited across the target sea-bottom surface.	Typically AC.	http://www.ngi.no/no/Prosjektnett/Opticap/; NGI and NIVA, 2012; Eek et al., 2010; Schaaning and Josefsson, 2011.

Footnotes:

1. In Scandinavia, AquaBlok®-based products are known as BioBlok®-based products.
2. OPTICAP (in Norway) is less a remedial product/technology and more a remedial "method".

Figure 3.4 Conventional and active capping materials, products and technologies (photo sources provided).

3.2.6 Additional considerations in design and use of isolation-capping remedies

As discussed in Section 3.2.3, proper designing of any conventional or active isolation cap should take into account a variety of site-specific processes (bioturbation, erosion, chemical isolation, etc.). Some additional factors should also be considered and evaluated to insure that the most appropriate isolation-capping and cap-construction approaches are being used. These additional factors include:

- Groundwater occurrence and influence.
- Geotechnical stability of the capped sediment system.
- Gas ebullition.
- Use of geotextiles when capping soft sediments, including fiberbank sediments.

3.2.6.1 Groundwater occurrence and influence

Ground and surface waters may flow upwards or downwards through a sediment cap, depending on site-specific conditions. The nature and magnitude of such flows may also vary spatially and/or seasonally. The occurrence and rate of groundwater upwelling is one of the most significant factors influencing isolation-cap design, including when selecting between conventional or active capping approaches (e.g. Winter, 2002; Reible and Lampert, 2014).

When significant groundwater upwelling is not occurring, contaminants dissolved in sediment porewaters tend to migrate up into and through a cap under the very slow process of chemical diffusion. In such cases, conventional isolation capping, using sand or crushed stone for example, can often provide adequate chemical isolation of sediment contaminants over the long term (Eek et al., 2008; Viana et al., 2008: Reible and Lampert, 2014; ITRC, 2014).

In contrast, when significant groundwater upwelling is occurring, porewater contaminants can migrate up into and through a cap under the much faster process of advection. In such cases, time to contaminant breakthrough into the BAZ of a conventional isolation cap may be too short to be protective. This is when use of some type of active-capping approach may be more appropriate, and necessary, to meet long-term performance objectives for chemical isolation of sediment contaminants by the cap (Reible and Lampert, 2014; Reible et al., 2006; Lowry et al., 2009; USEPA, 2013; Anchor QEA and SAO, 2014).

Possible occurrence and rate of groundwater upwelling should be investigated on a site-specific basis, and there are different ways to identify and measure it (Brodie et al., 2007; Chadwick and Hawkins, 2008; Merritt et al., 2010b; NAVFACS, 2009; Papadopulos & Associates, 2010; Rapaglia and Bokuniewicz, 2009). Difficulties in performing groundwater measurements are recognized, and significant variability across sites should not be discounted. Once in-hand, the measured or estimated upwelling velocity is entered into a cap model to determine, for example, if a conventional isolation sand cap of some thickness is going to be adequate or, if not, what active-capping material and cap design should instead be considered.

At some sites, there may be other advective forces involved, in addition to or instead of groundwater upwelling (e.g. tidal-pumping effects or rapidly changing pressure gradients). These other forces may also or instead need to be considered when evaluating and selecting the most appropriate conventional or active-capping approach and design (e.g. DNV GL, 2014; Reible et al., 2006).

3.2.6.2 Geotechnical stability of the capped sediment system

Two main aspects of geotechnical stability should be considered when designing and constructing conventional or active isolation caps: sediment bearing capacity and slope stability (Ebrahimi et al., 2014, 2016; Borrowman et al., 2013; Ling and Leshchinsky, 1998; Keeley and Wakeman, 2001; Rollings, 2000; Palermo et al., 2004; Mohan et al., 1999, 2000; Eek et al., 2003).

Sediment bearing capacity

To initially achieve then maintain geotechnical stability of a capped sediment system over time, the sediment profile must be able to physically support the submerged cap weight, or load.

Most contaminated mineral-based (minerogenic) sediments are fine-grained, with relatively high water and organic contents and low wet bulk densities. In combination, these characteristics create “soft” sediments with low sediment bearing capacities. Undrained shear-strength values in near-surface sediments of 2 kPa or even lower are not uncommon (Ebrahimi et al., 2014, 2016; Ling and Leshchinsky, 1998; Palermo et al., 2004. Soft sediments are typically most sensitive to bearing capacity-related failures during and immediately (days to weeks) after cap placement, and often at or near cap edges (e.g. Ebrahimi et al., 2014; Borrowman et al., 2013; Rollings, 2000).

A proper approach for cap construction (Section 3.6) is critical to avoid geotechnical failures, and to establish and maintain geotechnical stability of a capped sediment system. Geofabrics, like permeable geotextiles, can be incorporated at the base of isolation caps to provide the sediment with additional bearing support. However, there are a number of issues to carefully consider before incorporating geotextiles into isolation-cap design (see below).

When considering sediment bearing capacity in isolation-cap design and construction, a site-specific evaluation should be conducted by a qualified geotechnical engineer experienced in remedial sediment capping.

Slope stability

Submerged sediment surfaces are nearly always sloped to some degree, and some slopes (including gentler ones) are unstable, even before being loaded with a sediment cap. Thus, the inherent stability of the underlying slope should be investigated prior to capping. Once constructed, stability of the cap slope should also be investigated.

Sand isolation caps can be successfully constructed on submerged slopes as steep as 3:1 (horizontal:vertical) (e.g. Borrowman et al., 2013; Biologge, 2009). However, other factors also play significant roles in establishing and maintaining short- and long-term cap stability on submerged slopes, including: factor of safety; sediment bearing capacity; type of capping material placed; rate of material placement, including lift thicknesses; and cap-construction chronology, e.g. starting at the toe of the slope and building upwards (Rollings, 2000; Borrowman et al., 2013; Bailey and Palermo, 2005; Palermo et al., 2004).

As noted for sediment bearing capacity:

- Relatively soft sediments are typically more sensitive to slope stability-related failures (e.g. sliding and slumping) when loaded with a cap, especially during and immediately after cap placement.
- A proper approach for cap construction is critical when constructing on submerged slopes (Section 3.6).
- When considering slope stability in isolation-cap design and construction, a site-specific evaluation (including using site-specific bathymetric data of adequate vertical/lateral resolution) should be conducted by a qualified and experienced geotechnical engineer.

3.2.6.3 Ebullition

Gas ebullition (ebullition) is the microbially-driven process of gas formation (often mainly methane and carbon dioxide) in anoxic sediments, followed by gas buildup and eventual upward release (Yuan et al., 2007; Barabas et al., 2009, 2013; Adrieans et al., 2009). Ebullition is a naturally-occurring process even in clean sediments, and is usually more prevalent when large amounts of labile (easily degradable) organic matter are available (e.g. Himmelheber, 2008).

