

POST-DREDGING RESIDUAL SEDIMENT STABILIZATION

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ABSTRACT

The nature and characteristics of residual sediments have been discussed extensively. It has been shown that dredging leaves a post-dredging sediment surface much more susceptible to erosion than the sediment surface prior to dredging. The potential for erosion can be particularly acute for fine-grained sediments or sediments with a significant fine fraction. If the sediments are contaminated, post-dredging erosion may contribute significant constituent concentrations to the water column.

One approach to reduce sediment and contaminant loss is to increase the critical shear stress of the residual sediments through amendments. Sand, bentonite, kaolin and lime and a matrix of combinations, called “admixture”, were tested for relative effectiveness at increasing erosional strength of dilute sediments. Comparison of sediment mixtures was performed using a SedFlume apparatus. This research concludes bentonite clay provides the greatest resistance to erosion, requiring the least mass addition per mass of treated sediment. Bentonite was determined to be the most cost-effective admixture. The results will be used to assess the practicality of rapid stabilization of post-dredging surfaces.

Keywords: Dredging, residuals, residual sediment, contaminated sediment.

INTRODUCTION

Mechanical and hydraulic actions associated with dredging leave behind some loosened sediment not removed by the dredging operation (Bridges et al 2008). Palermo and Patmont (2007) present data showing residual sediment volumes from several projects ranging from 1.7 to 8.7% by mass of the dredging volume. These residual sediments remain in or near the dredging footprint in a very unstable state – high water content and destroyed soil structure. Palermo and Patmont (2007) show residual sediment dry densities in the range of 0.4 to 1.2 gm/cm³ from several mechanical dredging projects. At these low densities, residual sediments are more susceptible to erosion and transport than in their original state. A significant fraction of sediment and contaminant transport during dredging may result from erosion of these residual sediments. This paper investigates potential strategies for stabilizing residual sediments with commonly available dry materials to significantly reduce their erosion potential using data developed and presented by Starr (2007).

RELATED STUDIES

Sediment erosion depends on many factors including hydrodynamic conditions, sediment structure, bulk density, gas volume, mineralogy, and organic content. Multiple researchers (e.g., McNeil et al., 1996; Taylor and Lick, 1996; Jepson et al., 1997) have confirmed relationships between erosion and these parameters. Still, quantitative prediction of the sediment erosion based on measurement of bulk sediment properties remains elusive, partially because of the number of complex relationships that effect erosion (Gailani et al. 2001; Jones and Lick, 2001).

Cohesive sediments play a much larger role in water quality than non-cohesive sediments. Non-cohesive sediments are typically coarse-grained sands and gravel materials with high settling velocities, making them relatively stable except in high energy environments. Cohesive sediments consist primarily of silt and clay grains in a matrix of organic debris and microorganisms (Ravisangar et al., 2005; Black, 2002). Individually, these sediment particles are highly vulnerable to erosion; stability increases significantly when they are in a closely spaced matrix whose structure is held

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together by cohesion; cohesion is the tendency of sediment particles to stick together because of both physiochemical and biological factors.

Environmental contaminants associate primarily with fine-grained sediment particles and organic matter due to their relatively large surface area-to-mass ratio and reactive nature of their surfaces, creating stable complexes which promote sorption. (Ravisingar et al., 2001, 2005). Thus, transport of fine-grained, highly organic residual sediment is of particular concern for dredging projects removing sediments containing significant toxic constituent concentrations.

Jepsen et al. (2000) showed that gas generated by decay of organic matter increases erosion by creating voids, decreasing density, and destabilizing the sediment structure.

Cohesive sediments have been shown to erode in three distinct modes (Zreik et al., 1998). Surface erosion is defined as the process by which the electrochemical bonds between aggregated bed particles on the sediment surface are broken by the critical shear stress of the overlying water. The larger aggregates then break up or are transported according to the sediment transport processes described above. Mass erosion occurs by failure of the bed along an embedded plane. All of the sediment material above the failure surface is released into the water column and is transported downstream. The third mode of sediment erosion is fluidization which is a result of wave action followed by mixing. The fluidized bed is susceptible to movement with water current.

