Erodibility Characteristics of Cohesive Sediment Deposits in a Large Midwestern Reservoir

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Abstract

In September 2015, researchers from the U.S. Department of Agriculture’s Agricultural Research Service (USDA-ARS) and the U.S. Army Corps of Engineers Kansas City District collected eight six-inch diameter sediment cores from Tuttle Creek Lake, the largest reservoir on tributaries to the Kansas River. At varying depths, these cores were analyzed to determine the critical shear stress, erodibility, Atterberg limits, and bulk density of the reservoir sediment deposits. This paper documents the findings and correlations between sediment parameters and discusses implications for reservoir sediment management. Critical shear stress, erodibility, bulk density, and liquid and plastic limits of the reservoir sediment vary with distance from the dam and with depth below the reservoir bed. There is high erodibility and low critical shear stress closer to the dam. Erodibility of the sediment increases with depth into the deposit. This implies the removal of recently deposited sediments and sediments deposited closer to the dam would require less energy and be less expensive than removing older deposits and deposit farther from the dam.

Introduction

Sediment accumulation in reservoirs is a widespread problem with tremendous societal implications (Annandale 2013). Sediment accumulation replaces water storage needed for many purposes, including water supply, drought mitigation, navigation support, and environmental releases. Sediment accumulation is especially problematic in the Kansas River Basin in the Midwestern United States. Due to sediment accumulation and rising demand, large federal reservoirs will no longer be able to supply water against the design drought by 2057 (KWO 2018). At the same time, the downstream Kansas River is suffering from a lack of turbidity (Shelley et al. 2016).

Tuttle Creek Lake (Figure 1) is the largest reservoir in the Kansas River basin, with an original multi-purpose pool volume of 425,312 ac-ft. From 1963 to 2009, Tuttle Creek Lake lost 168,298 ac-ft of storage volume in the multi-purpose pool, which equates to a 41% loss. The average annual rate of sediment accumulation over this time period was 3,594 ac-ft/yr, which is close to the original design estimate of 4,151 ac-ft/yr. The flood control pool is also experiencing sediment accumulation, but at a much slower rate compared to the total flood control storage volume. The sediment deposits in the multi-purpose pool are 86 to 90% clay, 6 to 10% silt, and 4 to 6% sand with no observable change or gradient with depth (KBS 2013). The trapping
efficiency of the reservoir is 98% (Juracek, 2011). Loss of benefits and costly impacts accrue as sediment deposition continues.

![Map of Tuttle Creek Lake](image)

**Figure 1.** Location of Tuttle Creek Lake (Left). Tuttle Creek Lake (Right).

**Sediment Parameters for Reservoir Sediment Management**

Long-term reservoir sustainability requires the annual removal of sediment at the rate it enters the reservoir. Two methods for removing the sediment are drawdown flushing (more common outside the United States) and hydraulic dredging (more common in the United States). The efficiency of both these methods depends on the sediment properties.

Drawdown flushing includes lowering the reservoir pool completely to allow hydraulic forces to erode and flush out the sediment. The efficacy of this action depends on the erodibility of the sediment deposits. In cohesive sediments, site-specific measurements are needed to estimate the erodibility. The rate of erosion is often approximated by the following equation (Hanson and Cook 1997):

\[ E = k(\tau - \tau_c)^a \]

where

- \( E \) = the rate of erosion [units of volume per time]
- \( \tau \) = the applied shear stress [units of force per area]
- \( \tau_c \) = the critical shear stress, or the shear stress required to initiate motion [units of force per area]
- \( k \) = an erodibility coefficient, also termed the erodibility, which relates excess shear stress to rate of erosion [units of volume per force per time]
Hydraulic dredging also depends on soil properties. The ease with which material can be removed, transported, and deposited via hydraulic dredging methods is known as “dredgeability.” Spigolon (1993) indicates that the dredgeability of a material is related to sediment properties such as bulk density and Atterberg limits (i.e. limits of soil consistency or basic measure of a material’s critical water contents: shrinkage limit, plastic limit, liquid limit). These same erodibility and “dredgeability” properties are also important for other sediment removal methodologies such as hydrosuction and water injection dredging.