Formation, buildup and release of sediment-borne gases from capped sediment is usually not an issue, unless the cap is significantly damaged in the process and intended cap functions (e.g. chemical isolation of sediment contaminants) are unacceptably compromised over the long-term.

If periodic and uncontrolled passage of gas into and through a cap (e.g. Mutch et al., 2005) is not acceptable for a given project, the isolation cap could be designed to either effectively eliminate gas passage, e.g. include a basal geomembrane, or control gas release and passage through the cap e.g. install a gas-venting system (USEPA, 2013; Reible and Lampert, 2014; Yin et al., 2010; McLinn et al., 2010).

Total organic carbon (TOC) levels in typical contaminated minerogenic sediments are usually less than about 10 percent. When capping these sediments, the cap effectively “cuts off” additional inputs of natural organic matter to the sediment. As a result, ebullition may only be a significant concern during the first few years post-capping, while labile organics are still available for microbial degradation and gas generation (e.g. Johnson et al., 2010; Reible et al., 2006). After that, ebullition and its potential negative impacts to the overlying isolation sediment cap should be of much less concern.

One situation where ebullition can be of much greater concern is when capping NAPL-contaminated sediments (ARCADIS and Hart Crowser, 2008a, 2008b; McLinn and Stolzenburg, 2009a, 2009b; Ruiz et al., 2013). This is because: (1) NAPLs are organic-based, and thus may provide a large amount of potentially degradable organic substrate. More degradable substrate → more microbial activity → more ebullition → greater potential concern, (2) when significant ebullition occurs and if cap integrity is physically compromised during gas release (e.g. cracks formed in the cap), NAPL can migrate up through the cracks and break through the top of the cap, and (3) because they are hydrophobic, NAPLs can attach to migrating gas bubbles, thus providing yet another mechanism for upwards migration and potential cap breakthrough.

Use of cap modeling to predict long-term fate and transport of dissolved-phase contaminants when ebullition is not a factor is becoming well-established and accepted by most regulatory authorities, at least in the U.S. (Russell, 2015). However, further modeling-based work is needed to adequately predict gas ebullition and its effects on fate and transport of NAPL and dissolved-phase contaminants through sediments and sediment caps (e.g. Barabas et al., 2009; Yuan et al., 2009).

3.2.6.4 Use of geotextiles when capping soft sediments, including fiberbank sediments

Perceptions exist amongst some remediation practitioners worldwide, including in Sweden, that: (a) adequately constructing relatively thick caps overtop soft sediments is not feasible, and/or (b) if soft-sediment capping is considered feasible, some type of geofabric (often a permeable geotextile) should be included at the cap’s base to provide support for overlying (often bulk granular) capping material.

Fiberbank sediments (result from past discharges from pulp and papermill industries) could be substantially softer and weaker than the softest/weakest minerogenic sediments. Thus, use of basal geotextiles in three of the five isolation-capping projects completed to-date in Sweden – two of which involved fiberbank sediments (SGI Publication 30-4E) – may be justified.

Regardless, general conclusions on the need for geotextiles in fiberbank sediment capping are not advisable at this stage since: (1) very little bearing-capacity (undrained shear strength) data are currently available for fiberbank sediments (SGI Publication 30-5E) for comparison to data for minerogenic sediments, (2) global experience in capping fiberbank sediments is extremely limited (SGI Publication 30-4E and 30-5E), and (3) sediment conditions, including the need for geotextiles when capping, should be evaluated on a site-specific basis.

Challenges in capping soft sediments are well-known and readily acknowledged (Ebrahimi et al., 2014, 2016; National Grid, 2013; Bailey and Palermo, 2005; Palermo et al., 2004). However, it is also recognized that sediments with undrained shear-strength values of 2 kPa and even lower can be successfully capped, often (but not always) without using basal geofabrics for added support (Zeman, 1994; Cridge et al., 2009; National Grid, 2013; Fitzpatrick et al., 2002; Ling and Leshchinsky, 1998).

Additional support for soft-sediment capping is further provided by Dr. Michael Palermo, one of the world’s leading practitioners of remedial sediment capping. Quoting Dr. Palermo, “….. the USEPA’s misguided notion that soft sediment cannot be capped is contradicted by the fact that caps have been placed successfully on soft sediment at a number of sites” (National Grid, 2013). This sentiment was echoed by Prof. Danny Reible (National Grid, 2013), a practitioner firmly in the same league with Dr. Palermo.

To summarize:

- A proper construction approach is critical when constructing isolation caps overtop soft sediments (Section 3.6), especially when a basal geotextile is not incorporated into cap design.
- Including a basal geotextile in isolation-cap design substantially increases total capping costs.
- Adequate installation of basal geotextiles and similar geofabric products across submerged sediment surfaces can be challenging (Cridge et al., 2009; Carroll et al., 2009; Bailey and Palermo, 2005; Sevenson, 2006/2007; CCC, 2007). Such challenges tend to further increase total capping costs.
- The need for a costly basal geotextile in cap design should be evaluated on a site-specific basis and by a qualified geotechnical engineer with experience in remedial sediment capping.
- During project planning stages, assuming a geotextile is required in cap design without first conducting an adequate, site-specific evaluation could increase predicted total capping costs to the point a capping remedy is prematurely (and perhaps unjustifiably) eliminated from further consideration.
- The issues of whether or not a geotextile can be adequately installed across a submerged sediment surface and at a reasonable total cost are as important as the issue of whether or not geotextile inclusion in cap design is technically justified.

3.2.7 International experience with and use of conventional and active isolation-capping remedies

Please see SGI Publication 30-4E.