LABORATORY TESTING

Starr (2007) used a modified version of the SedFlume (McNeil, 1996) to measure and compare erosion rates of a high-water content marine sediment with the same sediment after adding a variety of dry materials to increase density and stability. Jin et al., (2001) had shown that addition of a few percent (by mass) of bentonite can increase resistance to erosion by almost two orders of magnitude. Bentonite has interesting thixotropic properties that make it viscous and easily eroded with first mixed, but forms a gel over time that makes it much more difficult to erode (Jones and Lick, 2001). With this as background, Starr (2007) identified similar, readily available materials that might be used to significantly decrease the susceptibility to erosion of high water content sediments.

Starr (2007) obtained fine-grained depositional sediment from a barren, dry basin adjacent to the Great Salt Lake near Salt Lake City, Utah to simulate a marine sediment. Table 1 shows the results of all characterization tests conducted on the sediments using appropriate ASTM methods.

Table 1. Simulated Marine Sediment Characterization (from Starr, 2007).

Solids Concentration (% by mass)	Conductivity (ms/cm)	Salinity (mg/g)	pH	Passing #200 Sieve %	Retained #200 Sieve %
63	68.1	51.8	8	25	75

The modified SedFlume (Figure 1) was used to determine the shear stress associated with incipient erosion, i.e. the critical shear stress, and the erosion rate at a shear stress of 0.60 Pa. The modified SedFlume was a straight flume with a consistent vertical cross-section (5.2 cm high x 10.7 cm wide) and a horizontal rectangular opening in the bottom (10.5 cm wide by 15 cm cross section) for a coring tube with sediment to be inserted. Water was pumped from a storage tank through a two-inch diameter pipe into the inlet section that can generate shear stresses in the range of 0 to 1.0 N/m² over the rectangular section. Flow and shear stress are regulated by a three-way valve which allows the portion of water flowing through the flume to be controlled; excess flow is return to the tank. A flow meter monitored the flow rate.

At the beginning of the test, a coring tube containing the test sample is inserted into the test section of the apparatus. The operator adjusts a piston which resides inside the coring tube to move the top level of the sediment so it is even with the bottom flow surface of the flume. Water flows over the test section eroding sediment. As the specimen erodes, the operator adjusts the position of the sample so that its top level is always even with the bottom flow surface. The amount of sediment eroded is defined as the rate of upward movement of the specimen (cm/s).



Figure 1. SedFlume apparatus used by Starr (2007)

The relation between flow rate and shear stress on a smooth surface can be determined as follows. For a pipe with a smooth surface,

$$\frac{1}{\sqrt{\lambda}} = 2.0 \log \left[\frac{UD\sqrt{\lambda}}{\nu} \right] - 0.8$$

where U = mean flow speed (m/s), ν = kinematic viscosity ($\text{m}^2 \cdot \text{s}^{-1}$), λ = friction factor (unitless), and D = hydraulic diameter (m). For rectangular cross sections, the hydraulic diameter is defined as:

$$D = \frac{4A}{P}$$

where A = cross-sectional flow area (m^2) and P = wetted perimeter (m). For full flow, this simplifies to

$$D = \frac{2hw}{h+w}$$

where w = flume width (m) and h = flume height (m). However, for partial depth flow, the equation for hydraulic diameter is:

$$D = \frac{4dw}{2d+w}$$

where d = flowing water depth (m) in the flume. Friction factor, λ , can be computed as

$$\lambda = \frac{8\tau}{\rho U^2}$$

where ρ = density of water (g/m^3), and τ = wall shear stress (N/m^2). The above equations can be combined to solve for shear stress as a function of mean flow speed.

For consistency, Starr (2007) attempted to measure erosion of each sample over a ten-minute period. Three samples of each sediment mixture were tested to ensure repeatability. Erosion rate was calculated as the total displacement of the piston in ten minutes. In some cases, however, the flow stream immediately washed all sediment from the sample cell. Samples that exhibited this response were defined as having “high” erodibility. There were also some sediment samples which eroded so slowly that changes in the sediment surface over time were nearly imperceptible. The timescale over which these samples eroded (>1 hour) made quantifying an erosion rate impractical. Samples that exhibited this response were defined to have “low” rates of erosion.

