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Environmental Laboratory

US Army Corps of Engineers®
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# Confinement of Contaminated Dredged Material Utilizing the OPEN CELL SHEET PILE™ System

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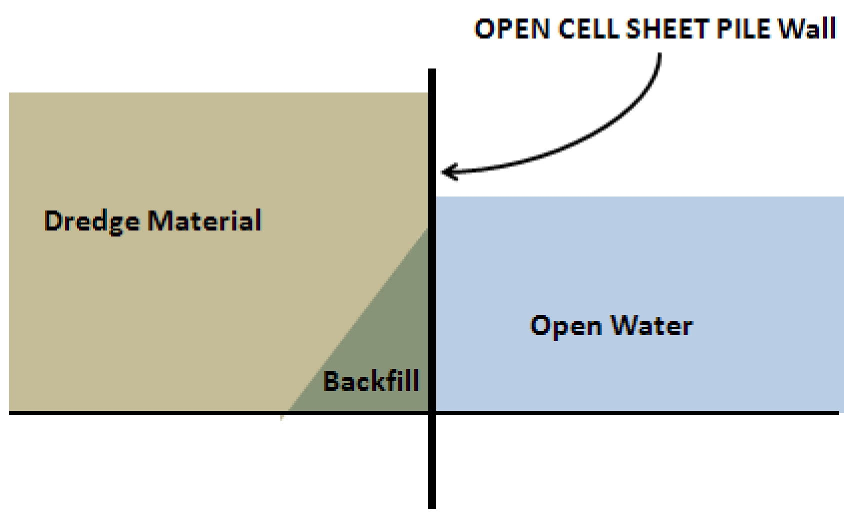

# Confinement of Contaminated Dredged Material Utilizing the OPEN CELL SHEET PILE™ System

## 1.0 Purpose of the Report

The US Army Corps of Engineers Research and Development Center Environmental Laboratory (ERDC-EL) entered into a Cooperative Research and Development Agreement (CRADA) with PND Engineers Inc. to perform a limited evaluation the OPEN CELL SHEET PILE system (OCSPS) for confinement for contaminated dredged material, similar to a Confined Disposal Facility (CDF).

This effort undertook an analysis of the expected efficiency of a Vertical Confined Disposal Facility utilizing the OPEN CELL SHEET PILE system and its ability to contain contaminants, , and how this compares to the effectiveness of CDF walls constructed in a traditional manner with sand and rock, although a sheet pile core is occasionally used. This assessment is supported by literature review of published and unpublished information, internal data, and numerical modeling results.

## 2.0 Scope of Work

The scope of the evaluation is limited to the environmental considerations of the OCSPS used for confinement of contaminated dredged material when compared with an earthen berm or rock dike. Specifically, a qualitative analysis of the net transport of contaminants around, over, under, and through the OCSPS will be compared with traditional construction practices using an earthen berm or rock dike for a CDF. The evaluation does not consider structural or geotechnical analysis, nor does it include any site specific or project specific data.

## 3.0 Background

PND Engineers, Inc. requested that ERDC-EL perform an evaluation of the OCSPS that would be used for confinement of contaminated dredged material. The containment structure would be similar in purpose to a conventional rock dike CDF, while using a different structural system.

The OPEN CELL™ system is a patented method for constructing bulkheads, docks and earth retaining structures. It uses vertically-driven interlocked flat sheet pile to form a wall of adjoining U-shaped cells. It consists of two portions: arc-shaped face sheets that form the exposed front, and straight tailwalls that run back into the earthen embankment. The two are joined by wye (Y) piles at the junction of the arcs and tailwalls. The constructed cells are filled with a granular material, typically coarse sand. Approximately 200 OCSPS structures have been built since 1981, primarily in Alaska, but increasingly across the rest of the United States. Examples of OCSPS applications are indicated below.

PND Engineers, Inc. provided design and construction support services for construction of an approximately 1,350-foot OPEN CELL bulkhead at the Cheniere Energy Sabine Pass LNG Terminal in Cameron Parish, Louisiana (OPEN CELL bBrochure 2010). The bulkhead was designed so it could be dredged or experience scour to elevation -45-ft. (OPEN CELL Brochure 2010).

Another OCSPS project was recently completed under the Corps of Engineers for the Iraqi Navy at Umm Qasr, Iraq. A 1200-foot long pier and seawall was built 150 feet offshore in 30 feet deep water, and containing 450,000 cubic yards of sand fill. The project was reviewed by ERDC – Coastal and Hydraulics Laboratory prior to construction.

The OCSPS was used for the dock facility at Dutch Harbor Marine Terminal in Dutch Harbor Alaska and was developed from concept design to completed construction (Figure 1 and Figure 2). The dock provided 46 feet of draft and created over three acres of upland land. Existing materials were characterized by soft soils over shallow bedrock (OPEN CELL Brochure 2010).