3.2.8 Summary of isolation capping

- Isolation capping involves placing one or more layers of cap material of one or more types overtop the surface of contaminated sediments.
- Performance objectives for isolation capping typically include: physical isolation of benthic (bioturbating) organisms from direct contact with underlying contaminated sediments, chemical isolation of the cap's bioturbation zone from sediment contaminants migrating up into and through the cap over time, and sediment stabilization against erosive forces.
- The "layer-cake" concept should be used to design isolation caps. This involves including different material layers at pre-determined thicknesses, each of which is intended to address or counter-act one or more processes acting on or in the cap (bioturbation, erosion, chemical isolation, consolidation, cap/sediment mixing, etc.).
- Various natural and/or man-made materials can be used in isolation capping. These include "passive" conventional materials (sediment, sand, crushed stone, geotextiles, etc.) and/or more effective "active" materials or amendments (sorptive materials like activated carbon or organoclay, low-permeability clays, etc.). When difficult to place through water on their own, active capping materials are often incorporated into easily placeable active-capping products or technologies (including AquaBlok® and related products, SediMite™, RCM™s, and OPTICAP).
- Conventional caps can be designed to meet performance objectives at many sites. However, there are cases when active caps are necessary or preferred given superior performance, cost-effectiveness, lower yet still protective thickness, etc.
- Over the last several decades, more than 120 conventional isolation-capping projects have been completed, initiated or planned worldwide, most in the U.S. and a considerable number in Norway (SGI Publication 30-4E). Such a global track record illustrates that capping, at least for contaminated minerogenic sediments, is a versatile and internationally established sediment remediation technology. Isolation capping is not new; novel and/or untested, and should not be considered as such.
- Five conventional isolation capping projects have been conducted to-date in Sweden (SGI Publication 30-4E).
- Fewer active isolation-capping projects have been conducted to-date, worldwide. Nevertheless, the project numbers are growing rapidly (SGI Publication 30-4E). Over the last 10 to 15 years, at least 40 active isolation-capping projects (pilot- or full-scale) have been completed, initiated, or planned in the U.S. or Norway alone. Many of these projects involve using AC, organoclay, or clay minerals as the active capping materials. Also, many of the projects use active-capping products or technologies to deliver active materials to submerged sediment surfaces.
- Using the growing track record of completed projects (and lessons learned) as a foundation, the remedial practices of conventional and active isolation capping continue to evolve, develop, and improve, internationally.

- Isolation capping remedies are proven technologies, both in terms of their technical performance and cost-effectiveness (see SGI Publication 30-3E). This assumes, however, site-specific caps are designed appropriately and constructed according to specifications. Isolation capping is also a versatile remedy and broadly applicable to a wide variety of sites and situations, especially when active materials and products are included in the “toolbox” of available capping materials.
- It should be emphasized isolation capping is not a “one-size-fits-all” remedial technology appropriate for use at all sites. A number of site-specific limitations are recognized for using isolation-capping remedies (SGI Publication 30-3E). Nevertheless, it should also be recognized use of active materials in isolation capping can address some of these limitations, as can thin-layer capping strategies.

3.3 Thin-layer capping

3.3.1 General description

Thin-layer sediment capping has been defined or described in different ways by remediation professionals.

The most widely accepted definition or description for thin-layer capping (as used herein) involves placing cap material overtop a contaminated sediment surface at a thickness approximately equal to the depth of the “well-mixed” bioturbation zone. The targeted layer thickness depends on the degree of risk reduction desired and the type of capping material used.

The well-mixed bioturbation zone can be 5 cm or less, but is more typically in the range of 5 to 15 cm, depending on populations of burrowing benthic organisms present, substrate type, salinity and other factors (Clarke et al., 2001; Glaser and Hovel, 2011; Lampert et al., 2011; Reible, 2016).

3.3.2 Objectives for thin-layer cap performance

The main objectives for thin-layer cap performance are to reduce – but not necessarily eliminate – organism exposure to and bioaccumulation of sediment contaminants. This means that while cap thickness is greater than bioturbation depths for most burrowing benthic organisms, some organisms may still occasionally penetrate deeper, and into underlying contaminated sediments.

Different levels of contaminant exposure and bioaccumulation reduction are achieved when bioturbating organisms either stay mainly within the capping layer or penetrate more deeply. Deeper penetration results in some degree of vertical mixing of capping material with underlying contaminated sediments. Reductions in contaminant exposure and bioaccumulation also depend on the capping material used.

When bioturbation-driven cap/sediment mixing occurs, a reduction in whole-sediment (total) contaminant concentrations also occurs by dilution (e.g. Palermo et al., 2004). However, when non-sorptive material like sand or crushed stone is used as cap material, reductions in total contaminant concentrations do not result in reduced contaminant concentrations in porewater, which is the most bioavailable phase (ITRC, 2011; NYDEC, 2014).

In contrast, when bioturbation-driven cap/sediment mixing occurs and a highly sorbent material like AC is included in the cap material, the mixing more-or-less naturally delivers the reactive material directly to where it needs to be within the biological zone. As a result of this process, significant reductions in porewater contaminant concentrations and thus exposure and bioaccumulation can be achieved within the post-cap BAZ (e.g. Ghosh et al., 2011; Menzie, 2012; Patmont et al., 2014; Cornelissen et al., 2011).

3.3.3 Approach to thin-layer cap design

Unlike isolation caps, thin-layer caps do not include function-specific layers to address certain site-specific processes (erosion, chemical isolation, sediment consolidation, etc.). Thus, the layer-cake concept is not used in designing thin-layer caps.

Instead, parameters dictating thin-layer cap design and thickness include: type of cap material used, including its ability to sorb contaminants; expected post-cap bioturbation depths; and target levels for reductions in contaminant concentrations in porewaters, exposure and bioaccumulation (USEPA, 2013; Lampert et al., 2011; Magar et al., 2009).

3.3.4 Use of conventional and active capping materials

Most conventional and active capping materials (including active-capping products and technologies) used in isolation capping are also used in thin-layer capping. Conventional materials not used in thin-layer capping include geofabrics and larger stones.

When using passive (non-sorptive) materials like sand or crushed stone, the layer thickness should at least equal the depth of the well-mixed bioturbation zone, in order to be most protective. In contrast, when using sorptive material, like AC, layer thickness can be less than the well-mixed depth and still be protective.

It should be noted that research on thin-layer capping has been conducted by numerous Swedish academics. Most research has focused on active thin-layer capping, often involving use of carbon-based sorbents. A partial listing of relevant references is included herein (Gunnarsson et al., 2015; Gustafsson et al., 2015; Josefsson, 2011; Samuelsson, 2012; Samuelsson et al., 2015; Renman et al., 2013).

Conceptual examples of conventional and active thin-layer caps are shown in Figure 3.5. Conventional thin-layer capping, using sand for example, is considered the same as Enhanced MNR (EMNR). Active thin-layer capping, using AC for example, is considered the same as *in-situ* treatment (SGI Publication 30-3E). Also see Figure 3.6.

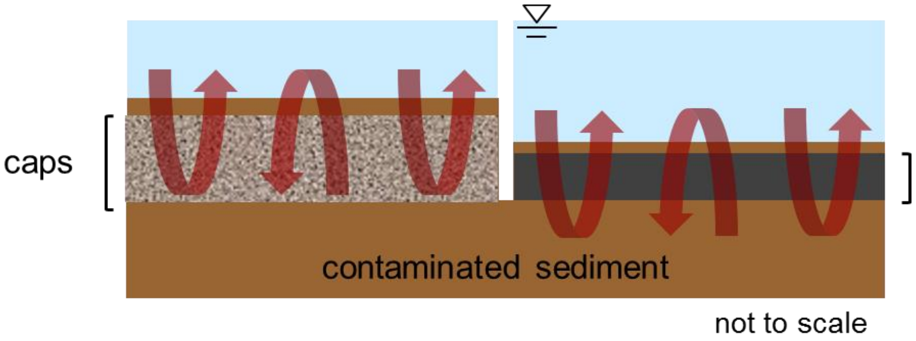

Figure 3.5 Conceptual examples of conventional (left) and active (right) thin-layer caps.

