ENVIRONMENTAL DREDGING VERSUS SHORELINE STABILITY

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ABSTRACT

Many sites with contaminated sediment are located along shorelines of industrial areas where there are steep slopes and existing bulkheads, docks or wharfs of unknown condition. Contaminated sediments often are present at significant depths adjacent to existing facilities. For those remediation projects where dredging is the selected remedy, the goal is often to remove all sediment with chemical concentrations above a cleanup action level. Dredging at the bottom of slopes or adjacent to existing waterfront facilities can cause landslides or failure of existing bulkheads, which creates a dangerous condition.

This paper (1) describes situations where deep dredging near existing facilities would lead to landslides or bulkhead failure, (2) gives examples of the types of temporary reinforcement that would be required to maintain a stable slopes or bulkheads, (3) gives examples of the costs and construction times for typical slope or bulkhead reinforcement systems, (4) discusses the implementation difficulties of the different bulkhead systems and (5) shows the difference in possible dredge volumes with different systems. Reinforcement systems described include cantilevered sheet pile retaining walls, anchored sheet pile walls (with upland tiebacks or batter piles), soldier pile walls, toe buttresses at the bottom of slopes, temporary excavations to remove upland weight, and pile-reinforced slopes. These systems will be compared to simply making the dredge slope less steep and not dredging as much volume near the shoreline.

In order to properly evaluate the benefits of deep dredging versus the cost and risk of temporary slope reinforcement, the stakeholders must have a reliable analysis of the existing conditions and the impact of dredging on the shoreline stability. The purpose of the paper is to promote understanding of practical limitations on dredging near existing waterfront facilities and to give some guidelines when consultation with geotechnical engineers is appropriate.

Keywords: Dredging, adjacent facilities, unstable slopes, bulkheads, steep slopes

INTRODUCTION

Many sites with contaminated sediment are located along shorelines of industrial areas where there are steep slopes and existing bulkheads, docks or wharfs of unknown condition. Contaminated sediments are often present at significant depths adjacent to existing facilities. For those projects where dredging is the selected remedy, the goal is often to remove all sediment with chemical concentrations above a cleanup action level. Deep dredging adjacent to existing facilities or at the bottom of slopes can cause landslides or failure of existing bulkheads, which creates a dangerous condition.

The cost, design and construction complications associated with deep dredging near existing facilities are not always well understood by stakeholders, especially during the feasibility study and remedy selection phase of sediment remediation projects. The result is that decisions are made without fully realizing the risks and impacts of those decisions. This can lead to project schedule delays, cost over-runs and anxiety for all parties during the design and construction phases of sediment remediation.

HOW CAN DREDGING CAUSE THINGS TO FALL DOWN?

In order to explain how dredging can cause landslide or bulkhead failure, it is helpful to start with a brief overview of the forces that act on soils and bulkheads. The best way to visualize the soil conditions and forces is to look at 2-dimensional cross-sections. Figure 1 is a general cross-section along a typical industrial waterfront, that shows both vertical bulkheads and slopes.

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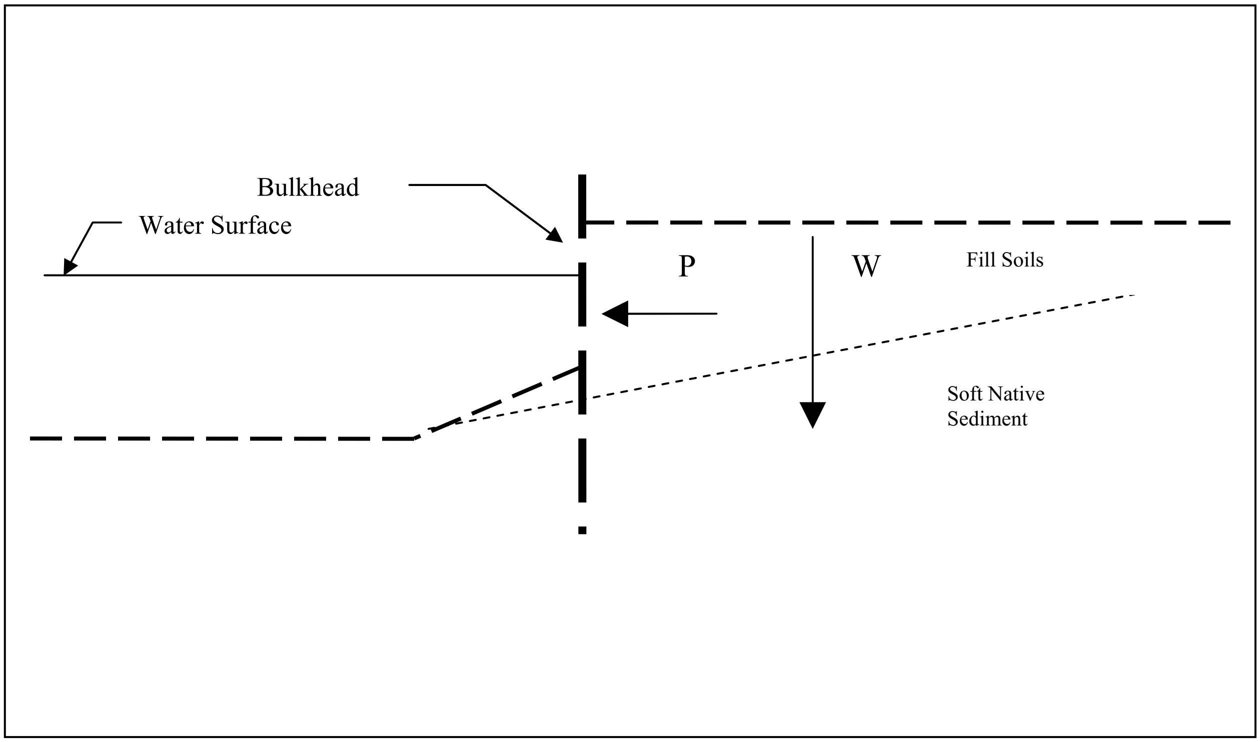