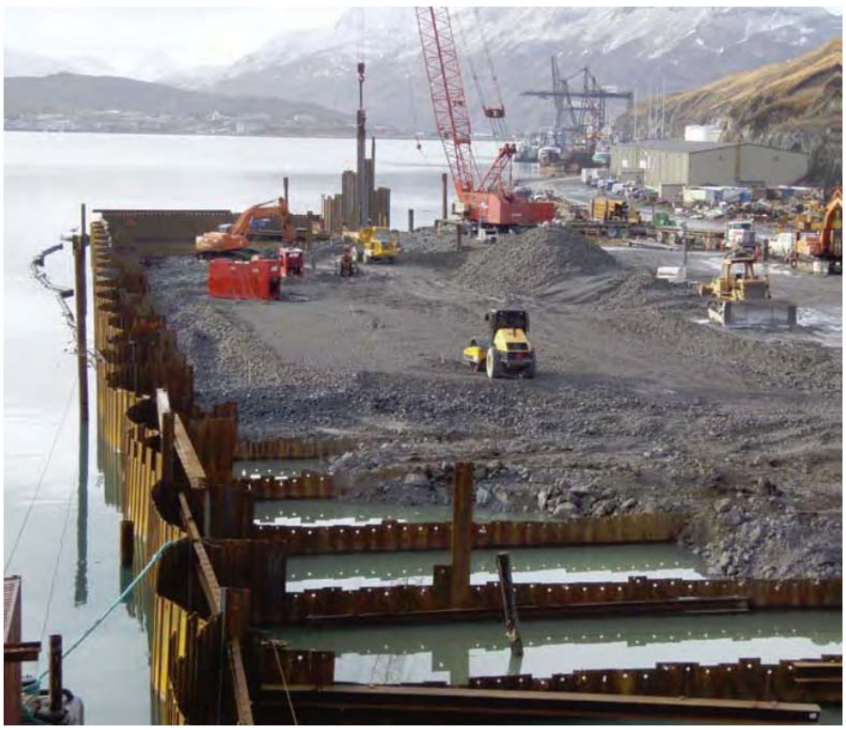

Figure 1. OCSPS during construction at Dutch Harbor Marine Terminal (OPEN CELL SHEET PILE Brochure 2010)

Figure 2. Completed OCSPS at Dutch Harbor Marine Terminal (OPEN CELL SHEET PILE Brochure 2010)

# 4.0 Confined Disposal Facility (CDF) Design and Construction

A Confined Disposal Facility can be constructed upland, near-shore, or in-water. The CDF is an engineered structure to confine dredged material (USACE 1987) and is constructed with earthen dikes around the perimeter to contain the dredged material. Typically, the dredged material contains contaminants of concern above a level acceptable for open-water disposal. In order to compare a traditional CDF constructed with an earthen dike to a CDF constructed using the OCSPS, a brief description of the CDF containment dike and the OCSPS is provided below.

## 4.1 Containment Dike

The footprint of a near-shore CDF is bound by land on the upland side and bound by water on the in-water side. The CDF is constructed of a perimeter dike beginning at the shoreline (land/water interface) and continues into the water creating an enclosed area below water surface. A cross section of typical CDF dike is shown in Figure 3. The perimeter dike relocates the land-water interface from the original shoreline to the newly constructed dike. The dredged material is contained by the perimeter dike and can be placed up to the ground level, thereby creating new land on the footprint of the CDF. The outside portion of the perimeter dike is now the shoreline and must withstand erosional forces from waves and currents. The CDF perimeter dike is commonly constructed of a sand or limestone core, covered with a poorly-graded-gravel or underlayer stone, which is covered by riprap or cover stone. The exposed shore on the in-water side must be covered and armored to resist expected wave activity. The core of the dike may be covered with a filter cloth to minimize loss of the sand or limestone core. In some CDFs, sheet pile has been installed through the middle of the dike. In these instances the sheet pile serves as a structural component during or after construction, but does not provide watertight integrity to the dike. The slope of the dike may be steeper on the CDF side than the open water side which is subjected to higher erosional forces caused by wind waves, currents, and ice.

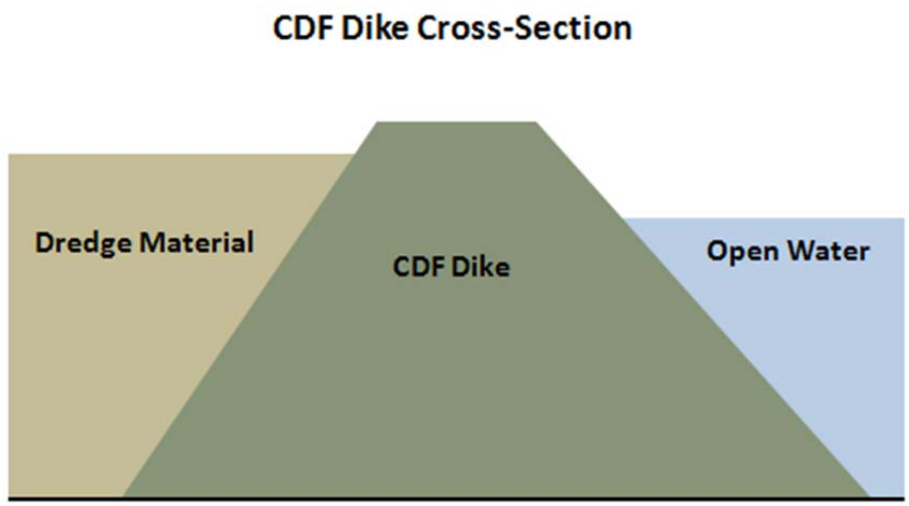


Figure 3. Cross-section of typical CDF dike

As dredged material is placed in the CDF, water infiltrates through the dike or may be decanted off the top through an adjustable weir. As time passes, water removal via infiltration may decrease as sediment fines build up in the dike. When a volume of dredged material is placed in a nearshore CDF, the same volume of water has to released until the dredged material breaks the water surface and builds land. The volume of dredged material is typical four times as large when hydraulically dredged than when mechanically dredged due to entrainment of 4 to 5 parts of carrier water per part of sediment during hydraulic dredging. Efficient removal of this water is required for successful CDF operation. For example, a 12-inch hydraulic dredge is placing material in a 50-acre CDF. The volume of material placed in one day would raise the water level approximately 4 inches if there is no drainage. A 30-inch hydraulic dredge is capable of raising the water level of a 150-acre CDF by approximately 9 inches a day without drainage (Appendix 1).

