Technical Memorandum

To: Andrew M. Millspaugh, Natural Resources Technology  
From: Michael R. Palermo, PhD, PE  
Date: 3 May 2016  
Re: Fountain Lake CDF Storage and Solids Retention

Introduction

Natural Resource Technology (NRT) is contracted to the Shell Rock River Watershed District, Minnesota, for design of a Confined Disposal Facility (CDF) for the Fountain Lake restoration project. NRT has engaged Mike Palermo Consulting to provide support for the CDF design, focusing on those aspects of the design related to solids retention and initial storage capacity during filling operations. This effort requires the analysis and application of data from a Long Tube Column Settling Test (LTCST) test conducted for the project.

Site Conditions and Sediment Characteristics

The Shell Rock River Watershed District is considering dredging to address a phosphorus loading problem in Fountain Lake. Sampling has indicated that higher phosphorous concentrations are in the upper layers of the lake bottom sediments. Hydraulic dredging is planned to remove the upper few feet of sediment.

A defined area has been acquired for construction of a CDF, consisting of two separated parcels. The West Cell parcel is envisioned for initial operations. The West Cell has a surface area of 37.8 acres within the proposed dike centerlines with a roughly triangular irregular shape.

A number of borings within the lake were taken and samples tested to characterize the sediments to be dredged. The physical properties of the samples indicate that the gravel plus sand fraction is an average of 24%, silt fraction average 48%, and clay fraction average 28%. The data for initial water content of the in-situ sediments was limited (the grain size analyses from the core samples apparently did not include a sample water content). A few void ratio values of the sediments were included in results for triaxial tests, with an average void ratio of 4.09. The specific gravity of sediment from the
LTCST test was $G_s = 2.45$, and this was the only measured value I found in all the data provided.

**Anticipated Dredging Operations**

NRT has provided a general description of the anticipated dredging operations. The lake restoration project is anticipated to require dredging between 1.0 to 1.5 Mcy of sediment over a 3 to 5 year period. This equates to approximately 300,000 cy of dredging each year. Active operations must occur within a dredging window of 5 months per year during May through October, with a schedule of active operations of 6 days per week, 12 hours per day. This equates to approximately 1542 hours per year available for dredging operations, occurring within a 150 day timespan. Hydraulic cutterhead dredges are assumed.

Dredge size and production rate will be determining factors for meeting the removal requirements and will determine the storage and solids retention behavior during the filling operations. The minimum required operating production rate for the project was estimated using the procedures in Chapter 6 of the ERDC Environmental Dredging Guidance (Palermo et al. 2008). The operating production rate must consider the Effective Working Time Efficiency (the actual percentage of the time the dredge is actively pumping). Considering the relatively thin cuts that would be required, an EWTE of 75% was assumed, a value between that recommended for navigation dredging and that recommended for remediation dredging. Application of the 75% EWTE results in 1156 possible operating hours within the 150 day annual filling period. For an annual volume of 300,000 cy and 1156 hours for dredging operations, the minimum required operating production rate is 259 in-situ cubic yards per operating hour.

Since Fountain Lake is an inland lake, the dredges must be truck-transportable. This requirement sets the maximum dredge size at about 18 inches. The production curves in Figure 4-2 of EM 1110-2-5027 (USACE 1987) were used to estimate a minimum dredge size. For a pipeline length of approximately 10,000 ft (from Fountain Lake to the west side of the West Cell following the pipeline route provided by NRT) and dredging depth of less than 20 feet, the minimum dredge size capable of meeting an operating production rate of 259 cy/hour is 14 inches. Production rates were also calculated for a range of dredge sizes from 12 to 18 inches considering the in-situ sediment density equivalent to void ratio of 4.07, 7.5% slurry concentration, and pipeline velocity of 15 fps. These calculations indicate that operating production of a 12 inch dredge is 254 cy/hr (just short of the required operating production rate of 259 cy/hr), while that for a 14 inch dredge is 347 cy/hr. Based on these estimates, a 14 inch dredge was assumed for the analysis of the initial storage and solids retention using the LTCST data.