Figure 1. Typical industrial waterfront cross-section.

It is difficult to describe and show 3-dimensional objects in 2-dimensional drawings. Cross-sections are commonly used by geotechnical engineers and geologists, but these may be hard to understand. To help show the concepts of using cross-section, the following pictures of a layer cake in Figures 2 and 3 may be helpful.

Figure 2. Cake cross-section view.

The photograph in Figure 2 shows a cross-section view of a layer cake. In this case, there are 3 layers of cake (chocolate, vanilla and chocolate) plus thin frosting layers between the cake layers. Each band of color in the cross-section represents a layer of the cake.

The photograph in Figure 3 shows a cross-section view of the cake. In this photograph, it is easier to visualize the 3 layers of chocolate, vanilla and chocolate cake as solid layers of uniform substance.

Figure 3. Cake 3-D view.

The photographs in Figures 4 and 5 show photographs of the cake with a side slope. The photograph in Figure 4 shows a 3-dimensional view of the cake with a slope on one side and a vertical slope on the end.

Figure 4. Cake with slope 3-D view.

Figure 5. Cake with side slope - cross-section view.

The photograph in Figure 5 shows a cross-section view looking at the end of the cake, so that the slope appears simply a sloping line. When using cross-sections, it is helpful to remember that each line actually represents a surface in 3-dimensions that extends in both directions perpendicular to the cross-section. Straight lines represent flat plane surfaces; therefore, straight horizontal lines represent flat horizontal surfaces (like the frosting on top of the cake, or floors), straight vertical lines represent flat vertical surfaces (like the frosting on the sides of the cake, or walls) and straight angles lines represent flat, sloped surfaces (like sloping theater floors).

The main force that causes landslides is simply the weight of the soil and groundwater under the force of gravity. The weight of the soil or structures at the top of a slope is constantly pushed down by gravity (arrow labeled “W” in Figure 1). The weight of the soil causes vertical stress in the soil. In addition, the downward force due to gravity results in the soil being slightly compressed, which results in lateral forces within the soil, which are called lateral earth pressures (arrow labeled “P” in Figure 1). When the ground surface is level, then the lateral forces are balanced and there is no possibility of landslides. However, when the ground surface is sloped, then there is an imbalance of lateral forces and the soil in the top of slopes or hills will move downward, unless there is something to hold it up.

The main something is the strength of the soil itself. Soil and rock have the ability to resist landslides due to a property called shear strength. While soft sediment and soils may not have much shear strength, they have much more shear strength than static liquids. Standing, liquid water is an example of a substance that has no shear strength. Water is not stable on any slope and flows until the surface is liquid. If you every tried to make a sloping water surface inside a swimming pool when you were a child, then you can appreciate what an impossible task that is. On the other hand, frozen water has shear strength and steep sloping surfaces are stable, as can be seen on glaciers and icebergs.