The design life of a CDF has commonly been 20 years. This figure is typically based on dredging activity and time to reach CDF capacity. It is not based upon expected life or future stability of containment dikes, which are expected to last indefinitely. Containment dikes are still important after the CDF is filled as they maintain erosional protection for open water forces and containment of the material inside the CDF. Containment dike integrity is affected by local conditions and should include a maintenance program throughout the life of the CDF for monitoring and repairs. Failure of a containment dike can result in exposure of sediments and loss of material from the CDF.

## 4.2 OPEN CELL SHEET PILE SYSTEM (OCSPS)

The proposed approach for confinement of dredged material using the OCSPS is similar to the near-shore CDF described above. The OCSPS face sheets and tail walls would be installed along the outer edge of the in-water boundary. The face sheets provide a vertical wall which can eventually be used as a dock or pier (see Figure 2). To properly load the OCSPS, an earthen berm would be installed on the inside portion of the OCSPS as needed for stability (Nottingham and McNabb 2011). The earthen berm on the inside of the containment area would be constructed of a poorly graded sand and/or gravel for stability of the OCSPS. The dredged material would be placed within the containment area after construction was completed. A cross-section of a typical OCSPS is shown in Figure 4.

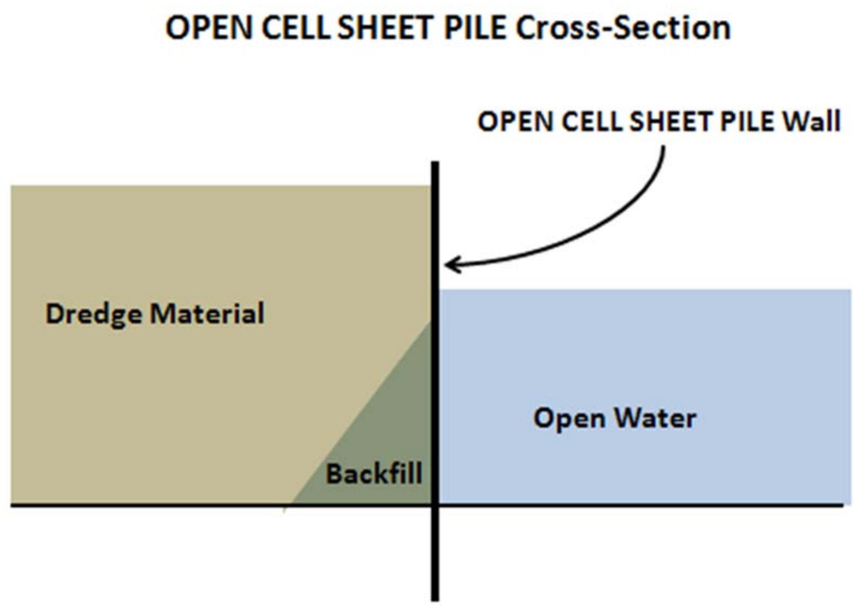


Figure 4. OPEN CELL SHEET PILE system cross-section

Dredged material placed using mechanical means generates less water and active dewatering will not likely be required. Accommodations may be required after a filling activity to allow for removal of ponded precipitation. If dredged material is placed hydraulically, excess water will require management. Because the OCSPS allows less drainage through the sheet piles compared with a CDF earthen or rock dike, the excess water will require decanting off the top of the confinement area through a weir in the OCSPS or being pumped from the confinement area. In either case, direct discharge to a waterway may be possible providing water quality standards are met. In the event that the effluent does not satisfy standards, management processes, such as physical and chemical water treatment prior to discharge can be employed. Examples include filtration, chemical coagulation and settling, and advanced processes. Project-specific conditions, including placement method, dredged material characteristics, and regulatory requirements will determine water management procedures.

Water removal is a key component of CDF operation. However, it must be remembered that CDFs are large retention and settling basins. The longer that water is maintained in a CDF, the more opportunity there is for solids to settle out. Removal of the solids from the water also removes much of the contaminants associated with the dredged material. Retention time is dependent upon the CDF available volume, area, and loading rate. CDFs with longer retention times should result in larges removal of solids in the CDF and thereby produce effluent that requires less treatment prior to discharge.

The design life of the OCSPS should be similar to other CDFs; however, corrosion of the steel will need to be considered in the design. Average corrosion rates of steel are estimated at 0.03 mm/yr for freshwater and 0.07 mm/yr in seawater without cathodic protection (McNabb, 2011). Sheets could be galvanized, coated, or cathodic protection may be included in the design; however, freshwater installations typically need no coatings or cathodic protection. Abutment life of 100+ years is estimated for most installations **(**Nottingham, 2008). With this estimated life, it is reasonable to expect that OCSPS structures would have life spans comparable to properly designed rock fill CDF dikes. As with any structure, periodic inspection and maintenance are key to obtaining longevity.

Dike erosion is not an issue with OCSPS as the containing structure is the sheet pile itself. As long as the OCSPS remains intact, there should not be a problem with erosion as there can be with earthen dikes. However, an analysis must be undertaken to insure that the OCSPS is capable of handling expected wave climates and that it is armored to do so.

OCSPS can theoretically be used to obtain greater retention times than a CDF. Considering that a specified area is to be used for CDF construction, a CDF utilizing the OCSPS with its vertical walls will have a larger volume contained within the footprint of the CDF than one using earthen and rock dikes. The total footprint of a CDF consists of the earthen perimeter dikes and the dredged material storage area. The height of the earthen dike is dependent upon the desired closeout elevation of the CDF, water depth, water levels, and expected wave climate among other things. The width of the CDF perimeter dike is a function of total dike height (above and below water level), underlying sediments foundation strength, and required slopes for geotechnical stability. It is possible therefore for significant portions of a CDF areal footprint to be occupied by earth and rock perimeter dikes.

As the OCSPS has vertical walls, for a given storage volume a smaller areal footprint is required. Alternatively, for the same areal footprint, a CDF utilizing OCSPS would have larger surface areas, which translate into increased retention times and settling. This is wholly due to the additional area required for the earth and rock perimeter dike being made available for dredged material settling and storage. The significance of this varies on a case by case basis and should be evaluated for a specific project for its relevance.