**Sampling and Testing**

In September 2015, researchers from the U.S. Department of Agriculture’s Agricultural Research Service (USDA-ARS) and the U.S. Army Corps of Engineers Kansas City District collected eight six-inch diameter sediment cores from Tuttle Creek Lake for purposes of determining the critical shear stress, erodibility, Atterberg limits, and bulk density of the reservoir sediment deposits. Sampling was accomplished by vibracoring a 10-ft long, 6-in diameter steel tube into the reservoir bottom. As the sample could slide from the pipe while the pipe was being extracted from the reservoir bottom, actual core thickness ranged from 62 to 110 inches. Figure 2 maps the sampling locations.

**Figure 2.** Sampling Locations
Following sample collection, USDA-ARS segmented the cores into 23, 6-in samples for jet erosion testing, 11, 3-in samples for Atterberg Limits, and 40, 2-in samples for bulk density testing. The protocol allows the assessment of both longitudinal and vertical variations in sediment parameters. The jet erosion testing was accomplished with a laboratory jet erosion tester (Hanson and Cook, 2004; see Figure 3). The test continued with a constant head until sufficient points were generated to define the curve, which due to differences in erodibility ranged from 2 to 129 minutes. In all cases, the final scour was similar (around 0.23 to 0.34 ft). The Blaisdell solution method was used to compute erodibility parameters (Blaisdell et al., 1981).

![Laboratory Jet Erosion Tester (Left). Core 8 after testing (Right).](image)

**Figure 3.** Laboratory Jet Erosion Tester (Left). Core 8 after testing (Right).

### Results and Relationships

The results of erodibility and critical shear stress for the eight cores are presented in Table 1. The erodibility data showed a general trend with depth and with distance from the dam. Deeper (older) deposits are markedly less erodible than the highest (newest) deposits. Fresh deposits have not had time to consolidate. Likewise, deposits further upstream are markedly less erodible than the deposits further downstream. This may be a function of grain size differences; finer grains transport further into a reservoir than coarser grains. However, Cores 7 and 8 did not sample the coarse-grained delta, the sample texture still suggested predominantly clay and silt, though no grain size analysis was conducted.

The critical shear stress results also indicated a trend with depth, with deeper deposits generally having higher critical shear. This effect is not nearly as pronounced as the change in erodibility. Unlike the erodibility, the critical shear stress does not vary with distance from the dam. Moreover, the cores sampled from the historic channel have higher erodibility and lower critical shear stress compared to adjacent cores in the historic floodplain.

The deepest two samples in Core 2 do not follow the overall trends with depth—they have greater erodibility and lower critical shear stress than several of the overlying samples. The data are insufficient to conclude whether this was a different type of sediment at this depth or error in sampling/testing.
Table 1. Erodibility (left) and critical shear stress (right) of reservoir sediment deposits with depth. Red = most erodible/lowest critical shear. Green = least erodible/highest critical shear.

<table>
<thead>
<tr>
<th>Depth (in)</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>Depth (in)</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
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<td>143</td>
<td>311</td>
<td>116</td>
<td>45</td>
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<td>42</td>
<td>18</td>
<td>3</td>
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<td>0.2</td>
<td>0.1</td>
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<td>0.3</td>
<td>0.3</td>
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<td>13</td>
<td>42</td>
<td>6</td>
<td>16</td>
<td>9</td>
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<td>0.6</td>
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<td>0.3</td>
<td>1.6</td>
<td>0.5</td>
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<td>24</td>
<td>24</td>
<td>15</td>
<td>17</td>
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<td>7</td>
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<td>67</td>
<td>10</td>
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<td>6</td>
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<td>1.6</td>
<td>1.5</td>
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<tr>
<td>90</td>
<td>44</td>
<td>26</td>
<td>-</td>
<td>6</td>
<td>-</td>
<td>26</td>
<td>-</td>
<td>-</td>
<td>90</td>
<td>0.2</td>
<td>0.2</td>
<td>1.5</td>
<td>0.3</td>
<td>0.3</td>
<td>1.8</td>
<td>1.1</td>
<td>-</td>
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</table>

The results of dry bulk density of the samples are presented in Table 2. The bulk density increases slightly with depth, but much more significantly with distance from the dam. This is likely due to coarser sediments depositing further upstream in the reservoir.
Table 2. Dry bulk density of reservoir sediment deposits with depth. Red = lowest bulk density. Green = highest bulk density.