As simply stated in an informative and humorous book on the basics of geotechnical engineering for homeowners (Handy 1995):

> *Landslides provide an aggressive correction for steepness when props are cut away at the bottom of a hill: When a hillside becomes so steep that the hill no longer is strong enough to hold itself up, there it goes, off into the river or ravine.*
>
> *Bulldozing away the bottom of a hill may seem like an innocuous enterprise to make a level place for a backyard garage or swimming pool, but also can lead to big trouble that will affect an entire neighborhood.*

Dredging at the bottom of slopes or in the lower part of slopes has the same effect as making the slope steeper or higher. When dredging or filling make a slope steeper or higher, the forces pushing the soil down increase and the forces resisting the movement decrease, which leads to an increase risk of landslides.

Water pressure also is a major factor in causing landslides. In waterfront sites, the groundwater table elevation is generally above low water levels in waterways (i.e. low tide in marine sites or normal flow in river systems) and may be above the high water levels (i.e. high tide in marine sites or flood flow in river systems). When the water level on the upland side of the waterfront is higher than the water level in the waterway, the difference in lateral water pressure increases the risk of landslides.

Since soil alone is not stable with vertical slopes, bulkheads or docks are commonly installed along industrial shorelines to provide sufficient water depths for shipping and adjacent upland areas for cargo handling. While bulkheads and docks do provide for a vertical slope, they still rely on soil strength for both vertical and lateral support. Bulkheads are one type of soil retaining structure that can be used to reinforce slopes. Soil retaining structures are described in more detail later in this paper.

All bulkheads must have sufficient strength to resist the lateral soil pressure exerted on the structure by the soil on the upland side. One way to visualize the forces is to think of a vertical bulkhead, or retaining wall, as a beam turned sideways. A horizontal beam in a building holds the weight loaded onto a floor and transfers that weight to one or more vertical columns, which are in turn supported by foundations in soil. A vertical bulkhead is pushed towards a waterway by lateral soil pressure. The bulkhead structure has to transfer that force into a “foundation” in order to prevent lateral displacement and failure. At the bottom of the bulkhead, the “foundation” is the soil at the bottom of the slope.

Many shoreline bulkheads have a “foundation” near the top of the bulkhead. This is some type of structure support system that helps keep the top of the bulkhead from being pushed towards the waterway. One common type of supports are anchor rods that extend back inland and attach to a concrete foundation or interior sheet pile wall. Another common type supports are piles that are driven at an angle (called batter piles), that provide lateral strength. Batter piles may be installed in the waterway and connected directly to bulkheads, or installed as part of a dock that is also used to help provide lateral support for an adjacent bulkhead. Batter piles may be installed in the upland and connected to the top of the bulkhead with anchor rods.

Dredging near an existing bulkhead removes sediment that is working as a “foundation” for the structure. When sediment is removed from the waterway side of the bulkhead (or front side), then the foundation is weakened. Dredging also increases the vertical distance between the top of the bulkhead and the bottom foundation, which is the same effect as making the bulkhead taller. This is analogous to making floor beams longer, which increases the loads and stresses on the beam and also increases the loads on the supporting columns and their foundations.

One example of bulkhead failure caused by over-dredging is given in a textbook on retaining wall design (Tschebotarioff 1973). In the section on design of anchored bulkheads, Tscebotarioff describes a failure of an existing bulkhead due to dredging. In this case, a bulkhead with 18 feet of water depth failed by “toe kickout” due to “inadvertent localized over-dredging by some 4 feet”. Dredging in the water in front of the bulkhead removed sediment that was serving as the “foundation” for the bulkhead and the bottom, or toe, of the bulkhead slide outward towards the water and the top of the bulkhead displaced back towards the upland.

Another example of bulkhead failure occurred in the Harbor of Gothenburg, Sweden and is also described in Tschebotarioff, 1973. In this case, piles were driven into shallow sand to support a quay wall. Figure 6 shows a cross-section through the quay wall, where the solid lines are the mudline before the sliding failure and the dashed lines are the mudline surface after failure. In these types of failures (called “global stability) , a large mass of soil, bulkhead structure, and docks slides in a rotation motion. The sediment in the waterway is pushed upward and the soil on the upland side is pushed downward. The soil mass slid along a surface in soft or weak soil that went below the bulkhead supports. In this case, the surface of sliding is shown by the deepest dashed lines.

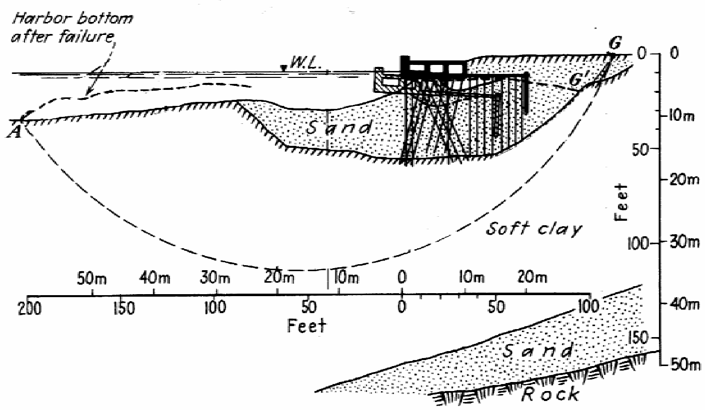

Figure 6. Bulkhead global stability.

