

Determination of Erosion Parameters of Coarse- Grained Materials Using a Small Flume

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Abstract

Overtopping is one of the major causes of dams and levees failure. There is uncertainty in estimation of the erosion parameters especially for coarse- grained materials that comprise the outer shell layer of dams as well as homogeneous levees that are constructed of such materials. In this paper, results from a box test performed on three coarse grained materials in a 0.3-meter wide flume are discussed. The three materials share the same median grain size D_{50} of 2 mm, however, they vary in fines content between zero to 20%. The box measured 0.3 m wide x 0.6 m long x 0.15 m deep. Each of the three materials was compacted in the box at near optimum moisture content and dry density as determined from standard Proctor test. Each material was tested at varying hydraulic loadings to determine the erosion rate after equal time intervals. The water depth and velocity were measured at each hydraulic loading using Pitot tubes and the acting bed shear was calculated. The effect of fines content and level of acting shear stresses is discussed in the paper.

1 Introduction

For flood risk assessment of both dams and levees, the earthen structures are assumed to breach when they are overtopped. However, for a more accurate assessment and to estimate a realistic time and width of breach, more understanding of the erosion rate and mechanism is needed especially for coarse-grained (typically non-cohesive) sand and gravel materials. For coarse-grained materials, the response of the particles to the hydraulic loading is mainly affected by the size, shape, and density of particles, while for the finer cohesive materials the response is affected by the cohesive bonding of the particles. The response of a mix of the two types of soils is governed by the relative fractions of the cohesive and non-cohesive particles.

The paper presents the results from soil erosion testing performed in a small flume on three compacted soil mixes. The soil mixes were sand with varying contents of fines and clay compacted in a box that was placed within the flume. Four box samples were tested for each soil mix, each at a different flow level where the water depth and velocity measurements were taken at

different stations along the flume and on top of the box. Water depth, velocity and bed shear were calculated using a discrete form of energy equation (Hughes, 2017)

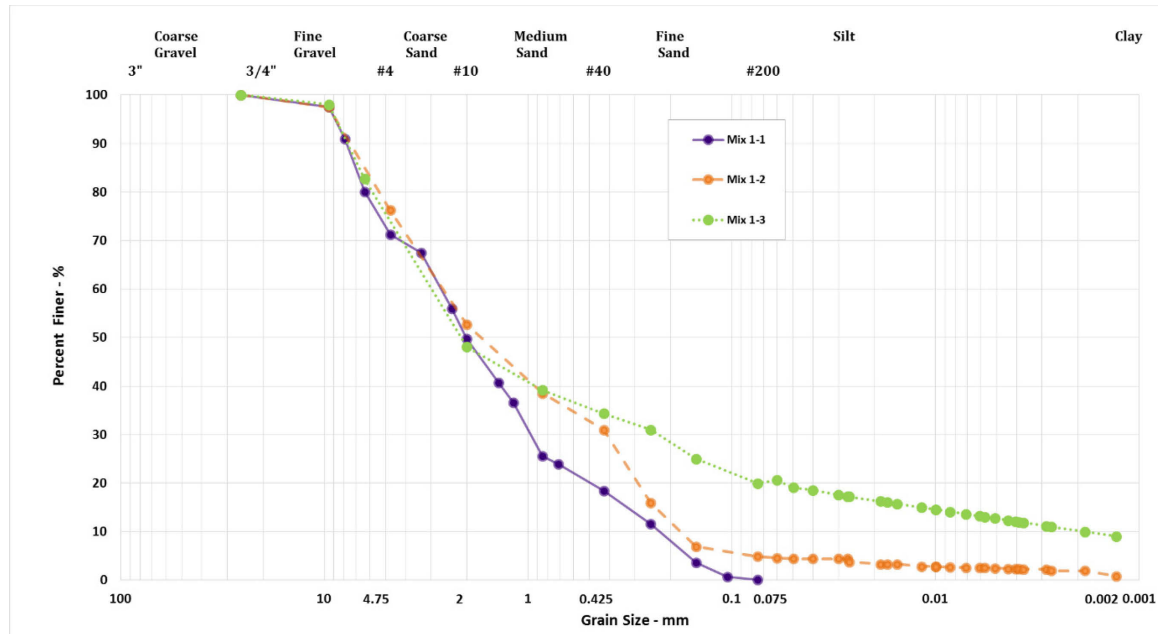
2 Material properties

Grain Size. The study was performed on three sand mixes that maintain a D_{50} of about 2 mm. Sands of different grains size distributions, pea gravel, silt, and kaolin clay materials were mixed in different portions to produce the three mixes. Figure 1 shows the grain size distribution of the three mixes 1-1, 1-2, and 1-3. For mixes 1-2, and 1-3, the addition of the silt and clay increased the fines content to about 5 and 20 percent and about 2 to 10 percent clay fraction ($<2 \mu\text{m}$), respectively. The gravel content in the three mixes varied between 23% and 30%. The uniformity coefficient: $C_u = D_{60}/D_{10}$, for the three mixes were greater than 6, however, only mix 1-1 has a curvature coefficient; $C_c = (D_{30}/D_{10}) \times (D_{60}/D_{30})$, that is between 1 and 3, indicating that only mix 1-1 is considered well graded material. In mixes 1-2 and 1-3, the plasticity index (PI) for the fraction passing sieve #40 was measured at 8% with a liq-

uid limit LL of 30%, and a plastic limit PL of 22%. Based on the above, mixes 1-1, 1-2, and 1-3 could be classified according to the unified soil classification