**Long Tube Column Settling Test**

A LTCST was performed for the project by Test America, and documented in a report dated 9/23/2013 (copy provided by NRT). The column test procedures followed a Test America SOP which generally follows the USACE procedures for the test described in the 1987 EM 1110-2-5027.
The LTCST characterizes three of the four types of settling behavior that may occur as the dredged material slurry is hydraulically placed in the CDF:

- Discrete settling occurs where the particle maintains its individuality and does not change in size, shape, or density during the settling process. Sediment particles that are sand size or greater will settle discretely and will segregate from the finer silts and clays, usually forming mounds of coarser material at the pipeline discharge point. This behavior is not evaluated in the LTCST but is accounted for in the CDF design for initial storage.

- Zone settling occurs where the slurry suspension forms a lattice structure and settles as a mass (the high solids concentration partially blocks the release of water and hinders settling of neighboring particles), and a distinct interface between the slurry and the supernatant water is exhibited during the settling process. Zone settling processes will define the required ponded surface area to allow the settling process to be maintained.

- Compression settling occurs by compression of the lattice structure over a time period of days to months. Compression settling processes will define the initial volume occupied in the CDF for a given volume of in-situ sediment dredged.

- Flocculant settling occurs where particles agglomerate during the settling period with a change in physical properties and settling rate. Flocculant settling may occur for the dredged material slurry mass as it is hydraulically placed in the CDF, or if the slurry mass undergoes zone settling, flocculent processes will occur for fine particles remaining in suspension above the interface. Flocculent settling processes define the concentration of suspended solids in the effluent discharged from the CDF.

The zone, compression, and flocculent settling behavior are all characterized by the LTCST. All of the above sedimentation processes may occur simultaneously in a CDF, and any one may control the design of the placement area.

NRT indicated the sample used for the LTCST was a composite of multiple core samples. The Test America testing report indicated the column test sample had sand fraction of 22.5%, consistent with the core sample average. These considerations indicate that the column test sample was representative of the in-situ sediment to be dredged.

Data in the Test America report included both the recorded interface height through a 15 day period and TSS samples collected from the column ports over time. The results indicated an interface forming within minutes of the start of test, similar to a salt-water sediment. This behavior for a fresh water sediment may be due to the relatively high silt content of the sediment.

Since I had not seen this settling test firsthand, I requested some additional details on how the test was conducted and how the data were presented. NRT and Barr Engineering (earlier involved with the test) could not answer these questions, but approved my contacting Test America directly. I was able to call Carrie Gamber at Test America, and we discussed these points:
• Physical characterization of the sample tested indicated a value for Gs = 2.45 which seems low. We agreed that this may reflect a high organic content in the fine fraction of the sediment.

• The slurry was mixed in the test to target a 150 g/l concentration for the slurry. The initial port samples at the start of the test was about 50 g/l. We agreed that this was likely due to immediate settling of the sand and rapid settling of silt fractions.

• Data indicates an interface formed almost immediately, even though this is a freshwater sediment. There were no photos taken of the test, but Carrie recalled that the slurry was a brownish color, consistent with a freshwater sediment. She also recalled that the slurry mass “settled like a rock”, indicative of a quick settling of the interface in the initial hours of the test.

• Interface Height was provided in the report as an increasing value with time. Carrie clarified that this was a measurement from the initial water surface at 7.0 feet in the column down to the falling interface as opposed to a height from the bottom of the column up to the interface.

• The drop in the column water surface due to port sampling was not recorded so no adjustment of the port sample heights was possible. But this is a minor adjustment which is optional, and does not significantly affect the test results.