HOW STEEP IS STEEP AND HOW DEEP IS DEEP?

The first step in evaluating the potential impacts of dredging is to recognize situations that require engineering evaluation. Figure 7 was prepared by the author as a general guideline for assessing the potential impact of dredging alternatives. The first step is to prepare representative cross-sections along the alignment of proposed dredging. The cross-sections must be located parallel to the steepest existing slope, so that the ground surface line show the correct slope. In other words, on a site plan, the cross-section location must be located parallel to the areas where the slopes are the steepest. On a site plan with ground surface elevation contours, this means that the cross-section must be perpendicular to the elevation contours that are the closest. If the cross-sections are skewed, then the slope will appear flatter than it is in the field.

After the sections are drawn showing the existing ground surfaces, draw two imaginary lines from the top of the highest level land area down into the water on each cross-section (solid lines in Figure 7). The bottom line should be drawn with a downward angle of 2 horizontal to 1 vertical (26.6 degrees) from horizontal. The top line should be drawn with a downward angle of 5 horizontal to 1 vertical (11.3 degrees). The imaginary lines should stop at a depth of 12.2 meter (40 feet) below low tide or lowest normal water level. The guidance presented is based on experience with typical water depths historically needed for navigation, which was generally less than 12.2 meter (40 feet). Although deeper water depths are now needed for larger ships, dredging deeper than about 12.2 meter (40 feet) is a special condition that requires site-specific analysis. The zone below the bottom line is the “critical” zone, the zone between the lines is the “caution” zone and the area above the top line is the “low-risk” zone”.

Proposed dredging into the critical zone would almost always cause an unstable, unsafe condition and would require slope reinforcement to protect existing facilities from damage. Proposed dredging in the caution zone may cause an unstable, unsafe condition. Proposed dredging in the low-risk zone could usually be done without slope reinforcement.

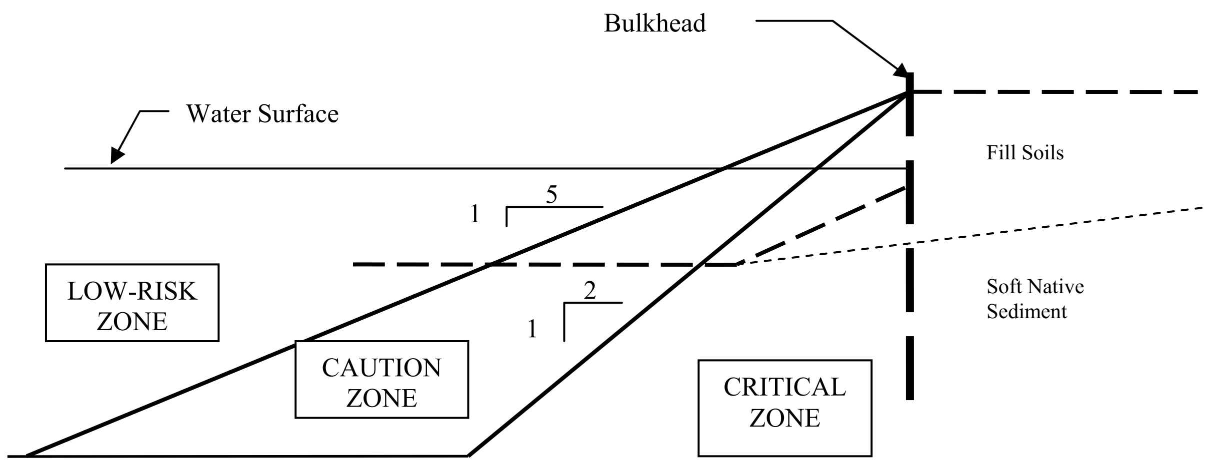

Figure 7. Guide to identify potential risk zones.

There are many situations along industrial waterfronts where the existing bulkheads and mudline surfaces are already in the "critical" zone. Un-reinforced slopes with angles of between 2 to 3 horizontal to 1 vertical are common and have performed well for years. Many industrial shorelines have been made with vertical bulkheads in the upper portion of the slope and sloped sediment on the lower portion. This does not imply that the existing conditions are unstable or unsafe. It means that no dredging should be planned near the shoreline without site-specific engineering evaluation. Likewise, it is common for industrial shorelines to be in the "caution" zone. Again, this means that a site-specific evaluation must be done before planning for dredging.