Each sediment mixture tested was mixed using an electric drill outfitted with a paint mixer until it appeared homogenous. The salinity of each diluted sediment sample was adjusted to 50 mg/g using solar salt solution for consistency. Following mixing, the mixtures were poured into rectangular coring tubes to a depth of 5 cm and immediately tested for resistance to erosion, thereby minimizing time for consolidation and manifestation of thixotropic effects to occur.

EXPERIMENTAL RESULTS

Erosion Rates Under Constant Shear Stress of 0.60 Pa

Simulated Marine Sediment

The simulated marine sediments at 60% initial solids concentration were determined to have an erosion rate of 0.2 cm/min at 0.60 Pa of shear stress. The sediment was diluted to solids concentrations of 60%, 50%, 40%, 30%, and 20% (w/w) solids and tested at a shear stress of 0.60 Pa; test results are summarized in Table 2.

Table 2. Erosion Test Results for Simulated Marine Sediment at a Shear Stress of 0.60 Pa (from Starr, 2007).

Sediment Concentration (% solids)	20	30	40	50	60
Erosion Rate (cm/min)	High	High	High	High	0.2

Given that the simulated marine sediment eroded at a rate of 0.2 cm/min at 60% in situ solids concentration, it is not entirely surprising that lower sediment concentrations exhibited immeasurably high erosion rates (defined as > 1 cm/sec) at all lower concentrations tested (20%, 30%, 40%, and 50%).

Simulated Marine Sediment with Dry Material Additions

Previous research (Jepsen et al. 1997) found the following correlation between shear stress, bulk sediment density, and erosion rates.

$$E = A \tau^n \rho^m \quad (1)$$

where E is the erosion rate (cm/s), τ is the shear stress (dynes/cm²), ρ is the bulk density (g/cm³); n, m, and A are constants that depend on the type of sediment. Roberts, et al. (1998) validated this relationship with a range of fine sediments both in the lab and in situ. They also found erosion of coarse particles to be independent of density.

Given this prior this observation, Starr (2007) tested the impact of increasing the density on the simulated marine sediment using a variety of readily available dry materials to increase the total density on sediment stability. The mixtures were tested immediately after mixing so that there would not be complicating affects from consolidation or thixotropic affects. While not the original purpose of the research, this is similar to adding stabilization materials to residual sediments after dredging.

Starr (2007) tested simulated marine sediment at 20%, 30%, 40%, 50%, and 60% initial solids concentrations amended with sand, bentonite, kaolinite, and Slaked Lime (hydrated, Type S), along with combinations of these materials, to achieve final solids concentrations from 25% to 70% solids. Erosion rates of the mixtures at a shear stress of 0.60 Pa were determined using the SedFlume (Table 3).

Table 3. Erosion rates (cm/sec) at 0.60 Pa Shear Stress (from Starr, 2007).

Initial Density (g/cm ³)	Final Density (g/cm ³)	Add. (%)	Dry Mixture Additive Composition						
			Sand	Bentonite	Kaolinite	1S:1B*	1S:1K**	Lime	1S:1L***
0.23	0.30	25		2.0		H			
0.23	0.37	50	H	0.24	H	0.16	H	H	H
0.23	0.45	75		0.16		L			
0.23	0.53	100	H	L	H	L	H	0.15	0.10
0.23	0.73	300	H	L	0.18	L	0.16	H	L
0.23	0.96	200	H	-	L		L	L	L
0.23	1.24	250	H	L	L	L	L		
0.37	0.73	67	H	L	0.22	L	0.22		
0.37	0.96	100						0.40	
0.37	1.24	130	H	L	L	L	L		
0.53	0.73	50	H	L	0.58	L	0.65		
0.53	1.24	75	H	L	L	L	L	0.025	
0.73	1.24	40	H	L	L	L	L		
0.96	1.24	17	H	L	L	L	L		