# 5.0 Potential Contaminant Pathways

Potential contaminant pathways of dredged material from a CDF include seepage through permeable dikes, effluent releases over a weir or through pumping, leachate drainage through the bottom of the CDF, volatilization, and runoff from storm events as shown in Figure 5 (USACE 2003). The amount of potential contaminant release will vary depending on the phase of CDF operations. During placement of dredged material, dominant contaminant transport processes may include seepage through permeable dikes, effluent releases, and leachate drainage. Immediately after placement, the dredged material in the CDF undergoes some level of consolidation and/or dewatering. During this phase and prior to long-term storage conditions (approx 3 months), the potential releases are similar to those of the placement phase. CDFs may include multiple placement events of dredged material and consolidation will occur as will resuspension of some of the previously deposited material.

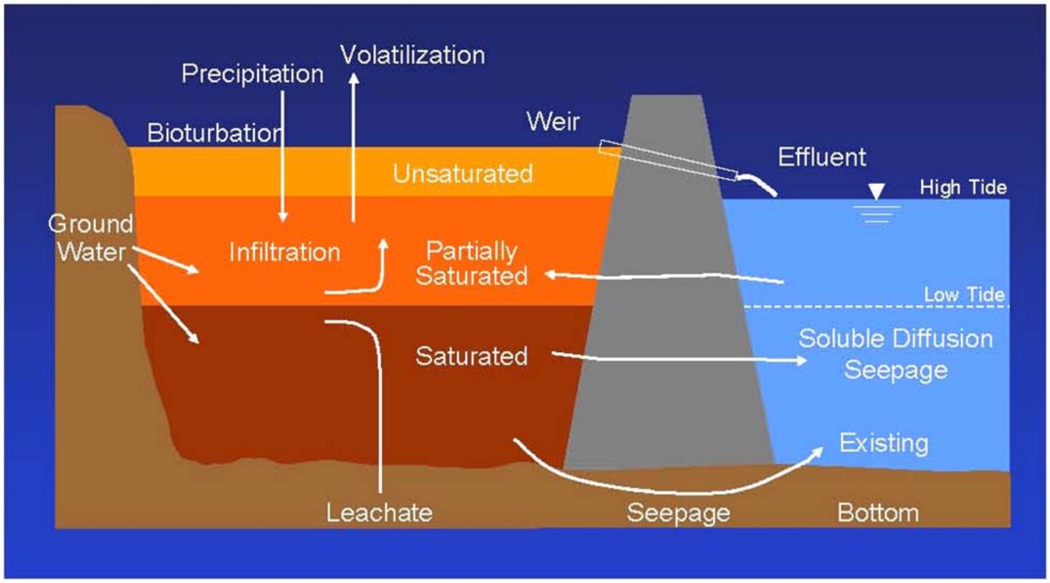


Figure 5. Potential Contaminant Migration Pathways (USACE 2003).

During long-term storage, the dredged material can be assumed to be fully consolidated and flow rates through the consolidated dredged material will be extremely low. Hydraulic conductivity, or coefficient of permeability, for silts and silts with sand is approximately $10^{-4}$ to $10^{-8}$ cm/sec, while clays will be $10^{-6}$ to $10^{-9}$ cm/sec (Lambe and Whitman 1969; Fetter 1980 ). Hydraulic conductivity for consolidated dredged material in a CDF is expected to be $10^{-6}$ cm/sec or lower. In CDF used for multiple placements in support of annual dredging events, a shallow layer of the previously consolidated material is resuspended with each new dredging event. This results in solids in suspension from the current dredging project as well as consolidated layer(s) in the CDF, until the dredged material settles and consolidates once again. Contaminant pathways are evaluated below.

# 6.0 Evaluation of OPEN CELL SHEET PILE System

As described above, dredged material within a CDF is typically contained using dikes constructed of sand, crushed limestone, and rock. The OCSPS is proposed to replace the containment dikes to contain the dredged material. It is important to note that construction of an OCSPS incorporates earthen fill on the inside portion of the OCSPS. The height of this fill can be as high as the elevation of the high water level. Comparison of the traditional CDF containment dike with the OCSPS will be considered in two phases of CDF Operations: (1) during placement of dredged material; and (2) post consolidation of the dredged material (long-term storage). Each phase is described below comparing the earthen dike for containment of dredged material with the OCSPS.

## 6.1 Comparisons during Placement of Dredged Material into CDF

Dredged material placement into the CDF will be performed using either mechanical equipment, hydraulic equipment, or both. During placement, excess water is allowed to be released from the CDF while sediment is contained within the CDF. For most dredging projects, contaminants are associated with the solid particles and are not in the dissolved phase. Therefore, a well operated CDF limits contaminants released by containing the solids and minimizing suspended solids in water released. However, if water does not meet the criteria for release from the CDF, additional engineering controls are required or water treatment will be needed. Water management during placement of dredged material in a CDF obviously requires significant consideration.

Water management during placement is dependent on the water content of the dredged material. Water content of mechanically dredged material will be much lower when compared with hydraulically dredged material. If sediment is mechanically dredged and placed into the CDF using hydraulic equipment, the water content of the placed material will be similar to hydraulically dredged material because of hydraulic conveyance limitations. Water content of mechanically dredged material can be expected to be approximately 20% greater than in situ water content. In situ water content is expected to range from approximately 0.8 to 1.2 parts water (by weight) to parts dry sediment (by weight). Water content of hydraulically dredged or hydraulically placed material can be assumed to be approximately 6 parts water (by weight) to 1 part dry sediment (by weight).