Data Analysis for Zone Settling

Since the slurry for the Fountain Lake sediment exhibited an interface in the initial hours of the test, zone settling of the slurry mass occurred, and measurements of interface height versus time were collected from the start of the test through a time period of 15 days. The zone settling results for the Fountain Lake sediment are shown plotted in the attached Figure 1. The zone settling data correspond to the initial portion of the interface vs. height data, usually that recorded during the first day of the test. The slope of the initial portion of the curve is the zone settling velocity, with the result for Fountain Lake sediments at 0.42 ft/hr. This settling velocity is an expression of the rate at which a clarified supernatant water depth is produced by the process of zone settling. The filling rate of slurry due to dredging over the area of the containment must be less than the settling velocity to allow the clarified ponded water depth to be maintained. This process is evaluated by calculating either a minimum required ponded surface area in the containment for a given inflow rate, or, a maximum allowable flowrate for a given surface area available for ponding.

The minimum required ponded surface area for the maximum dredged size useable for the site (corresponding to an 18 inch dredge size with inflow rate of 26.5 cfs) was computed using procedures in Section 4-3 of EM 1110-2-5027 (see attached computation sheets). The required ponded surface area was 5.2 acres for an 18 inch dredge. This area was increased to 14.4 acres by applying a Hydraulic Efficiency Correction Factor (HECF) of 2.77, considering the hydraulic efficiency of the basin (see attached computation sheets). These results indicate that the available surface area in the Fountain Lake West Cell is more than adequate for effective zone settling for dredge sizes even larger than an 18 inch.
Data Analysis for Compression Settling

The compression settling behavior is defined by the latter portion of the interface height versus time data for the time period from day 1 up to the end of the test period of 15 days. The interface heights are converted to equivalent solids concentrations and are plotted as concentration versus time on a log-log plot. Results for the Fountain Lake sediment are shown plotted in the attached Figure 2.

The volume required for a given dredging operation (in this case dredging 300,000 cy in a given year over a 150 day filling period) is computed using the void ratio of the in-situ sediments and the estimated void ratio in the CDF as defined by the compression settling curve solids concentration. Only the fine fraction of the sediments will undergo the volume change, and the sand fraction volume is separately accounted for as the percentage of sand in the in-situ sediments. Additional volumes for ponding depth and freeboard also must be accounted for in determining the total required diked volume. These computations were made for a fill time of 150 days, using the procedures in Section 4-3 in EM 1110-2-5025 (see attached computation sheets). These results indicate that the volume of fine grained silt and clay fraction of the material would be increased (bulked) by a factor of about 1.49 in the CDF during the filling period of 150 days. Considering the sand fraction, which is not bulked, the overall bulking factor for 300,000 cy dredged would be about 1.36, with the total volume occupied in the CDF at the end of filling of about 408,000 cubic yards. The required diked volume for the initial year of dredging must also account for ponding and freeboard. For example, assuming an average ponded depth of 2.0 ft and a freeboard of 3.0 ft over an area of 34.7 acres, an approximate additional 302,000 cy of volume would be required, resulting in a total required diked volume for the first year of dredging of approximately 710,000 cy at the end of the 150 day filling period. Compression settling will continue at the end of the filling period, and the volume occupied by the fine-grained sediment will be reduced by this settling over a period of months.

The entire required diked volume for the full 5 year effort is not a simple multiplier of the volume for the first year. Long term consolidation of the previously placed layers, and drying of the layers between active filling periods will result in additional volume reductions over time.

Data Analysis for Flocculent Setting

Since zone settling occurred for the slurry mass, with an interface forming at the start of the test, flocculent processes occur in the supernatant water above the falling interface. The flocculent settling data consist of TSS determinations for samples taken from the side ports in the column located above the falling interface as settling progresses. Procedures for analysis of these data are found in Section 4-2 of EM1110-2-5027. The concentrations of the port samples are converted to percentages of the initial TSS above the interface for the first port sample, and are plotted as percentages of TSS remaining in suspension versus the water depth of the sampled ports. The percentages of removal for
various ponded water depths can then be graphically determined and used to develop a plot of TSS versus mean retention time for the quiescent conditions in the column test. The flocculant data reduced to a plot of column supernatant TSS versus retention time for a ponding depth of 2 feet (considered the minimum average ponding depth for design) for the Fountain Lake sediments is shown in the attached Figure 3. This plot is for the quiescent conditions in the test column, and an estimate of the TSS in the CDF effluent must account for the flow conditions for the CDF geometry and the potential for resuspension of the sediments by wind and flow conditions within the pond.