Notes:

H = high erosion rate too high to measure (> 1 cm/sec)

L = immeasurably low erosion rate

*1S:1B = dry additive was equal parts sand and bentonite

**1S:1K = dry additive was equal parts sand and kaolinite

***1S:1L = dry additive was equal parts sand and Lime

Sand did not appear to have any stabilizing effect on the simulated marine sediments during Starr's tests. In contrast, all other mixtures significantly reduced erosion rates. It was observed during testing that the samples hydraulically separated in the sample cell, i.e. fine-grained sediment eroded leaving the heavier sand particles behind. The range of amendment required to impact erosion varied. Bentonite combined with sand seemed to be the most successful mixture of all. Adding just 50% as much mass to 20% solids decreased the erosion from too rapid to measure with the SedFlume to stable at 0.60 Pa of shear stress. Kaolinite and lime, both with and without sand, was similarly successful, but required significantly more dry mass be added to achieve those results. Amended samples with final concentrations of 70% solids exhibited immeasurably low erosion rates except those amended with sand.

Starr (2007) reported that sediments amended with bentonite to both 50% and 70% solids were and stiff, like modeling clay; similar results were found with kaolinite for final solids concentrations of 70%. Sediments with a 20% initial solids concentrations amended with kaolinite to 50% solids were observed to have a fluid yet viscous consistency. Samples that had 30% and 40% initial concentrations were observed to have increasingly watery and less viscous consistency. While workable, these amended sediments exhibited less resistance to erosion than sediments amended to similar final concentrations with bentonite.

Samples amended with equal mixtures of bentonite or kaolinite and sand to 50% total solids concentrations exhibited erosion rates identical to those that had been modified with bentonite or kaolinite alone. All samples amended with sand and bentonite to 50% solids were determined to have unmeasurably low erosion rates.

All samples amended to 70% solids exhibited immeasurably low erosion rates. Even the 60% simulated marine sediment became more erodible when sand was added to the matrix – presumably because the reduction in overall cohesion. It had a 0.2 cm/sec erosion rate by itself, but the rate increased to more than 1 cm/sec when sand was added to the matrix to increase the density from 60% to 70% solids.

Critical Shear Stress

Starr (2007) conducted additional SedFlume tests on the same simulated marine sediment at 20% initial solids concentration to evaluate the effect of varying shear stress on erodibility. Simulated marine sediment at 20% initial solids concentration was amended with kaolin, bentonite, equal parts sand and bentonite, lime, and a mixture of equal parts sand and lime.

In these tests, the sample was placed into the SedFlume and flow initiated across the sample. The flow rate was increased slowly (generally in $9.5 \times 10^{-4} \text{ m}^3/\text{sec}$ (15 gpm) increments) until signs of the incipient erosion were detected, the incipient flow rate was recorded and testing concluded. The initial sign of erosion was defined as any visually observable suspension, removal, and transport of sediment particles from the sample. In some cases, cohesive sediments were observed lifting into the water stream in one large piece, yet not breaking off or washing away. This was deemed a visual indication of erosion even though the particles were not transported away. Critical shear stress results are summarized in Table 4.

Table 4. Incipient shear stresses, τ (Pa), and associated velocities, U (m/sec), for sediment mixtures starting at 0.23 g/cm^3 (from Starr, 2007).

Initial Density (g/cm ³)	Final Density (g/cm ³)	Add. (%)	Dry Mixture Additive Composition							
				Sand	Bentonite	Kaolinite	1S:1B*	1S:1K**	Lime	1S:1L***
0.23	0.30	25	τ (Pa)	-	H	-	H	-	H	H
			U (m/s)							
0.23	0.37	50	τ (Pa)	-	0.36	H	0.36	-	0.11	0.05
			U (m/s)		0.34		0.34		0.17	0.11
0.23	0.45	75	τ (Pa)	-	0.47	-	0.47	-	-	-
			U (m/s)		0.40		0.40			
0.23	0.53	100	τ (Pa)	-	-	0.11	-	-	0.36	L
			U (m/s)			0.17			0.34	
0.23	0.73	150	τ (Pa)	-	-	0.47	-	-	-	-
			U (m/s)			0.40				
0.23	0.96	250	τ (Pa)	-	-	L	-	-	-	-
			U (m/s)							