HOW CAN SLOPES BE REINFORCED?

In those situations where dredging would result in an unacceptable risk of landslide or failure of existing structures, the slopes could be reinforced with a variety of methods. This section describes some of the common methods of slope reinforcement, which are grouped into categories of (1) reducing the loads on the slope, (2) increasing the shear strength of the soil, or (3) installing bulkhead structures.

Reducing Loads on the Slope

One of the most common methods of reducing the risk of landslides is to make the slopes flatter. For existing industrial sites, this could be done be designing a dredge slope with a flatter angle or by leaving a horizontal "bench" adjacent to existing structures.

Another less common method of slope re-grading would be to lower the upland ground surface elevation during the time of dredging, then raising the slope after backfilling in the river. This may be feasible at contaminated industrial sites where the site is vacant. One of the differences between navigation dredging and dredging to remove contaminated sediment is that it may be possible to place backfill in the waterway after dredging. Backfill could be placed in the river to serve as a berm, or toe buttress, that increases slope resistance to landslides by providing more weight at the bottom of the slope. Since removal of contaminated sediment is temporary, it may be practicable to implement some temporary slope re-grading or reducing loads on the adjacent upland side of a shoreline. The sequence would have to be strictly enforced and would be as follows:

- Demolish existing structures and excavate the area on the upland side of the shoreline down to a temporary elevation,

- Dredge to remove contaminated sediment,
- Backfill in the dredge area,
- Fill in the upland area to the desired ground surface elevation.

As described above, there may be situations where loads on the upland area adjacent to existing bulkheads could be temporarily reduced during dredging contaminated sediment. Slopes and bulkheads are generally designed to support heavy live loads on the upland side of the shoreline. At vacant sites, it may be practical to make sure that no cargo or construction equipment is placed near the shoreline between the time dredging starts and the backfill is placed in the waterway. At active sites, it may be possible to coordinate with the site operators to move all cargo and equipment away from the shoreline during dredging.

A common situation at contaminated industrial sites is that there is upland soil or groundwater contamination and containment is part of a selected remedy. One component of the containment may be a groundwater barrier constructed parallel to the shoreline. One impact of a barrier is that the groundwater elevation is typically higher on the upland side than on the water side. As explained above, differential groundwater elevations result in a significant increase in risk of landslides. The load during dredging can be reduced if the contaminated sediment dredging is completed before sealing the groundwater barrier. For example, if sheet pile is used for the groundwater barrier, the joints could be left unsealed until after dredging and backfilling in the waterway. This would help keep the groundwater level close to the water level in the waterway, which would reduce risk of landslides or failure of existing structures.

One method of permanently reducing loads on a slope is to install pile-supported slabs or docks in the upland area. This could be used in the situation where existing loads are carried by slabs on grades or deteriorated piles, but future use required high load carrying capacity. New piles would transfer the load to deeper soil units, which would reduce the forces that cause increased risk of landslides. Another method is to use “lightweight fill”, which weighs significantly less than conventional soil. One type of lightweight fill is expanded aggregate, which is a manufactured product similar to pumice. The material looks like artificial stones with numerous small air pockets throughout the stones. These materials weigh ½ to 2/3rd as much as conventional sand or gravel backfill. Another type of lightweight fill is made by stacking rigid foam boards that are similar to rigid Styrofoam insulation panels. These can be stacked, then covered with conventional soil.

Increase Soil Strength

There are several methods that can be used to increase the shear strength of the soil or sediment, including grout injection, deep soil mixing, vibro-compaction, consolidation under preloading, or soil freezing. Each method has advantages and disadvantages; some are only applicable to fine-grained soil or coarse-grained soils and some are only applicable to upland soils.

Grout injection could be done either in sediment or upland soils and could be done with any soil types. In this method, holes are drilled into the soil or sediment with hollow augers, then grout is injected under high pressure into the holes as the augers are withdrawn. This is repeated on close spacing to form a zone of soil with increased soil strength.

Deep soil mixing is another method of adding cement to the soils to increase strength. This could be done with most soil types, but is best done in upland soil areas. Large-diameter holes are drilled into the soil, them cement is added to the soil loosed by the auger. As with grout injection, this is repeated on close spacing to form a zone of soil with increased soil strength.

Vibro-compaction is a method of increasing the density of sand soils and could only be done on upland soils. This is usually done by dropping large weights onto the ground surface, which increases the density and shear strength of sand soils.