It is apparent from Figure 3 that reductions of TSS to low values requires a long retention time in the quiescent column. NRT has indicated that a 30 mg/l TSS concentration was a target value. Clearly, this cannot be met with gravity settling alone. Therefore, an estimate of the effluent TSS was computed for the inflow rate of a 14 inch dredge and geometries of the West Cell using the procedures in Section 4-2 in EM 1110-2-5027 (see attached computation sheets). The flowrate corresponding to a 14 inch dredge (16 cfs), ponded depth of 2 ft, and pond over the full 37.8 acres were assumed. The theoretical retention time for these conditions is approximately 56 hours. This time must be adjusted to account for hydraulic efficiency, so the mean retention time using a HECF of 2.77 is approximately 20 hours. Using Figure 3, the column TSS for a retention of 20 hours is approximately 305 mg/l. This concentration is for the quiescent column, and must be adjusted by a resuspension factor of 1.5, considering the size of the CDF and anticipated minimum ponding depth. The resulting estimated TSS in the effluent is approximately 457 mg/l. A lower TSS can be achieved with increased retention time. In a similar manner, the TSS in effluent was therefore calculated as approximately 390 mg/l with a 4 ft average ponding depth. But this ponding depth may require higher dike heights to allow for the total diked volume during filling, and the improvement is marginal with respect to meeting a low effluent TSS. These effluent TSS estimates are comparable to those commonly seen for freshwater fine grained sediments. Extremely large ponding depths or treatment of the effluent using approaches such as filtration or chemical flocculation would be needed to meet a TSS standard of 30 mg/l.

Also, construction of a spur dike would improve the hydraulic efficiency of the pond geometry and would therefore lower the TSS in effluent for a given ponding depth. Figure 4 shows locations for the inflow point and weir and a proposed location of a spur dike, considering the irregular triangle shape of the West Basin.

**Weir Design Parameters**

The data analyses for solids retention and initial storage volume account for conditions within the CDF. However, the ponded water must be discharged from the CDF over a weir during filling operations in such a manner that the settled solids are not resuspended by the flow velocity at the weir. This requires that the weir has an adequate weir crest length. The required weir crest length for the flow conditions of a 14 inch dredge (16 cfs, assumed ponding depth at the weir of 3 feet, and zone settling conditions was determined by the nomogram in Figure 4-7 of EM 1110-2-5027. The required weir length was 18 feet.
Regarding structural design of the weir, there are many options. A recent improvement in overall weir structural design has been developed by the USACE Jacksonville District (Maglio et al 2014). I would recommend that this design be considered for the Fountain Lake weir.

Summary

- The settling characteristics of the Fountain Lake sediments were comparable to those commonly found for freshwater fine-grained sediments. Zone settling occurred comparatively quickly, and the estimated area of the CDF pond needed to maintain effective zone settling during filling was 14.4 acres, so the Fountain Lake West Cell is more than adequate to maintain effective zone settling.
- The compression settling results indicated that the fine fraction of the sediments would bulk by a factor of approximately 1.49 for a filling period of 150 days. Considering that the sand fraction will not bulk, the overall bulking factor was 1.36.
- The flocculent settling results for the suspended fines in the ponded water indicated that the effluent TSS concentrations would be approximately 457 mg/l, considering a minimum average ponded depth of 2 feet, flow rates for a 14 inch dredge, and resuspension potential for the CDF. This is much higher than the target TSS concentration of 30 mg/l indicated by NRT, therefore deeper ponding depths or treatment of the effluent would be required to reduce TSS.
- A weir crest length of 18 feet is required to allow for discharge of the effluent without resuspension of the settled material near the weir.
- The initial volume requirements during filling do not account for the long-term volume changes that would occur during the full 3 to 5 year timeframe for use of the CDF. Long term consolidation and drying of previously placed layers will result in additional volume reductions.