Notes:

H = erosion observed at flows too low to measure

L = No erosion observed at highest flowrate

*1S:1B = dry additive was equal parts sand and bentonite

**1S:1K = dry additive was equal parts sand and kaolinite

***1S:1L = dry additive was equal parts sand and Lime

Simulated marine sediment at 20% solids was amended with kaolin to 30%, 40%, 50% and 60% final solids concentrations were tested in the manner described above. At a final solids concentration of 30%, erosion was observed at the lowest flow rate $\sim 0.3 \times 10^{-3} \text{ m}^3/\text{sec}$ ($\sim 5 \text{ gpm}$). Incipient erosion was observed at flowrates of $0.95 \times 10^{-3} \text{ m}^3/\text{sec}$ (15 gpm) and $2.2 \times 10^{-3} \text{ m}^3/\text{sec}$ (35 gpm) for 40% and 50% solids concentration samples, respectively. Sediment mixtures at 60% solids concentration remained stable through the maximum flow rate of $2.5 \times 10^{-3} \text{ m}^3/\text{sec}$ (40 gpm).

Based upon previous testing, critical shear stress tests with bentonite focused on a narrower range of final solids concentrations - 25%, 30%, and 35%. Samples amended to 25% solids with bentonite eroded immediately, while samples amended to 30% and 35% displayed initial signs of erosion at $0.95 \times 10^{-3} \text{ m}^3/\text{sec}$ (15 gpm) and $1.9 \times 10^{-3} \text{ m}^3/\text{sec}$ (30 gpm) respectively. Similar results were found when sand and bentonite were combined equally as the additive. Samples with a final solids concentration of 25% eroded at the lowest shear stress, but samples at 30% and 25% final solids concentrations did not experience erosion until $1.3 \times 10^{-3} \text{ m}^3/\text{sec}$ (20 gpm) and $1.6 \times 10^{-3} \text{ m}^3/\text{sec}$ (25 gpm) respectively. Note that the addition of sand increased the stability at lower additive proportions, but decreased the stability at higher proportions.

Sediment amended with lime to 25%, 30% and 40% final densities followed a similar trend. Sediment with a final solids concentration of 25% eroded immediately upon the introduction of flow. Samples amended to 30% and 40% final solids concentrations were much more stable and incipient erosion did not occur until flow rates of $0.95 \times 10^{-3} \text{ m}^3/\text{sec}$ (15 gpm) and $1.9 \times 10^{-3} \text{ m}^3/\text{sec}$ (30 gpm) respectively.

RELATION TO SEDIMENT PROPERTIES

Susceptibility to erosion varies with sediment density and sediment properties through a series of complex, interrelated phenomena. Liquidity is a convenient metric to integrate sediment density with these other sediment characteristics that affect erodibility. The Liquidity Index (LI) is defined as:

$$LI = \frac{(\omega - L)}{(LL - L)} \quad (2)$$

where LI = Liquidity Index (unitless), ω = water content (%), LL = Liquid Limit (%), and PL = Plastic Limit (%).

Liquid Limit and Plastic Limit (herein referred to as Atterberg Limits) tests were completed on many test samples at a range of densities. Table 5 shows the computed Liquidity Index for each sample and the measured erosion rate at a shear stress of 0.6 Pa. Many of the samples either observed immeasurably high erosion rates at 0.6 Pa (indicated by H in Table 5 and arbitrarily assigned an erosion rate of 1 cm/sec in Figure 2) or immeasurably low erosion rates (indicated by L in Table 5 and taken as 0 cm/sec in Figure 2). One sample was at density greater than the Plastic Limit resulting in a negative Liquidity Index. Figure 2 shows that measured erosion rates at a shear stress of 0.6 Pa increase with the Liquidity Index of the sediment sample.

Table 5. Erosion rate (cm/min) variation with Liquidity Index.