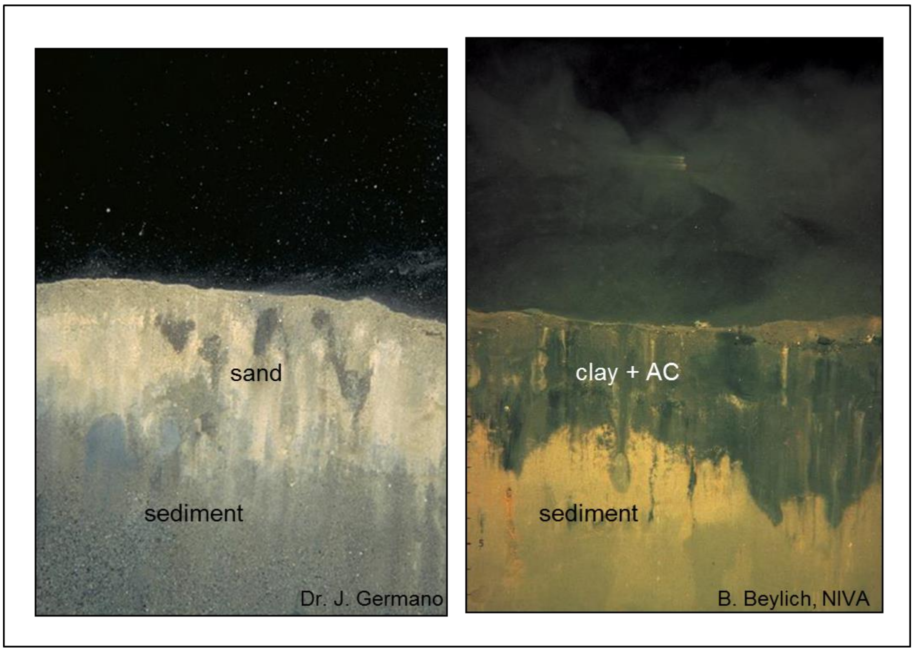

Figure 3.6 Conventional (left) and active (right) thin-layer caps, both, ~ 5 cm (photo sources provided).

3.3.5 Additional considerations in design and use of thin-layer capping remedies

3.3.5.1 Groundwater occurrence and influence

When significant groundwater upwelling is occurring, a conventional sand isolation cap may not provide adequate long-term protection for benthic organisms against exposure to migrating contaminants (Section 3.2.6). With groundwater upwelling, if an isolation-layer thickness of sand cannot provide adequate protection, it can be assumed a thinner layer of the same material would provide even less protection.

Lampert et al. (2011) concluded that a thin-layer sand cap can effectively reduce PAH bioaccumulation provided its thickness is greater than the depth of active and rapid bioturbation. However, the authors emphasize this is limited to systems dominated by molecular diffusion in the sediment underlying the biologically active zone. They go on to say if other mechanisms exist to maintain pore water concentrations high (e.g., groundwater upwelling), such a cap will not reduce contaminant bioaccumulation.

Even with significant groundwater upwelling, an active thin-layer cap containing highly sorbent AC can greatly decrease contaminant bioavailability and bioaccumulation. This will increase the cap’s effective lifespan to a much greater degree than the effective lifespan of an equally thin but non-sorptive sand layer.

Superior performance of such an active thin-layer cap, however, will not be achieved indefinitely. As for active isolation caps (Section 3.2.6), once steady-state conditions are reached, the active thin-layer cap will be no more effective at reducing contaminant bioavailability and bioaccumulation than a sand layer of similar thickness.

3.3.5.2 Geotechnical stability of the capped sediment system

In isolation capping, sediment bearing capacity and slope stability need to be considered because of the thicker layers and greater loads being placed overtop submerged sediment surfaces (Section 3.2.6). Insuring a proper approach is used to construct thicker and heavier isolation caps – namely, the cap-lift strategy (Section 3.6) – is also critical to maintaining geotechnical stability of the capped sediment system. This is especially the case when capping on slopes and capping soft sediments.

Thin-layer capping involves placing much lighter loads overtop submerged sediment surfaces. Thus, the geotechnical issues of sediment bearing capacity and slope stability should usually be less of a concern. However, even gentle sediment slopes can be inherently unstable, and this possibility needs to be considered before loading such slopes with even relatively lower-weight thin-layer caps.

One of the benefits to using the cap-lift strategy for cap construction is typically achieving a lower degree of material mixing at the cap/sediment interface (Section 3.6). Minimal cap/sediment mixing is advantageous in conventional thin-layer capping. This is because less mixing during construction creates an initially “cleaner” layer of non-sorptive material and thus further decreases direct organism contact with sediment contaminants.

In active thin-layer capping (using AC, for example), more cap/sediment mixing during cap construction – not less – may however be advantageous. This is because construction-related mixing would promote rapid and extensive contact between AC particles and sediment contaminants, at least to some depth. Accelerated material contact should result in more rapid reductions in contaminant concentrations in porewaters, and thus reductions in contaminant exposure. In essence, some degree of construction-related cap/sediment mixing would give the natural process of bioturbation-driven cap/sediment mixing a significant “head start”.

This is not to say the cap-lift strategy should not be used to also construct thin-layer caps. Regardless, the cap-lift strategy should typically be used to construct thin-layer caps since layer placement in controlled and even thicknesses is an integral component of this construction strategy (Section 3.6).

3.3.5.3 Ebullition

As noted in Section 3.2.6, the physical integrity of even a relatively thicker and heavier isolation cap could be compromised by releases of sediment-borne gas through the cap. Thus, it is reasonable to assume gas releases could have even greater disruptive impacts on thinner and lower-weight caps. Gas-induced disruptions to a thin-layer cap could compromise the cap’s ability to physically and chemically isolate sediment contaminants.

But the main performance objectives for thin-layer capping are reductions in contaminant exposure and bioaccumulation – not elimination of exposure and bioaccumulation through complete sediment isolation (Section 3.3.2). Thus, cap performance objectives may still be met even when some degree of gas-induced disruption occurs to a thin-layer cap, especially when active (sorptive) materials are included in the cap. The extent to which disruptive gas releases result in unacceptable levels of increased contaminant exposure and bioaccumulation should be evaluated on a site- and project-specific basis.