<table>
<thead>
<tr>
<th>Depth (in)</th>
<th>Core #1</th>
<th>Core #2</th>
<th>Core #3</th>
<th>Core #4</th>
<th>Core #5</th>
<th>Core #6</th>
<th>Core #7</th>
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<td>0.41</td>
<td>0.44</td>
<td>0.87</td>
<td>1.04</td>
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<tr>
<td></td>
<td>0.37</td>
<td>0.40</td>
<td>0.46</td>
<td>0.48</td>
<td>1.06</td>
<td>0.74</td>
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<tr>
<td>23</td>
<td>0.36</td>
<td>0.36</td>
<td>0.40</td>
<td>0.46</td>
<td>0.48</td>
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<tr>
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<td>0.48</td>
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<td></td>
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<td>0.47</td>
<td>0.47</td>
<td>0.52</td>
<td>0.49</td>
<td>1.21</td>
<td>1.16</td>
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<td>67</td>
<td>0.45</td>
<td>0.51</td>
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</table>

The results of Atterberg Limits (Liquid Limit and Plastic Limit) are presented in Table 3. The Atterberg Limits were only determined for Cores 1, 2, 3, 6, and 8. There appears to be a decrease in both the Liquid Limit and Plastic Limit with distance from the dam. Changes with depth are harder to generalize.
Table 3. Atterberg Limits. Liquid Limit (Left) and Plastic Limit (Right). Red = highest limit. Green = lowest limit.

Figure 4 illustrates the relationship between critical shear stress and erodibility. As expected, increasing critical shear correlates with decreased erodibility. Bulk density vs. erodibility for segments containing both tests is plotted in Figure 5. For Cores 1 – 6, which consist mostly of clays and silts, the erodibility drops over a very small range in bulk density. The results of bulk density versus erodibility for Cores 7 – 8 suggest that more sand may have been present, even though visual inspection of the samples indicated they were still predominantly fines.
Figure 4. Relationship between Critical Shear Stress and Erodibility

Figure 5. Relationship between Bulk Density and Erodibility

Figure 6 illustrates that the erodibility significantly decreases further upstream compared to closer to the dam. This effect is especially pronounced for the top-most sample in each core (indicated by red dots in Figure 6). Figure 7 displays erodibility as a function of depth. As seen,
the erodibility decreases significantly in the deeper deposits. The two deepest samples, both from Core #2, have relatively high erodibility. As mentioned before, they also have surprisingly low critical shear.

**Figure 6.** Relationship between Distance from Dam and Erodibility. Red = the top-most sample in each core.

**Figure 7.** Relationship between Depth and Erodibility
Conclusion and Implications for Management

The results of jet erosion testing of 32 samples from 8 sediment cores in Tuttle Creek Lake indicated that the erodibility ranged from 1 to 316 (cm$^3$/N-s). The two major factors influencing the critical shear stress, erodibility, bulk density, and liquid and plastic limits of the material are distance from the dam and depth below the reservoir bed. These findings carry important implications for sediment management at Tuttle Creek Lake.

First, sediment characteristics are highly favorable for erosion (high erodibility and low critical shear stress) close to the dam. This is encouraging, as lower-cost sediment management options target sediments close to the dam for movement through or over the dam.

Second, the erodibility of the material increases with depth into the sediment deposit. This implies that significantly more energy would be required to remove sediment if left to consolidate, versus removal soon after it deposits. The longer it sits, the harder it is to remove.

The variability and trends in this reservoir underscore the need for sufficient sampling and testing of reservoir sediment deposits at other reservoirs where sediment management actions are being considered.

References


Hanson, G.J. and Cook, K.R. 2004. Apparatus, testing procedures, and analytical methods to measure soil erodibility in situ. ASABE Applied Engineering in Agriculture. 20(4), 455-462.