γ (g/cm ³)	Liquid Limit	Plastic Limit	Plasticity Index	Liquidity Index	E _{0.6} (cm/min)	τ_c (Pa)
0.53	112.1	39.7	72.4	1.52	H	
0.96	47.2	28.0	19.2	2.03	H	
0.73	115.8	39.8	76.0	0.79	H	
1.24	62.6	50.0	12.6	-0.56	0.025	
0.73	48.6	27.3	21.3	3.41	0.18	0.47
0.73	45.1	26.6	18.6	3.95	0.18	
0.73	43.8	26.0	17.8	4.16	0.22	
0.37	118.6	30.7	87.9	2.30	0.24	0.36
0.96	61.4	47.3	14.1	1.40	0.4	
0.73	48.3	24.1	24.2	3.14	0.58	
0.53	54.1	26.0	28.1	4.41	L	0.11
0.73	60.9	50.6	10.2	4.84	L	
0.37	46.2	25.6	20.6	10.07	L	H
0.37	54.8	25.6	29.3	7.08	L	0.36
γ = Wet density (g/cm ³)						
τ_c = Incipient shear stress (Pa)						
E _{0.6} = Erosion rate at 0.6 Pa (cm/min)						

Table 5 also includes incipient shear stresses (Pa) for some of the samples. Those values are plotted versus Liquidity Index of the sediment mixtures in Figure 3. The results show that incipient shear stress varies with Liquidity Index.

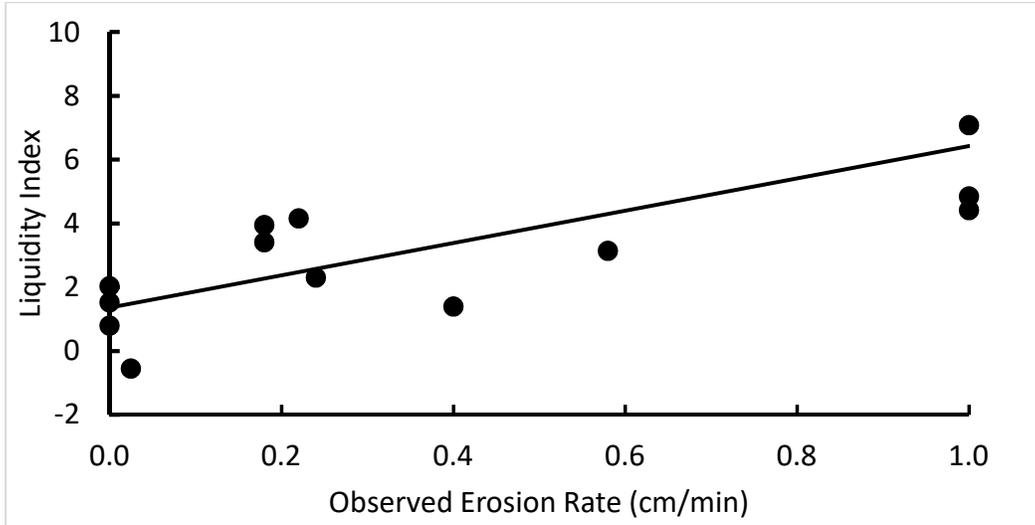


Figure 2. Observed erosion rates at a shear stress of 0.6 Pa relative to Liquidity Index of sediment samples; immeasurably high rates arbitrarily assigned a value of 1.0 cm/sec.