One situation where gas release through a thin-layer cap could result in significant contaminant release and exposure is when capping NAPL-contaminated sediments. Given its lower thickness and weight, a typical thin-layer cap would probably offer little physical resistance to gas-assisted

NAPL passage completely through the cap. Even including a highly sorbent material like organoclay in the cap may do little to effectively reduce organism exposure to the NAPL. For these reasons, conventional and even active (organoclay) thin-layer capping of NAPL-contaminated sediments is usually not appropriate.

3.3.6 International experience with and use of conventional and active thin-layer capping strategies

Please see SGI Publication 30-4E.

3.3.7 Summary of thin-layer capping

- The remedial concept of thin-layer capping has been described in different ways. The most widely accepted description (as used herein) is placement of cap material overtop a contaminated sediment surface at a thickness approximately equal to the depth of the well-mixed bioturbation zone (5 to 15 cm).
- The main performance objectives for thin-layer capping are to reduce – but not necessarily eliminate - organism exposure to and bioaccumulation of sediment contaminants.
- Different levels of contaminant exposure and bioaccumulation reduction are achieved when bioturbating organisms either stay mainly within the capping layer or penetrate more deeply. Deeper penetration results in some degree of cap/sediment mixing. The type of cap material used has a significant influence on the exposure and bioaccumulation reductions achieved.
- Parameters dictating thin-layer cap design and thickness include: type of cap material used, including its ability to sorb contaminants; bioturbation depths; and target levels for reductions in contaminant concentrations in porewaters, exposure and bioaccumulation.
- Most of the same conventional as well as active capping materials and products used in isolation capping are also used in thin-layer capping.

- When using conventional (non-sorptive) capping material like sand or crushed stone, the layer thickness should at least equal the depth of the well-mixed bioturbation zone to be most protective. Conventional thin-layer capping is often considered the same as the remedial approach of EMNR.
- When using active capping material, like highly sorbent AC, the layer thickness can be less than the depth of the well-mixed zone. This results in some degree of bioturbation-driven cap/sediment mixing. Increased contact between AC particles and sediment contaminants leads to significant reductions in contaminant concentrations in bioavailable porewaters. In turn, porewater reductions result in significant reductions in contaminant exposure and bioaccumulation. Active thin-layer capping, especially when using AC, is often considered the same as the remedial approach of *in-situ* treatment.
- To-date, far fewer thin-layer capping projects (conventional or active) have been completed worldwide than isolation capping projects (SGI Publication 30-4E). Regardless, international interest in and use of thin-layer capping remedies is growing steadily, especially in the U.S. and Norway. Increased use of active thin-layer capping (*in-situ* treatment) incorporating AC sorbents is especially noteworthy. Over the last 10 years or so, a total of approx. 10 conventional thin-layer (EMNR) projects and approx. 15 AC-based *in-situ* treatment projects have been completed in the U.S. and Norway.
- Like isolation capping, thin-layer capping: (a) is a proven and internationally accepted sediment remediation technology, (b) is versatile and broadly applicable to a wide variety of contaminated-sediment situations, especially when active materials like AC are included in the “toolbox” of active-capping materials, (c) must be implemented using appropriate, site-specific designs, and (d) will not be appropriate for all sites, either in conventional or active forms.

3.4 Deposition of new sediment after capping

At many sites, some amount of deposition of typically finer-grained sediment can often occur overtop a cap over time (Figures 3.3 and 3.5). New sedimentation is especially common overtop caps constructed in inherently lower-energy, depositional environments.

Ideally, the newly deposited sediment will not be contaminated. In such cases, it should provide habitat material when deposited overtop isolation caps, including within void spaces at the top of armored caps (Figure 3.3). When deposited overtop thin-layer caps over time, the new sediment will provide additional (and expanding) vertical separation between bioturbating organisms and the underlying contaminated sediment (Figure 3.5).

Post-cap sediment deposits could instead be significantly contaminated, for various reasons. This new contamination may pose unacceptable risks to benthic organisms – regardless of how well the cap is physically and chemically isolating the underlying sediment contamination. In such cases, active materials could be used for in-place treatment of these new contaminant inputs. For example, a thin layer of sorbent material, like AC, could be placed across the cap surface as a final construction phase. As particle-bound contaminants deposit overtop the cap over time, benthic burrowing organisms colonizing the cap would then naturally mix the new contaminated sediment with the underlying AC. Conceptually, this is an “upside-down” variation of the Method B approach for *in-situ* sediment treatment (see SGI Publication 30-3E).

When using AC for *in-situ* sediment treatment, remediation professionals often acknowledge post-cap contaminant inputs are indeed being treated in the above-described fashion. However, most consider such treatment as an unintended “bonus” when targeting treatment of the underlying (already deposited) sediment contamination. There is merit in developing and refining this upside-down treatment variation as an intentional and designed *in-situ* remedial approach in its own rite (e.g. Jersak, 2012).

3.5 Selecting the most appropriate capping approach

Four different, end-of-spectrum capping-strategy plus material-type combinations have been presented herein:

- Conventional isolation capping.
- Active isolation capping.
- Conventional thin-layer capping (~ EMNR).
- Active thin-layer capping (~ *in-situ* treatment).

In practice, project-specific sediment caps incorporating conventional and/or active materials are often hybrids, falling somewhere along the isolation ↔ thin-layer spectrum in terms of remediation objectives and cap design.

As when selecting the most appropriate remediation technology in general (removal, *in-situ* capping, MNR, etc.), selecting the most appropriate capping approach is a site- and project-specific process. Furthermore, the selection process should consider and balance multiple factors, including: rate and degree of risk reduction needed, contaminant type(s) and concentration(s), site conditions and sediment characteristics, and costs.

3.5.1 General capping strategy – isolation or thin-layer?

As discussed in previous sections, performance objectives for isolation and thin-layer capping are not the same. For any project, specific cap-performance objectives should be decided and agreed upon before the cap-design phase is initiated. Typically, site-specific performance objectives can best be met using either – but usually not both – an isolation or thin-layer capping strategy. Thus, the decision of whether to follow an isolation or a thin-layer capping approach is one that is made more-or-less “automatically”.

Thin-layer capping strategies should generally be most appropriate in depositional environments, where an erosion-protection layer is not required. This is because: (a) thin-layer capping is generally considered the same as EMNR, at least when using conventional materials like sand, (b) the remedial approach of EMNR is fundamentally based on the remedial approach of MNR, and (c) a main site condition requirement for MNR is a relatively lower-energy, depositional environment.

Thin-layer capping may also be appropriate in dredged areas, which are inherently depositional. In such areas, risks posed by residual, post-dredge sediment contamination are managed not only by presence of a thin-layer cap, but also by new (and hopefully not contaminated) sediment naturally depositing overtop the cap over time.