All the estimates of storage capacity and solids retention are based on the column settling test results coupled with appropriately conservative assumptions for flowrate and site conditions during filling.

References


If there are any questions, please contact me at mike@mikepalermo.com or call at 601-831-5412.

Sincerely,

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Figure 1. Zone Settling Interface Height vs. Time

Figure 2. Compression Settling Test Data for Column Concentration vs. Settling Time
Figure 3. Column Suspended Solids vs. Column Retention Time

Figure 4. Proposed locations for inflow, weir, and spur dike.
Zone Settling

Hydraulic Efficiency Correction Factor using Eq. 4-14 from EM 5027

\[ \frac{T_d}{T_f} = \frac{T_f}{\text{HECF}} = \text{Hydraulic Efficiency} = 0.9 \left[ 1 - \exp \left( -0.2 \frac{T_d}{W} \right) \right] \]

Roughly triangular shape

\[ L = \sim 2000 \text{ ft} \]
\[ W = \sim 1200 \text{ ft} \]

\[ \frac{1}{\text{HECF}} = 0.36 \quad \text{HECF} = 2.77 \]

Zone Settling Velocity = 0.42 ft/sec from Figure 1.

Area for Zone Settling using Eq. 4-5 from EM 5027

\[ A_2 = \frac{Q_i (3600)}{V_s} \quad Q_i = 26.5 \text{ cfs for 18'' dredge} \]

\[ A_2 = \frac{26.5 (360)}{0.42} = 227,143 \text{ ft}^2 = 51.2 \text{ acres} \]

Considering HECF

\[ A_2 (\text{HECF}) = 51.2 \times 2.77 = 141.4 \text{ acres} \]

West Cell = 376.8 acres > 141.4 acres

Therefore adequate to maintain Zone settling.
Compression Settling

Filling time = 150 days for 200,000 cu y

Using Figure 2, for Ks (150) = 75 days average filling time
Concentration in CDF = 350 g/l
Void ratio in CDF e_0 = 6.57

Void ratio of sediment in-c.-cu = 4.07

Using Eq. 4-3 and 4-4a in EN 50276

26.2% sand \( V_s = 200,000 \times 0.263 = 78,700 \text{ cu y} \)

73.7% fines \( V_f = 200,000 \times 0.787 = 221,100 \text{ cu y} \)

Vol. fines in CDF \( V_a = V_f \left[ \frac{e_0 - e_1}{1 + e_1} \right] \)

\[ V_a = 221,100 \left( \frac{6.57 - 4.07}{1 + 4.07} \right) \]

\[ V_a = 221,100 \times (1.49) = 335,971 \text{ cu y} \]

Vol. sand in CDF \( V_s = 78,700 \text{ cu y} \)

\[ V_f = V_s + V_a = 408,399 \text{ cu y} \]

Overall Bulkings = \( \frac{408,399}{200,000} = 2.04 \)
Flocculent Settling

Ponded area = 37.8 acres
Minimum ponded depth = 2 ft

Eq. 4.12 from EM 5027,

\[ A_{dp} = \frac{Q_d}{H_{pd} (12.6)} \]

Conversion:

\[ T = \frac{A_{dp} H_{pd} (12.6)}{Q_d} \]

\[ T = 37.8 \times 2 \times 12.6 = 870 \text{ hours} \]

\[ T_d = \frac{T}{HECF} = 870 / 2.27 = 383 \text{ hours} \]

From Figure 2, TSS = 305 mg/L.

From Table 4.1 of EM 5027,
Resuspension Factor = 1.5 for ponds < 100 acres and depths < 1.5 ft

\[ T_{CEF} = T_{CEF,0} \times \text{REF} \]

\[ = 305 \times 1.5 \]

\[ T_{CEF} = 457 \text{ mg/L with 2 ft avg ponding} \]

Similarly, \[ T_{CEF} = 390 \text{ mg/L with 1 ft avg ponding} \]