Based on typical CDF sizing, mechanically dredged placed material will require no release of water during placement. However, hydraulically placed dredged material will require some release of excess water. Typically this is through a discharge weir or via leakage through the constructed dike. If all dredged material is contained within the CDF without release of water or associated suspended solids, contaminants will not be released unless there is a pathway beneath the sheet pile.

The containment structure, whether the OCSPS or an earthen dike, will be required to contain most or all solid particles to the extent practical while releasing water that meets regulatory requirements. The retention time necessary to meet regulatory requirements will be a function of the dredged material characteristics and the size and shape of the CDF. Placement rates will also affect the amount of settling time prior to release from the CDF.

Release of potential contaminates associated with water and/or solids can be over, under, around, or through the CDF earthen dike or OCSPS. Releases over the dike or OCSPS will be regulated during placement. Sufficient settling time will likely enable the discharge to meet permit requirements.

Releases around and under the dike will be similar to the OCSPS. Releases around each system will have similar pathways and releases under the dike will have a slightly shorter pathway compared to that of OCSPS. The sheet piles of the OCSPS are installed below the mudline. Therefore the travel distance to the outside of the containment area would be longer for an OCSPS CDF than one utilizing conventional dikes.

Releases through the dike or OCSPS will be dependent on the seepage rate, contaminant attenuation, the carbon content of the earthen fill, and the porosity of the dike or OCSPS. The seepage rate will be a function of hydraulic gradient and hydraulic conductivity, as well as the cross-sectional area. The cross-sectional area of the OCSPS will be that of the total length of joints, whereas the cross-sectional area of the dike or berm will be the width dimension multiplied by the height dimension.

The flow rate through the earthen dike (Figure 6) can be estimated using the Dupuit Equation (USEPA 1996):

$$q = K\,(h_1^2 - h_2^2)/2L$$

where,

q = discharge per unit length of dike

K = hydraulic conductivity of dike

$h_1$ = pond water elevation above base of dike

$h_2$ = outside water elevation above base of dike

L = horizontal distance separating surface of pond and surface of outside water body

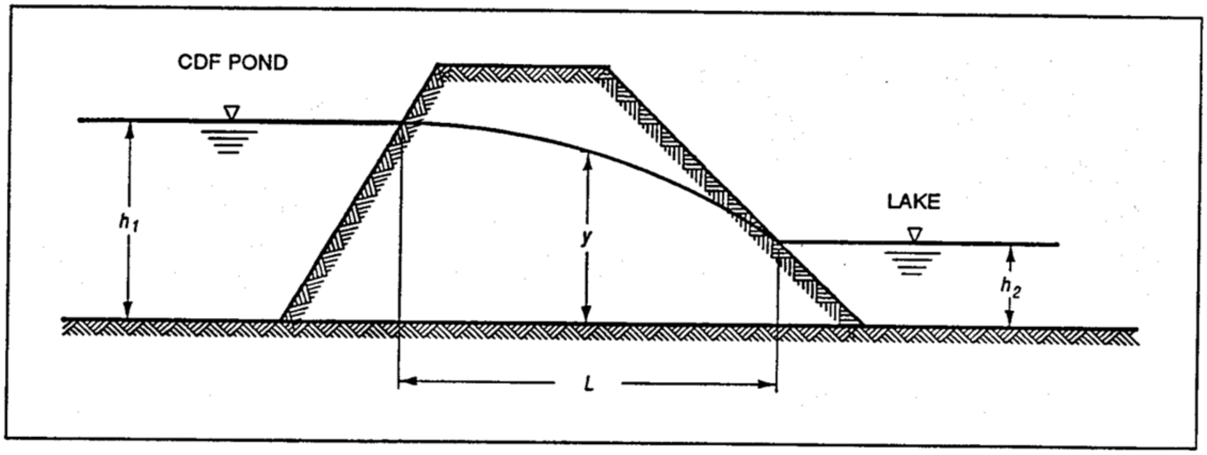


Figure 6. Definition Sketch for Dupuit's Equation (USEPA 1996).

Contaminant attenuation can occur through chemical transformation, biodegradation, adsorption to carbon content within the earthen berm, or other means of chemical reduction within the dike. For the CDF constructed in an area of tidal fluctuations, the seepage rate will be in both directions, allowing some level of dilution to occur within the dike. It is expected that the OCSPS will allow some level of interaction between tidal waters and the containment area, depending on the joints of the sheet pile, the characteristics of the dredged material and the fill on the inside of the containment area. Although adsorption of dissolved contaminants is probably insignificant (USEPA 1996), physical filtration is expected in a dike constructed with fine sand or crushed limestone. Contaminant attenuation within the CDF dike will be similar to the OCSPS with fill. In both cases contaminant attenuation is assumed to be very low due to limited retention time within the dike or fill and limited organic carbon within the dike and fill. Earthen dike physical filtration will be greater than the OCSPS, although no more than twice the level due to the fill constructed on the inside of the OCSPS. This statement is based upon the assumption that the flow through the OCSPS can only occur as leakage through the sheet pile joints. It is unlikely that submerged sheet pile joints would allow significant flow to pass as flow pathways would soon be clogged with fines from the fill on the inside of the OCSPS. Therefore, long-term transport through the submerged portion of an OCSPS is expected to be nil.