Isolation-capping strategies are usually more appropriate for use in-higher energy environments, where some type of erosion-protection layer is required.

In selecting between isolation versus thin-layer capping, there are obviously more factors to consider beyond just the hydrodynamic conditions at a site. These additional factors include: rate and extent of risk reduction required, contaminant type(s) and concentration(s), sediment characteristics, etc. For example, an active isolation cap incorporating organoclay is appropriate for use at a NAPL-contaminated site even if the site is relatively lower-energy and depositional.

Furthermore, even though an isolation cap can and should be used at some lower-energy sites (as in the above example), the reverse is not necessarily appropriate. That is, placing an unarmored, thin-layer cap in a relatively higher-energy, erosional environment is usually not appropriate.

3.5.2 Isolation capping – conventional or active?

When capping is the most appropriate remedy for a given site, and when isolation capping in particular is the best strategy for meeting pre-defined objectives for cap performance, a conventional isolation cap should be considered as the initial "default" approach – unless one or more of the following can be concluded:

- A conventional isolation cap will not adequately meet long-term cap-performance objectives for chemical isolation.
- An active isolation cap can adequately meet cap-performance objectives and be cost-competitive with a conventional isolation cap.
- Even if an active cap is a bit more expensive, the additional cost is justified if the cap can provide far-superior performance over a conventional isolation cap.
- Use of an equally-performing active cap may still be attractive to involved stakeholders (for various reasons), even if it is a bit more expensive.

The rationale for considering conventional isolation capping as the default approach includes the following:

- Despite the rapidly growing global track record for active capping, the list of conventional isolation capping projects completed to-date worldwide is considerably more impressive (SGI Publication 30-4E).
- A wide variety of conventional materials, especially granular earthen materials, are often appropriate and locally available at a reasonable delivered cost.
- Depending on the contaminant content, sediments dredged for navigational purposes can often be used as capping material. At some sites, this can serve two needs at once: a source for capping material and a means for sediment disposal.
- A conventional isolation-capping remedy provides a "baseline" to which different active isolation-capping remedies may be compared, both technically and economically.

3.5.3 Thin-layer capping – conventional or active?

As discussed previously, active capping materials like AC can significantly reduce contaminant concentrations in porewaters, significantly lowering organism exposure to and bioaccumulation of sediment contaminants. Conventional capping materials, like sand or crushed stone, can do none of these things effectively.

Because of such inherent differences in material performance: (a) when using non-sorptive material like sand, the layer thickness should at least equal the depth of the well-mixed bioturbation zone to be most protective, and (b) when using AC, the layer thickness can be less than the well-mixed depth and still be protective.

Differences in material performance, respective layer thicknesses required, and relative costs are all factors that need to be considered early on when selecting conventional or active materials for use in thin-layer capping at a given site.

Furthermore, as noted previously, conventional thin-layer capping is considered the same as EMNR whereas active thin-layer capping (e.g. with AC) is considered the same as *in-situ* treatment. Remedial objectives for EMNR are not necessarily the same as those for *in-situ* treatment (SGI Publication 30-3E). Thus, in addition to the above factors, the desired remedial objectives for sediment remediation should also be firmly in-mind when selecting between conventional or active thin-layer capping.

Additional note on use of AC in active thin-layer capping (*in-situ* treatment): Secondary effects from AC amendments on some species of benthic organisms have been reported, including some negative impacts on certain ecotoxicological endpoints like organism survival, growth, lipid content, and/or behavior (Kupryianchyk et al., 2015; Janssen and Beckingham, 2013; Janssen et al., 2012; Jonker et al., 2009). More research is needed to evaluate these secondary effects, including under what species-, sediment- and AC-specific conditions such effects may be more likely to occur (e.g. Janssen and Beckingham, 2013; Nybom et al., 2016). Practically speaking, secondary negative effects from AC amendments will need to be balanced and weighed against AC’s clearly demonstrated effectiveness in significantly reducing bioavailability of sediment contaminants to benthic organisms (e.g. Kupryianchyk et al., 2012 a).

3.6 Cap construction

This section addresses cap construction through placement of loose capping materials, like bulk masses of sand or crushed stone. Methods for placing other types of capping materials, like geofabrics, are not addressed herein.

Many different mechanical- or hydraulic-based approaches (equipment-plus-placement method combinations) can be and have been used to construct sediment caps at a wide variety of sites with water depths ranging from ~ 0 m (e.g. Fitzpatrick et al., 2002) up to almost 100 m (e.g. NGI and NIVA, 2012). Some examples of approaches to cap construction are shown in Figure 3.7.

Regardless of the bulk material placed or approach used to place it, certain objectives should be met when constructing any isolation or thin-layer cap overtop a submerged sediment surface. These objectives include:

- Cap construction in a controlled manner.
- Cap construction in a geotechnically stable manner.
- Minimal sediment re-suspension during cap construction.