Fine-grained soils gain strength when they are compressed, or consolidated, under the weight of new fill or other loads. This could be done for either upland soils or sediments. The most common method of loading is to place soil fill on the ground or mudline and waiting for the soil to gain strength.

Soil freezing is not a common method due to high cost and risk of damage to existing facilities as the porewater in the soil expands when frozen. This is a temporary method and could be used for contaminated sediment dredging where backfill can be placed after dredging or where the upland ground surface or load could be temporarily removed.

Install Bulkhead Structure

Shoreline bulkheads are one of the most common methods of reinforcing waterfront slopes. Bulkheads act as soil retaining walls and provide for vertical slopes along shorelines. At many industrial sites the existing bulkheads were made using timbers and wood piles. Today, steel sheet piles are probably the most common bulkhead material. They are used in several configurations such as vertical cantilever walls, anchored walls, or circular cofferdams. Chapter 7, Slope Stability Protection, in Design Manual 7.1 (Navy 1982), gives more information on types of structures that can be used to reinforce slopes.

Vertical cantilever walls are the simplest in concept and usually straightforward to construct. The walls are simply driven vertically and connected to form a continuous wall. These walls are supported by the soil or sediment below the bottom of the dredge elevation in the waterway. The soil weight and any cargo or equipment loads on the upland side of the wall exerts a lateral force (due to active soil pressure) that pushed the wall towards the waterway. This force is resisted by the strength of the deeper sediment on the waterway side of the wall (passive soil pressure). Figure 8 shows an example of vertical sheet piles being driven to support a slope prior to dredging (Navy 2000). In this case, sheet piles were installed at the low-tide level to prevent a landslide caused by dredging contaminated sediment at the bottom of an existing slope.

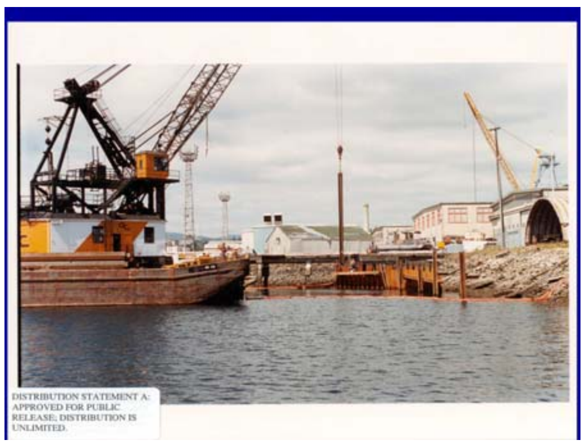

Figure 8. Vertical cantilevered sheet piles.

Anchored walls are similar to cantilevered walls, except that they have an anchor rod near the top of the wall that provides additional support for the wall. The anchors are usually made from steel rods that extend back into the upland soil and are supported to an "anchor" system. The anchor may be concrete foundations, earth anchors, or an interior sheet pile wall. For upland retaining walls, it is possible to install multiple rows of anchors in the wall. For bulkheads, it is not possible to install anchor rods below the water surface. Therefore, most shoreline bulkheads are limited to one row of anchor rods that are installed above the low tide level.

Circular cofferdams are made by driving steel sheet piles in a circular shape with interconnecting sheets between the circular sections. The inside of the cells are filled with sand or gravel soils. These structures are commonly used for both temporary and permanent structures and are effective for most sediment conditions.

WHAT IS THE COST AND BENEFIT OF SLOPE REINFORCEMENT?

Typical Slope Reinforcement Costs

The direct construction costs for slope reinforcement systems varies widely, but a general rule is that the steeper the overall slope, the more expensive the system. The lowest capital cost method is usually to simply make the slope flatter. As described above, this can be done by reducing the depth of dredging or by a temporary reduction in the upland fill along the shoreline. On the other extreme, vertical slopes are generally the most expensive since they require a bulkhead structure that has sufficient strength to support soil, groundwater and live loads on the upland side.

The cost for making the slope flatter can be estimated using the same dredging or soil excavation unit costs as for work that is not near the shoreline. If the soil is removed temporarily, then there will be costs for excavation, transport to a temporary stockpile area, loading and transport back to the site, and re-compaction. If the soil is contaminated, then it may have to be taken off-site for disposal or treatment, then replaced with imported fill from conventional backfill sources.