Seepage through the OCSPS will occur at a higher rate during initial placement, but is expected to decrease with time as fine-grained material fills the joints. All seepage is assumed to be through joints of the OCSPS. Delft Geotechnics conducted a study that established a methodology for assessment of seepage resistance of steel sheet pile (ProfileARBED). The study concluded for steel sheet pile without a sealant and through multiple layers of soil with hydraulic conductivity ranging from $10^{-5}$ to $10^{-9}$ cm/s, the ratio of discharge through the wall to the total discharge ranged from 11.5% to 98.2%, depending on the permeability of the soil layer beneath the sheet pile. The total discharge included seepage through the sheet pile joints as well as under the sheet pile wall. Therefore, hydraulic conductivity of soils directly below the sheet pile will be inversely proportional to the ratio of discharge through the wall to the total discharge. Instances where soils beneath the sheet piles had high permeabilities, $10^{-5}$ cm/s, then the percentage of the discharge through the wall joints is a smaller portion, 11.5% of the total. Instances where soils underneath sheet pile have lower permeability result in higher percentages of the discharge, 98.2%, could be through the joints. This is because the bottom permeability is so low that essentially there is no vertical flow. Care must be exercised when reviewing these numbers in that total flow in the two cases is not the same and the percentages are indicating relative amounts of flow through the two pathways.

A seepage rate of the OCSPS was measured at a Skagway, Alaska site and found to be approximately 1 cubic foot per minute along an 8 ft vertical joint with a single interlock Alexander, 2011). The permittivity was calculated as 0.0003 $sec^{-1}$ and compared to typical geotextile permittivity of 0.05 to 1.5 $sec^{-1}$ (Alexander, 2011). Alternatively, assuming a joints height of 8 ft and a width of each sheet as 1.67 ft (Alexander, 2011), the hydraulic conductivity would be approximately 0.078 $ft^3$/min per $ft^2$ for each sheet. With a total OCSPS sheet pile length of 600 ft and height of 8 ft, the total flow rate for the OCSPS would be approximately 360 $ft^3$/min or 2,687 gallons per minute (Appendix 1). Note that this assumes each sheet has a flow rate of the 1 $ft^3$/min with a hydraulic gradient of 8 feet. With a reduced hydraulic head, the flow rate through each joint would be reduced. For a CDF undergoing filling, typical hydraulic gradients could be as low as one to two feet which translate into flows of 0.063 $ft^3$/min for two feet of head per joint. (Appendix 1).

The seepage rate through sheet pile joints can be controlled with various sealants to reduce rates to a negligible amount. In addition, seepage rate decreases as the joints fill with soil particles. Placement of solid material next to the wall either intentionally or via deposition from the water column will decrease seepage at the joints as the flow pathway to the joint becomes more occluded and the joint itself becomes clogged with sediments. However, it must be remembered that by retarding the seepage, more water will be retained inside of the CDF which must ultimately be removed by some means such as pumping or controlled discharge structure.

## 6.2 Comparisons during Long-Term Storage of Dredged Material in a CDF

Dredged material placed into the CDF undergoes a consolidation process as the water is drained from the dredged material. Immediately after placement consolidation begins. During long-term storage, potential contaminant losses from the containment area will be similar to the earlier phase of placement, while the dredged material continues to be submerged. Should the dredged material become exposed, contaminant losses can include volatilization and runoff during storm events. These losses would be similar in a CDF constructed with a dike and the OCSPS. Evaluation of these potential contaminant pathways should be considered during characterization.

During long-term storage, the potential contaminant losses from the containment area include seepage through permeable dikes, and leachate drainage under, over, around and through the containment area. Each of the potential contaminant losses will be similar as during placement of dredged material. However, after the dredged material has consolidated, flow through it will be reduced as the permeability of the consolidated material is lower.

**Fluid Flow within Dredged Material**

Flow though a porous medium, such as soil or a containment dike, can usually be described by Darcy's Law. Darcy's Law becomes invalid with high velocities of liquid flow through soil or low and high velocities of gas flow through soil, but in the case of saturated soil (dredged material placed behind the OCSPS or a rock dike), the equation has been proven valid in many experiments (Lambe and Whitman 1969).

Through experimentation, Darcy determined that,

$Q = -k\, dh/dl\, A$

Where,

$Q$ = Rate of Flow

$K$ = hydraulic conductivity (also known as coefficient of permeability)

$dh/dl$ = hydraulic gradient (pressure head difference/difference in length)

$A$ = Area of flow

Note: the negative sign indicates flow direction toward lower hydraulic head

Darcy's Law is also valid for unsaturated flow conditions. However the hydraulic conductivity (k) for unsaturated conditions change as the moisture content of the soil changes (Fetter 1980). Unsaturated flow through dredged material in a CDF will be primarily vertical and will not be considered in this evaluation of OCSPS for a CDF, because the potential concern is horizontal flow through the containment system of a CDF.

Given Darcy's Law of flow, the hydraulic conductivity, and the hydraulic gradient, the flow for a given time can be determined. Fluid flow in the dredged material should be considered separately from flow through the OCSPS or the rock dike. The flow rate through the dredged material will be dependent on the type of material and the amount of time the material has had to consolidate. Silts and clays will have a lower hydraulic conductivity than sands. Silts and clays allowed to settle and consolidate will have a lower hydraulic conductivity than initially placed dredged material. As the hydraulic conductivity decreases, the amount of flow through the dredged material decreases for the same head difference. Hydraulic conductivity for a typical consolidated dredged material in a CDF can be as high as $10^{-5}$ cm/sec or as low as 3 x $10^{-8}$ cm/sec.

For example, a CDF dike has a hydraulic conductivity of $10^{-5}$ and the hydraulic gradient is assumed to be 0.1 (1 ft elevation decrease for every 10 ft length), the Darcy velocity is $10^{-6}$ cm/sec or 0.086 cm/day or 31.4 cm/year. If the CDF has a cross-sectional area perpendicular to the containment system of 600 ft wide and 20 ft high, the flow through the dredged material would be approximated at 250 gallons per day over the area of 12,000 $ft^2$.

Determining the flow rate through the OCSPS or the earthen dike during the long-term storage phase will be similar to the process described above during the placement of dredged material phase. That is, the seepage rate will be a function of hydraulic gradient and hydraulic conductivity, as well as the cross-sectional area. The cross sectional area of the OCSPS will be that of the total length of joints, where as the cross sectional area of the dike or berm will be the width dimension multiplied by the height dimension. The seepage rate through the sheet pile will be no greater than the seepage rate through the dredged material, unless there is surface flow, which would only occur with storm events during the long-term storage phase.