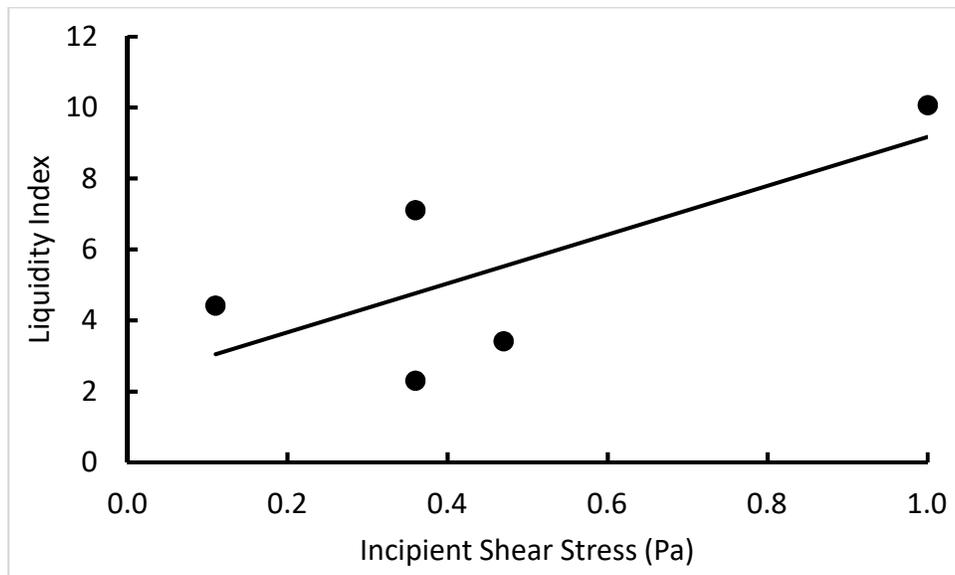


Figure 3. Observed incipient shear stresses with Liquidity Index of sediment samples.

APPLICATION TO DREDGING RESIDUALS

Starr's results provide useful information about the potential use of commonly available dry amendments - specifically, sand, bentonite, kaolinite, lime, and some combinations - to significantly increase the stability of low density bottom sediments like the characteristics expected of dredging residuals. Sediment residuals have been reported to be 5 to 20% (by mass) of the sediment volume targeted; some of that, returns to the dredged surface with no significant change in physical properties (e.g. dense clumps) and similar resistance to erosion as prior to dredging and surrounding bottom sediments. Some, however, has its physical structure destroyed, entrains additional water, and rests on the bottom in a fluid-like state, similar to a nepheloid layer. This layer of low-density sediment can be highly susceptible to erosion, especially immediately after dredging. The primary purpose of this paper is to investigate the potential for stabilizing this layer.

Neither the physical characteristics or volume of this low density post-dredging residual layer have been fully defined. An initial concentration of 20% solids (equivalent to 278 kg/m³ or a water content, ω , of 400%) is a reasonable estimate of the worst-case scenario. This is approximately the transition concentration between particle settling and primary consolidation (which occurs at a much slower rate) for many sediments.

The residual sediment layer thickness likely varies considerably depending upon the dredging operation, environment, and sediment properties. Low density residual layers greater than 20 cm are less likely as the mass associated with increased depth will likely lead to density stratification. Thus, for this assessment, only residual sediment depths to 20 cm are considered. The results and assessments, however, can be translated proportionally to other depths.

Typical dry bulk densities of the dry materials tested by Starr (2007) as amendments are approximated from a range of sources to be:

- Sand 1600 kg/m³
- Bentonite 800 kg/m³
- Kaolin Clay 800 kg/m³
- Lime 560 kg/m³

Combined dry bulk densities, based upon equal part mixtures, would be approximately:

- 1:1 Sand:Bentonite 1200 kg/m³
- 1:1 Sand:Kaolinite 1200 kg/m³
- 1:1 Sand:Lime 1080 kg/m³

Applying amendments as a proportion of the sediment mass being stabilized is a simple way to discuss potential scenarios. In that vein, Table 5 shows approximate amendment layer thicknesses that correspond to the residual sediment mass at 20% solids and thicknesses ranging from 5 to 20 cm. these thicknesses are based upon typical bulk material densities presented above.

Table 5. Approximate layer thicknesses for different dry amendments required to match residual sediment mass for specific layer thicknesses at 20% solids (278 kg/m³ or a water content, ω , of 400%).