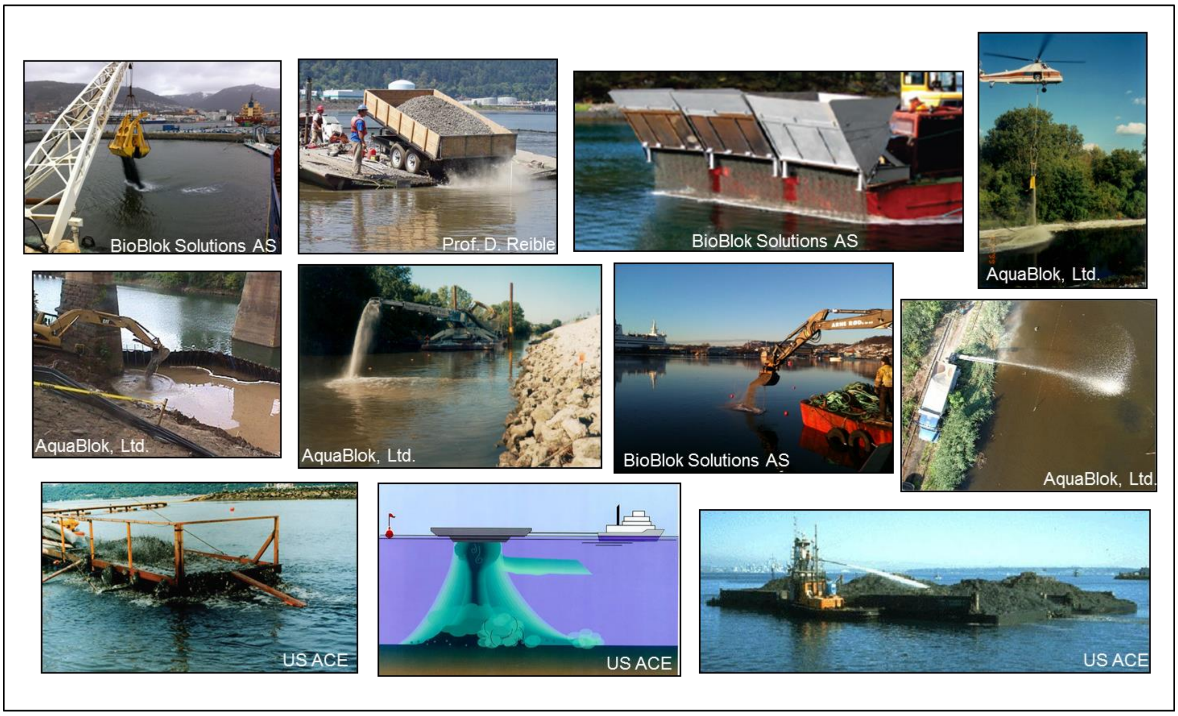

Figure 3.7 Equipment-plus-placement-method combinations for cap construction (photo sources indicated).

3.6.1 Cap construction in a controlled manner

Controlled cap construction refers to material placement through water such that the material settles and deposits evenly and uniformly across the target surface and at the layer thickness intended, within acceptable (and previously agreed on) limits or ranges (e.g. Mastbergen et al., 2004).

Because there is less margin for vertical error, the need for adequately meeting target placed-material thicknesses tends to be more critical when: (a) constructing thin-layer caps, and (b) when building up an isolation cap by placing successive, thinner layers of capping material (see below).

Having adequate vertical control during cap construction is especially important when placing high-value active-capping products or materials like AquaGate+™, SediMite™, or water-soaked GAC. From a cost point-of-view, no more product or material should be placed than is needed to adequately meet cap-performance objectives.

3.6.2 Cap construction in a geotechnically stable manner

A proper approach to cap construction is critical for establishing and maintaining geotechnical stability of the capped sediment system, both when capping relatively soft sediments and when capping sediments (particularly soft sediments) on submerged slopes (Section 3.2.6).

A proven-effective cap-construction approach commonly used by U.S. and Norwegian contractors to achieve and maintain geotechnical stability of the capped sediment system, especially when capping relatively soft sediments, is what can be referred to as the “cap-lift strategy” (Bailey and Palermo, 2005; Palermo et al., 2004; Parsons, 2013; Ebrahimi et al., 2014, 2016).

The cap-lift strategy is defined herein as gradually (rather than rapidly) building up a total capping layer and can further be described as follows:

- First, a thin layer, or lift, of material (often ≤ 10 cm) is placed evenly and uniformly across the submerged sediment surface, and in a controlled manner (as defined above). Typically within a couple weeks or so, the underlying sediment consolidates beneath the load by "squeezing out" sediment porewaters up through this initial layer. This sediment consolidation and dewatering process results in the sediment gaining bearing strength.
- Then, with the increased sediment bearing strength, a second lift of material of equal or somewhat greater thickness is placed. This results in further sediment consolidation and increased strength.
- Finally, subsequent and often thicker material lifts are progressively placed until the total target cap thickness is constructed.

Use of the cap-lift strategy is especially necessary when constructing relatively thicker (isolation-scale) caps overtop "bare" sediment surfaces, e.g. when no basal geotextile is present. When implemented correctly, use of the cap-lift strategy for cap construction can often (but not always) eliminate the need for incorporating costly geotextiles into cap design, even when capping soft sediments (Section 3.2.6, geotextiles sub-section).

3.6.3 Minimal sediment re-suspension during cap construction

Regardless of how much care is exercised by the contractor, at least some sediment re-suspension always occurs during cap construction. Aspects of cap construction causing re-suspension include: during material impact with the sediment surface, during re-positioning of barge-based construction equipment with tugboats, etc. Regardless, there is still merit in minimizing re-suspension of often-contaminated sediment to the extent possible and practical. Less re-suspension means less re-suspended sediment (turbidity) to aquatically control or confine (e.g. using silt or bubble curtains).

Use of the cap-lift construction strategy not only results in a more geotechnically stable capped sediment system, but can also significantly minimize sediment re-suspension during material placement, particularly during placement of initial material lifts (e.g. Lyons et al., 2006).

The cap-lift strategy can also minimize mixing of cap and sediment materials (Palermo et al., 2004; Bailey and Palermo, 2005; Zeman and Patterson, 1997). Less mixing results in achieving more discrete (sharper) cap/sediment interfaces. This, in turn, translates to a "cleaner" (more contaminant-free) cap base.

In summary, selection of the most appropriate cap-construction approach for meeting cap-construction objectives (e.g. Figure 3.7) is a project- and site-specific process. This selection process should involve considering and balancing a wide variety of factors including: cap design; materials used; site conditions, including water depth, water flow, and bottom slope; sediment characteristics, including sediment strength; equipment availability and cost; and contractor experience.

3.7 Monitoring

Two different types of monitoring are involved when conducting any capping project: construction monitoring and performance monitoring. Long before field phases of a capping project begin, written plans should be in place that precisely describe each monitoring effort in detail (what, where, when, how often, for how long, how, replication, manner in which collected data will be used, etc.).

Construction monitoring is conducted during and immediately after cap construction. Performance monitoring is conducted after (to long after) cap construction and construction monitoring are completed.

3.7.1 Cap-construction monitoring

The overall goal of cap-construction monitoring is to insure the cap design is being constructed according to pre-defined specifications, including within allowable thickness tolerances.

In addition to monitoring during the actual construction process, some types of monitoring should also occur shortly after (days to weeks) the cap is constructed. Monitoring shortly after construction should focus on geotechnical stability of the capped sediment system, since it is at this early stage a cap is typically most sensitive to possible bearing capacity and especially slope-related failures.

Construction monitoring often involves the use of various physical and/or geophysical equipment and techniques (Figure 3.8) to collect different types of data from above and below the water surface. Such techniques and equipment include: GPS positioning, pre- vs post-cap bathymetry, sediment profile imaging (SPI) cameras, side-scan sonar, sub-bottom profiling, visual inspections by divers and/or remote operated vehicles (ROVs), and core collection and inspection.

Monitoring sediment re-suspension (turbidity) is often a component of construction monitoring. Turbidity monitoring is typically conducted in conjunction with using aquatic barriers (e.g. silt or bubble curtains) intended to control and contain any sediment re-suspension created during the cap-construction process.

For reference, examples of cap-construction monitoring programs developed and implemented for selected conventional or active sediment capping projects are provided herein (Anchor QEA and Parsons, 2012b; BBL, 2006; Horne and Sevenson, 2004; Colton, 2010; Alcoa, 2005).