# 7.0 Conclusions

The US Army Corps of Engineers Research and Development Center Environmental Laboratory (ERDC-EL) entered into a Cooperative Research and Development Agreement (CRADA) with PND Engineers Inc. to perform a limited evaluation the OPEN CELL SHEET PILE system (OCSPS) for confinement for contaminated dredged material, similar to a Confined Disposal Facility (CDF). PND Engineers, Inc has used the OCSPS in applications that include marine construction for docks and bulkheads.

Based on the scope of the evaluation, limited to environmental considerations, the OCSPS under some cases can be as effective for controlling environmental risk for containment of dredged material when compared with an earthen berm or rock dike typically used for a CDF. Site-specific conditions, dredged material characteristics, regulatory requirements, and other approval constraints must be evaluated for final acceptance; however, the OCSPS can be designed and built to meet or exceed earthen dike criteria for a CDF.

CDFs using OCSPS have a potential for smaller footprints for the same storage capacity in comparison to CDFs constructed using conventional rock and earthen dikes. Alternatively, a CDF employing OCSPS technology will require less space for dike construction and can therefore have a larger dredged material capacity for the same areal footprint when compared to CDFs using conventional dikes. OCSPS provide external vertical walls which can be an aid in the placement of dredged material on the inside of the CDF using mechanical means or in waterfront access after the CDF has been filled.

OCSPS CDFs will only have leakage at the joints in the sheet pile wall.  In comparison, CDFs constructed with rock dikes are porous and permeable, allowing water to infiltrate and pass through.  Sheet pile joints will close over time as a result of aging and clogging with trapped sediments.  As a result, flow through the OPEN CELL SHEET PILE system should decrease to the point that a "watertight barrier" is formed.  When this occurs there is no direct pathway through the CDF wall for contaminant transport.  Removal of excess water either from dredging activities or precipitation will be an operational issue.  When this occurs, procedures and techniques used for CDFs constructed with conventional rock and earthen dikes could be employed.

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# APPENDIX 1

# Dredge Water Computations

**FIND:**

Height of water raised in a CDF during pumping for:

1. 12" dredge with velocity of 15 ft/s and a 50-acre CDF.
2. 30" dredge with velocity of 15 ft/s and a 150-acre CDF

**SOLN:**

**12" dredge**

Flow rate

$Q = A * V$

Where

Q = volumetric flow rate in $ft^3/s$

A= Flow cross sectional area in $ft^2$

V = flow veloci ty in ft/s

$Q = \pi d^2 V/4$

$Q = \pi/4 * (12\ in/12\ in/ft)^2 * 15 \quad (ft^2)(ft/sec)$

$Q = 11.78\ ft^3/sec$

*Assume 80% operational efficiency (19.2 hours per day)*

*Total Volumetric loading* $= 0.8 * 11.78\ ft^3/sec * 60\ min/hr * 60\ sec/min * 24\ hr/day$

$= 814{,}300\ ft^3/day$

*Height = volume/area*

$= 814{,}300\ ft^3/day / (50\ acre * 43560\ ft^2/acre)$

= 0.37 ft or 4.5 inches

**30 " dredge**

$Q = \pi d^2 V/4$

$Q = \pi/4 * (30\ in/12\ in/ft)^2 * 15 \quad (ft^2)(ft/sec)$

$Q = 73.63\ ft^3/sec$

*Total Volumetric loading* = $0.8 * 73.63\ ft^3/sec * 60\ min/hr * 60\ sec/min * 24\ hr/day$

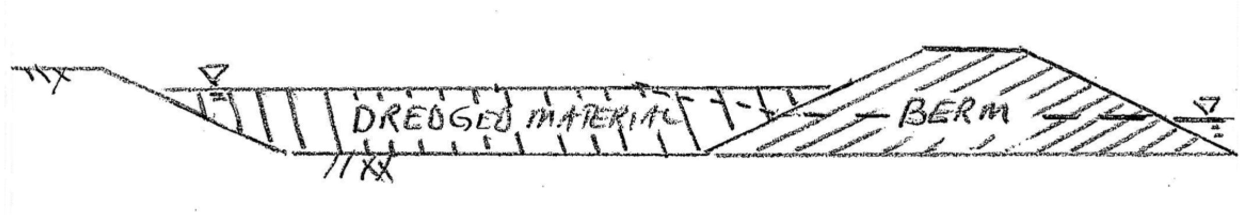
= $5{,}089{,}300\ ft^3/day$

*Height* = *volume/area*

= $5{,}089{,}300\ ft^3/day / (150\ acre * 43560\ ft^2/acre)$

= 0.78 ft or 9.3 inches

# Dredged Material




**Find:**

Flow rate through Dredged Material

Use:

$$Q = \pi \text{ K } \frac{[{H_1}^2 - {H_2}^2]}{\ln\left[\frac{R_2}{R_1}\right]}$$

Assume: Head at center of Crown of water table ($H_1$) is 10' and water table at outside of CDF ($H_2$) is 8'.