Residual Thickness at 20% solids (cm)	Thickness of Equivalent Amendment Mass (cm)				
	Sand	Bentonite or Kaolinite	1:1 sand and bentonite or kaolinite mix	Lime	1:1 sand and lime mix
5	0.71	1.4	1.0	2.0	1.1
10	1.4	2.9	1.9	4.1	2.1
15	2.1	4.3	2.9	6.1	0.60
20	2.9	5.7	3.8	8.1	4.2

When discussing amendments, sand would seem to be a logical choice. It is easy to apply and has been shown to be a successful capping material. Jepsen et. al (1997) and Roberts, et al. (1998) found a strong correlation between increased density and decreased erodibility. Sand is an effective way to rapidly increase the overall density. However, Tables 3 and 4 suggest that sand may not effect erosion as an amendment. It is important to remember that Starr's testing was for a different purpose and the samples were thoroughly – and presumably evenly – mixed. This resulted in fine sediment exposed at the surface that was observed to erode. It may be that proper application of sand on top of the residual layer would leave trap most of the residuals beneath the sand layer and significant less fine material would at the surface, exposed to erosive forces. Further, Starr did not attempt to quantify the extent of erosion. If so, his experiments may have shown much lower mass loss due to erosion in the sand-sediment mixture. Starr's results certainly suggest that additional work should be done on the use of sand as a residual stabilization material prior to its use.

In contrast, bentonite was found to be a very effective amendment, alone and when combined with sand. Just 50% additional mass of bentonite, or equal proportions of sand and bentonite, significantly stabilized the sediment. Although the tests to prove it were not all conducted, the results suggest that adding an equivalent mass of bentonite or sand-bentonite mix to the residual mass may entirely arrest erosion under modest flow conditions. Table 5 shows that mass of bentonite alone represents only about 30% of the residual depth. About 20% of a sand and bentonite mix would provide an equivalent mass. So, for a 10 cm depth residual layer, the required amendment mass would only be 2 to 3 cm in depth.

The complication of bentonite is application. Sand settles quickly through the water column, allowing surface application (although that may not be best). Bentonite settles very slowly and will quickly hydrate; it would have to be placed at or near the bottom to be effective. Some commercial products are available that attempt to address this problem. Additional research would also be needed to evaluate how field applications – in contrast to the complete mixing by Starr – might positively or negatively impact the effectiveness.

Kaolinite and lime showed similar effectiveness as bentonite, both with and without sand. They required more amendment to achieve a similar degree of effectiveness. Kaolinite required the most, but still only about twice that of bentonite. There could be some reasons, such as cost, for using kaolinite or lime in lieu of bentonite on site specific bases. The same application issues exist for kaolinite and lime as for bentonite.

CONCLUSIONS AND RECOMMENDATIONS

Dredging residuals are a relatively new concern and our knowledge about their characteristics remains limited. Data associated with some large contaminated sediment dredging sites suggest that residuals may be responsible for a significant proportion of the overall suspended sediment and contaminant transport associated with these projects. This paper reviewed prior work by Starr (2007) for a different purpose to see if it provides insight into potential stabilization materials and effectiveness for residual sediments.

Starr's data suggest that amending residuals with a modest amount of common dry materials – sand, bentonite, kaolinite, and lime - may effectively reduce the risk of sediment and associated contaminant transport. Test results show that equivalent amendment depths of 20 to 30% of the residual depth, if completely mixed, would significantly reduce their erodibility.

While these data provide a good starting point, further study is needed to further refine these results and evaluate their application to residual sediments.

- Additional characterization of dredging residuals is needed to understand their characteristics.
- Further SedFlume (or similar) erosion studies need to be conducted on samples that are more representative of residual sediments. Rather than being well-mixed, residual sediments are likely to vary in density with depth.
- Post-amendment residual sediment profiles need to be better understood. Specifically, if the amendment successfully traps the residuals beneath the new layer, it represents a very different situation than if the two become well-mixed like the samples tested by Starr. Sand, for example, did not seem to be effective in a well-mixed state; however, if it can successfully trap the residual sediment beneath a relatively pure sand layer, it may be very effective and reducing transport risks.
- Application measures need to be developed and perfected for non-sand amendments. The application approach may affect the final stabilized sediment profile and its susceptibility to erosion.

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