Lightweight fill is much more expensive than conventional earth fill. For example, the unit cost for expanded shale aggregate material is estimated to be $36 to $48 per ton compared to $10 to $15 per ton for imported sand and gravel fill [2]. To facilitate cost comparisons, the unit costs in this paper will be applied to a hypothetical shoreline 305 meter (1,000 feet) long. If fill was placed 3 meter (10 feet) deep over an area 305 meter (1,000 feet) long by 30.5 meter (100 feet) wide, a volume of 28,320 cubic meters (1,000,000 cubic feet) of fill material would be needed. This would require 34,043 metric tons (37,500 tons) of lightweight fill or 56,734 metric tons (62,500 tons) of conventional fill. If we use an average cost of $42 per ton for expanded shale and $12.50 per ton for conventional fill, the direct cost difference for material alone would be about $800,000 ($1.58 – $0.78 million).

Steel sheet pile is probably the most common type of material used for shoreline bulkheads. The costs are generally proportional to the total weight of steel used in the bulkhead system. Steel sheet piles used for bulkhead typically have unit weights of 957.6 to 1,915.2 newtons/m^2 (20 to 40 pounds per square (psf) foot) of wall and a typical total installed cost is $1,500 per ton for wall driven from land with average soil conditions.

A simple vertical cantilevered wall needs to be driven below the dredge depth in order to be stable. One approximate guideline is that the depth below the dredge elevation should be 2 times the exposed height. For example, if the height of the wall between the upland ground surface and the dredge depth was 3 meter (10 feet), then the total length of sheet piles would need to be 9.1 meter (30 feet) (10 feet exposed height plus 20 feet below the dredge depth). If sheet piles that weighed 1,436.4 newtons/m^2 (30 psf) were used, then the total weight needed for 305 meter (1,000 feet) of shoreline would be 408.5 metric tons (450 tons) (1,000 feet x 30 feet x 30 psf) and the direct cost would be about $700,000.

The maximum height of exposed bulkhead wall that can be supported with cantilevered walls is 1.5 to 4.6 meter (5 to 15 feet), depending on the soil conditions and the upland loads. Higher walls with exposed heights of 4.6 to 12.2 meter (15 to 30 feet) can be constructed using anchored sheet piles, but the maximum height could be less if there are soft soils at the site. This system requires vertical sheet piles, horizontal steel beams along the top of the sheet piles, anchor rods and an anchor system. It is not possible to give accurate guidance for estimating the cost of anchored wall systems because the length of steel sheet pile, size of anchor rods and type of anchor system depends on site-specific soil and loading conditions. However, for illustrative purposes, assume that an anchored wall with an exposed height of 4.6 meter (15 feet) will be used. The sheet pile length does not need to be as deep as cantilevered wall, so assume that 12.2 meter (40 foot) long sheet can be used. However, they would have to be stronger to support a higher wall. If the sheet piles weighted 1,915.2 newtons/m^2 (40 psf), then the total weight needed for a wall 305 meter (1,000 feet) long would be 726 metric tons (800 tons) (1,000 feet x 40 feet x 40 psf) and the cost for the sheet piles alone would be about $1,200,000. There would be additional costs for the horizontal beam, anchor rods, anchors and associated earthwork. The cost for this work would raise the total cost to around $2,000,000.

Benefit Versus Cost

This section of the paper will compare the benefit of removing additional contaminated dredged material with the additional cost of slope or bulkhead reinforcement.

The first case considered will be with a cantilevered sheet pile wall 3 meter (10 feet) high, which would have a direct cost of $700,000. The total construction cost needs to include mobilization, site work and demobilization and would raise the total to $1,000,000. In addition to construction costs, the total cost has to include design and project management, which would add roughly 20%, for a total cost of $1,200,000.

With no bulkhead, dredging would typically be done from the shoreline with a slope of 3 horizontal to 1 vertical, which is the area between the existing mudline and dredge cut shown on Figure 9. This means that the dredging depth would be able to reach a depth of 3 meter (10 feet) at a distance of 9.1 meter (30 feet) from the bulkhead.

[2] Prices shown in this paper are based on Means 2004 and the authors experience unless notes otherwise. Costs for specific projects are not used to maintain confidential business information.

With a bulkhead in place, dredging could be done to a depth of 3 meter (10 feet) at the face of the bulkhead; however, even with a bulkhead, the dredge would still can not safety remove all sediment up to the bulkhead structure because the dredge equipment could damage the bulkhead and dredge cutters are not designed to remove all sediment adjacent to vertical surfaces. The incremental volume that could be removed with the bulkhead would be the volume of a triangular prism of material 3 meter (10 feet) deep, 9.1 meter (30 feet) wide and 305 meter (1,000 feet) long and is shown on Figure 9. The volume of this prism would be 4,205 cubic meter (5,500 cubic yards). This means that the additional cost of bulkhead construction to remove this sediment would be $1.2 million for an incremental volume of 4,205 cubic meter (5,500 cubic yard), which would give an incremental unit cost of about $168 per cubic meter ($220 per cubic yard).