K = $10^{-5}$ cm/sec = 3.28 x $10^{-7}$ ft/sec

$$\frac{R_2}{R_1} = \frac{Distance\ from\ CDF\ Center\ to\ Dike}{Distance\ from\ CDF\ center\ to\ Edge\ of\ Water\ Table\ Crown}$$

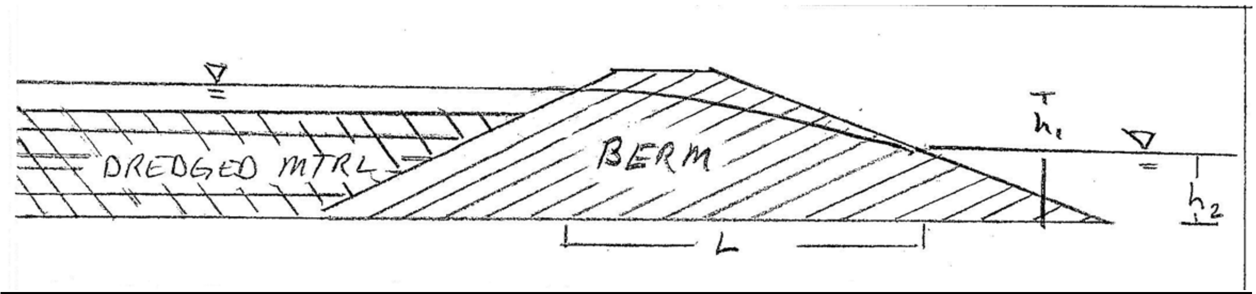
$$= 2.0$$

$$Q = \pi * 3.28\text{x}10^{-7} * \frac{[10^2 - 8^2]}{\ln[2]}$$

$$= 0.53x10^{-5}\ \frac{ft^3}{sec}$$

$$= 0.024\ gpm$$

# BERM FLOW




**FIND**:

Flow rate through Berm using Dupuit's Equation:

$$q = \text{discharge per unit length of Berm}$$

$$= \text{K}\,\frac{[\,{h_1}^2 - \,{h_2}^2]}{2\text{L}}$$

Assume:

K = $10^{-2}$ cm/sec = $3.28\text{x}10^{-4}$ ft/sec

$h_1$ - $h_2$ = Δh = 10' – 8'

L = 3.5' (right) + 8' (top width) + 17 (left) = 28.5'

$$\text{q} = 3.28 * 10^{-4}\left[\frac{\text{ft}}{\text{s}}\right]\frac{[10^2 - \,8^2\,]\text{ft}^2}{2(28.5)\text{ft}}$$

$$= 2.07 * 10^{-4}\;\;\frac{\text{ft}^3}{\text{s} - \text{ft}}$$

Assume Berm length is 600 ft = $L_b$

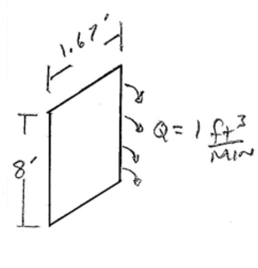
$$Q = q * \,L_b$$

$$= \;2.07 * 10^{-4}\;\left[\frac{\text{ft}^3}{\text{s} - \text{ft}}\right] * \;600[\text{ft}]$$

$$= 0.124\;\left[\frac{\text{ft}^3}{\text{s}}\right]$$

$$= 56\text{ gpm}$$

# Flow through Sheet Pile Joints




**<u>Find</u>:**

Total flow through wall 8 ft high with joint spacing 1.67 ft.

$$Q = total\ flow\ through\ wall\ joint\ \left(\frac{ft^3}{min}\right)$$

$$= 1\ \frac{ft^3}{min} \quad (Alexander, 2011)$$

$$q = unit\ flow\ rate\ \left(\frac{ft^3}{min}\ per\ ft^2\ wall\right)$$

$$= \frac{1\ \left(\frac{ft^3}{min}\right)}{8\ (ft) * 1.67\ (ft)}$$

$$= \ 0.0748\ \left(\frac{ft^3}{min}\ per\ ft^2\ wall\right)$$

Assume wall is 600 ft long and 8 ft high

$$Q_t \ = Total\ flow\ through\ wall \left(\frac{ft^3}{min}\right)$$

$$= 0.0748\ \left(\frac{ft^3}{min}\ per\ ft^2\ wall\right) * 600\ (ft) * 8\ \ (ft)$$

$$= 359.3\ \left(\frac{ft^3}{min}\right)$$

$$= 2687\ gpm\ over\ total\ wall\ length\ of\ 600\ ft$$

If the water surface elevation difference is less, then the flow rate would be less. Assuming that the elevation difference is 2 feet, the flow through the joints could be computed as a ratio of the observed flow and water surface height difference. $Q = \frac{1}{2}qh$

$$q = 2\ \frac{Q}{h}$$

$$= 2\ \frac{1\ \frac{ft^3}{min}}{8\ ft}$$

$$= 0.25\ \frac{ft^3}{min}\ at\ 8\ ft$$

Flow rates at different water column heights are computed using linear interpretation based upon total height of 8 ft..

| h | $h/h_{total}$ | q | $Q_h$ |
|---|---|---|---|
| 0 | 0 | 0 | 0 |
| 1 | 0.125 | 0.031 | 0.016 |
| 2 | 0.250 | 0.063 | 0.063 |
| 3 | 0.375 | 0.094 | 0.141 |
| 4 | 0.500 | 0.125 | 0.250 |
| 5 | 0.625 | 0.156 | 0.391 |
| 6 | 0.750 | 0.188 | 0.563 |
| 7 | 0.875 | 0.219 | 0.766 |
| 8 | 1.000 | 0.250 | 1.000 |

Where

$$Q_h = total\ flow\ to\ depth\ h$$

$$= \frac{1}{2}\ q\ h$$

For example, if h = 2 ft then $Q_{h} =$

$$Q_h = \frac{1}{2}\ q\ h$$

$$= \frac{1}{2} * \ 0.063 \left(\frac{ft^3}{m}\right) * 2\ (ft)$$

$$= 0.063\ \left(\frac{ft^3}{m}\right)$$

Therefore for a water surface difference of 2 feet, flow through the joints would be 0.063 $ft^3$/min, assuming that the only difference in the two cases is the water surface height difference. If this flow rate is applied along a 600 ft wall, the total flow rate is 22.46 $ft^3$/min or 168 gpm.