3.7.2 Cap-performance monitoring

The overall goal of cap-performance monitoring is to collect and evaluate various types of post-cap data and other information over time to determine if physically and/or chemically-oriented objectives for cap performance have been, and continue to be, adequately met (or not).

If and when cap-performance monitoring indicates the cap is not performing as intended, or indicates some type of damage has occurred to the cap, immediate modifications or repairs to the cap are required.

Cap-performance monitoring typically occurs during multiple events and often for a period of at least several years. A wide variety of physical/geophysical, chemical, hydraulic, and/or biological techniques can be used for cap-performance monitoring.

The types of monitoring equipment and techniques used (Figure 3.8) will depend on the specific objectives for cap performance, and available budget. Such techniques and equipment can include: many of those used in construction monitoring (discussed above), settlement plates to track sediment (and cap) consolidation, depth-discrete chemical analyses of bulk capping materials and cap porewaters, use of benthic flux chambers and groundwater seepage meters, sedimentation traps, and bioassays.

Figure 3.8 Examples of some cap construction and performance monitoring equipment and techniques.

Key aspects of cap-performance monitoring should be determined early on, during cap design (Reible, 2016). Such aspects should include: (a) where monitoring will occur relative to the cap's BAZ – top, bottom, or below, (b) what contaminant phase will be monitored – porewater, particle-bound, or both; and (c) how monitoring will be conducted – e.g. measuring porewater contaminant concentrations *in-situ*, core collection and depth-discrete chemical analysis, etc.

Over time, costs for cap-performance monitoring – including cap repair, when needed – can add up significantly. Thus, anticipated monitoring and maintenance costs should be factored into initial estimates for total costs for any capping project.

For reference, examples of cap performance-monitoring programs developed and implemented for selected conventional or active sediment capping projects are provided herein (Knox et al., 2012; Menzie, 2012; ARCADIS BBL and Hart Crowser, 2008a, 2008b; Eek et al., 2009; Jacobs, 2003; Wilson and Romberg, 1995; ASTSMNO, 2009; Germano et al., 2011; Alcoa, 2006; SEG, 2005).

4. Conclusions

The following conclusions are drawn from this document as well as supporting (appended) documents:

- Contaminated minerogenic (mineral-based) sediments have been identified in at least 17 of Sweden’s 21 counties. Contaminated fiberbank (cellulose-based) sediments have been identified in at least 10 counties. Sediment contamination is clearly a national problem – not just a local or regional problem.
- Sediment risk assessments have been conducted at some Swedish sites. At most sites, risks have been classified at high to very high levels, indicating sediments need to be remediated. Sediment risk assessments and classifications are still needed at many sites, beyond just identifying contaminant occurrence. When these assessments and classifications are completed, the need for sediment remediation at many more sites in Sweden will likely become evident.
- Proven-effective and internationally-accepted ex-situ and *in-situ* technologies are available for remediating contaminated sediments. These include: removal (dredging), MNR, EMNR, *in-situ* capping, and *in-situ* treatment. Each technology has recognized advantages and limitations relative to the others.
- Results of a preliminary review indicate only a small number of contaminated sediment sites have been remediated so far in Sweden, a total of less than 20. As noted above, this is probably a small fraction of the total number of sites requiring remediation, nationwide.
- Most sediment remediation conducted to-date in Sweden has been through removal by dredging (approx. 10 projects) (note: this does not include projects involving maintenance dredging, mainly for navigational purposes). Fewer sites have been remediated using some form of capping (six projects).
- Given no limitations, complete removal of all sediment contamination and at a reasonable total cost would obviously be the optimal remedial approach at any site. However, the realities are contaminant removal, e.g. by dredging, is rarely complete and associated total costs are typically high, often prohibitively so. Thus, technically- and cost-effective alternatives to removal are needed.
- Resulting in part from shortcomings inherent to removal-based remedies, *in-situ* remedial technologies – especially capping – have become increasingly more popular and widely used over the last two to three decades. Another major reason for significant international growth in sediment capping is that it has been shown to work.
- Capping is a flexible remedial technology in that different capping strategies (isolation and thin-layer) and different cap materials (conventional and active) can be combined and successfully applied to a broad range of contamination and site conditions.
- Well over 180 capping projects, in different forms, have been conducted worldwide over the last several decades, most in the U.S. and many in Norway. Virtually all projects involve contaminated minerogenic sediments. Such a global track record confirms capping is indeed an internationally established sediment remediation technology, at least for minerogenic sediments.
- Theoretically, capping (in one or more forms) should also be appropriate for remediating many of Sweden’s contaminated fiberbank sediment sites. However, global experience in capping these unique, anthropenically derived sediments is extremely limited. Because of this lack of experience – coupled with the sediments’ unusual characteristics and attributes

– there are many unknowns related to how fiberbank sediments will respond to different types of capping remedies, including how well capping remedies will function for fiberbank sediments over the long term.

- When capping contaminated minerogenic or fiberbank sediments at coastal sites, consideration should be given to how best to design capping-based remedies that will remain effective over the long-term even when sea-level changes and/or land uplift results in significant changes to site conditions (water depths, aquatic erosion regimes, submerged slopes, etc.).

In closing, the following points in particular should be emphasized:

- Capping in general will not be an appropriate remedy at a number of sites, for various reasons. Furthermore, when capping is considered appropriate for a given site, some types of capping will likely be more appropriate than others (while some types may not be appropriate at all). Whether or not capping is an appropriate remedy and, if so, which type and cap design is most appropriate, are all decisions that must be made on a site- and project-specific basis.
- Cap monitoring should be conducted during and after construction, to insure the cap is constructed according to specifications and is performing over time as intended.
- No single sediment remediation technology – including capping – is “one-size-fits-all” and thus appropriate for all sites and projects. There should also not be a preconceived notion a particular technology, like dredging or capping, is best for a given site. Selecting which remediation technology or technology combination is most appropriate is a site- and project-specific process. This remedy selection process must systematically consider and balance many different and sometimes conflicting factors, not just costs.
- No sediment remedy or remedy combination – regardless of how well it is designed and implemented – will protect a site over the long-term if significant contaminant inputs continue after remedy implementation. Thus, identifying and controlling contaminant sources are critical, and preferably before sediment remediation occurs.
- Due to both the technical complexity and the high costs associated with complete removal of contaminated sediments from aquatic environments, there will be a significant number of sites where this is not considered a realistic option. Risks posed by sediment contamination will instead, in many cases, need to be effectively managed in-place. *In-situ* capping, in its various forms, is one proven technology that can be an option in these cases.

5. References

Please see SGI Publication 30-6E for all references cited herein.

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