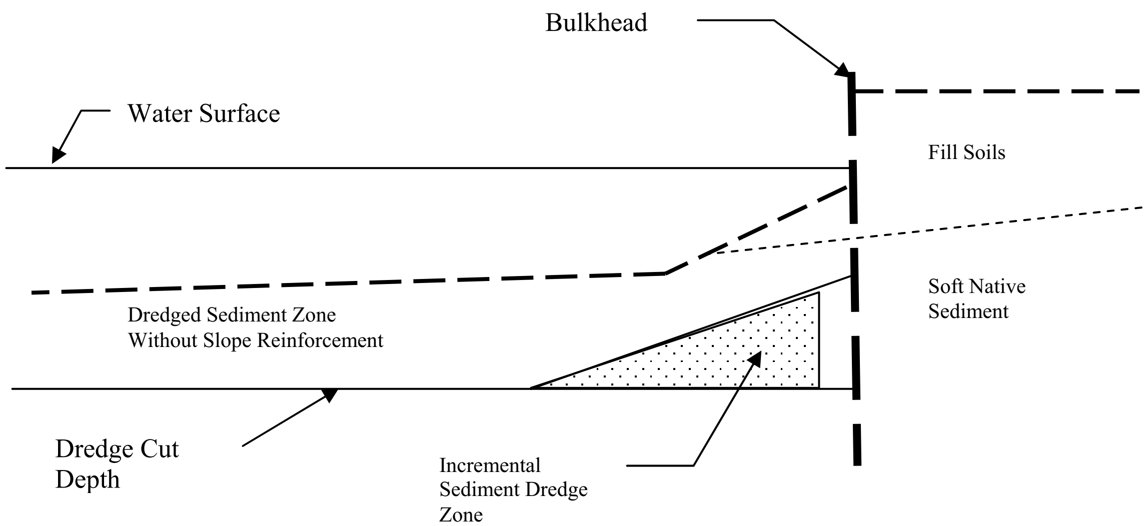

Figure 9. Example dredge options.

Consider the case with an anchored sheet pile wall 4.6 meter (15 feet) high, which would have a direct cost of about $2,000,000. As with the cantilevered wall, you need to add costs for mobilization, site work and demobilization, which would raise the cost to $2,500,000. Adding 20% for design and project management would give a total cost of $3,000,000. The additional volume that could be removed would be a triangular prism 4.6 meter (15 feet) high, 13.7 meter (45 feet) wide and 305 meter (1,000 feet) long, which would have a volume of about 9,558 cubic meters (12,500 cubic yards). The additional cost of bulkhead construction to remove this sediment would be $3 million for 9,558 cubic meters (12,500 cubic yards), which would give an incremental unit cost of $183.5 per cubic meter ($240 per cubic yard).

Although the two examples described above are hypothetical, there do represent realistic costs for projects of actual projects. In fact, at some contaminated sediment sites there are thick deposits of very soft silt or clay sediments and the cost of bulkheads is higher than shown in the above examples.

CONCLUSIONS

Contaminated sediment can be safely dredged along existing shoreline structures, but a geotechnical engineering evaluation is required to determine a safe slope or what kind of slope reinforcement would be required. The lowest cost is generally to use a sloped dredge cut surface and use in-place capping to remedy sediment adjacent to existing structures.

Decisions about how close to remove contaminated sediments near shoreline structures should be made after engineering evaluation compares the incremental cost of shoreline reinforcement with the incremental benefit of removing a relatively small volume of contaminated sediment. This evaluation should be made during the remedy selection phase of sediment remediation projects.

It is best for all parties, oversight regulatory agencies, project sponsors and the public, to avoid unanticipated consequences during design and construction. If removal decisions are made without appreciation of the impacts, then required modifications during design and construction could lead to cost over-runs, project delays and loss of credibility with other stakeholders or the public.

There is no general rule on when the additional cost of shoreline reinforcement is appropriate or when it would be excessive. At many sites, the soil on the upland side of the shoreline is also contaminated and soil or groundwater containment is part of the upland site selected remedy. In this case, the value of a small amount of additional sediment removal would be low. If site conditions were appropriate for sediment capping, then containment of contaminated sediment should be viewed as an extension of adjacent upland soil containment. On the other hand, if contamination levels in all soil and groundwater at a site can be reduced to cleanup levels, it may not make sense to leave a small volume of contaminated sediment that would restrict future site use.

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