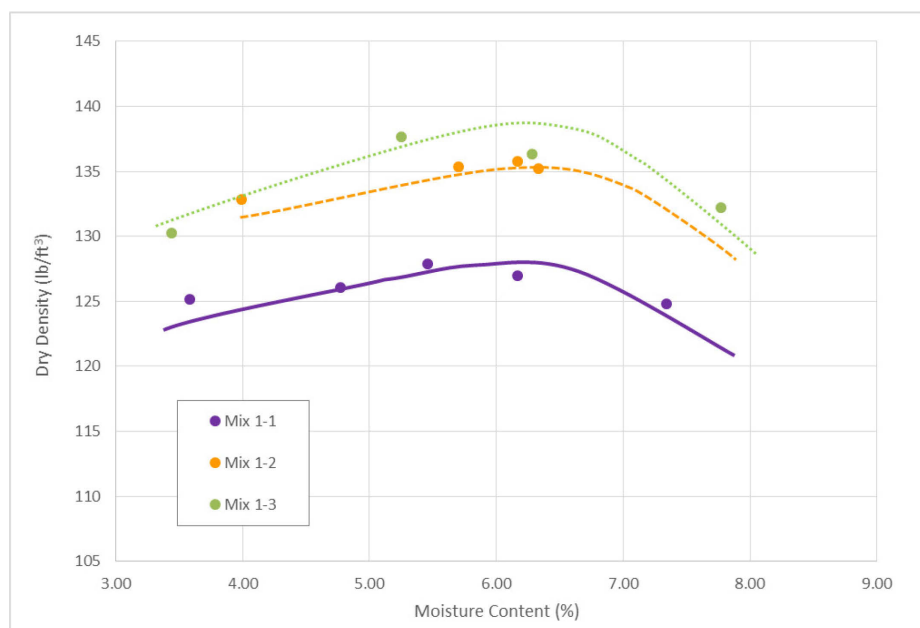
system (USCS) as well graded sand (SW), well graded sand-silty sand (SW-SM), and clayey sand (SC), respectively.

Figure 1. Grain size distribution for soil mixes 1-1, 1-2, and 1-3



Density. To prepare the three mixes, compaction was performed according to the standard Proctor test (ASTM D698-12) as shown in Figure 2. The dry density of the mixes increased with the fines content, however, the optimum water content remained within a narrow range between 6 and 7 percent. For evaluation of erosion, density conditions were selected near optimum as follows: water content; $w_c = 6\%$, 7% , 7% , and dry density; $\gamma_d = 127$ pcf, 135 pcf, and 137 pcf for mixes 1-1, 1-2, and 1-3, respectively.

Figure 2. Compaction curves for soil mixes 1,2 ,3 and 4 using Standard Proctor (ASTM D-698).



Jet Erosion Test. The laboratory Jet Erosion Test (JET) was performed on compacted samples of the three mixes. The JET was performed according to ASTM Standard D-5852-07 with some modification suggested by Hanson (2001) regarding the data processing procedure. The critical shear stress, τ_c was determined to be 1.42, 0.589, and 1.08 Pa, and the Erodibility Coefficient k_d to be 105.6, 143.2, and 8.9 cm³/N-s for mixes 1-1, 1-2, and 1-3, respectively. All the three soil mixtures are categorized as “Very Erodible” material according to Hanson and Simon’s classification.

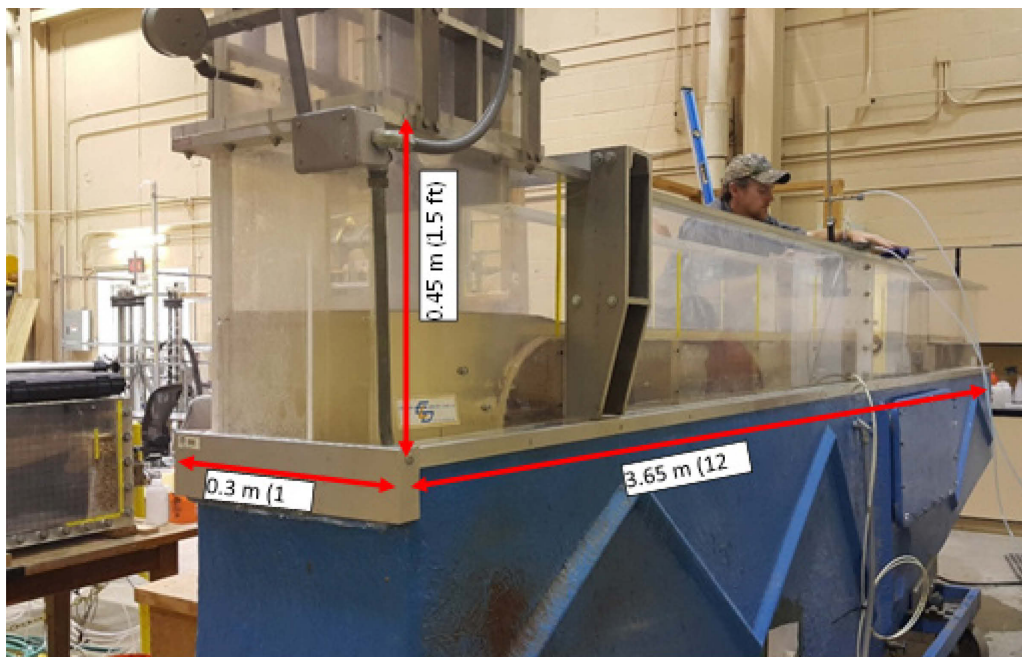
3 Small flume testing

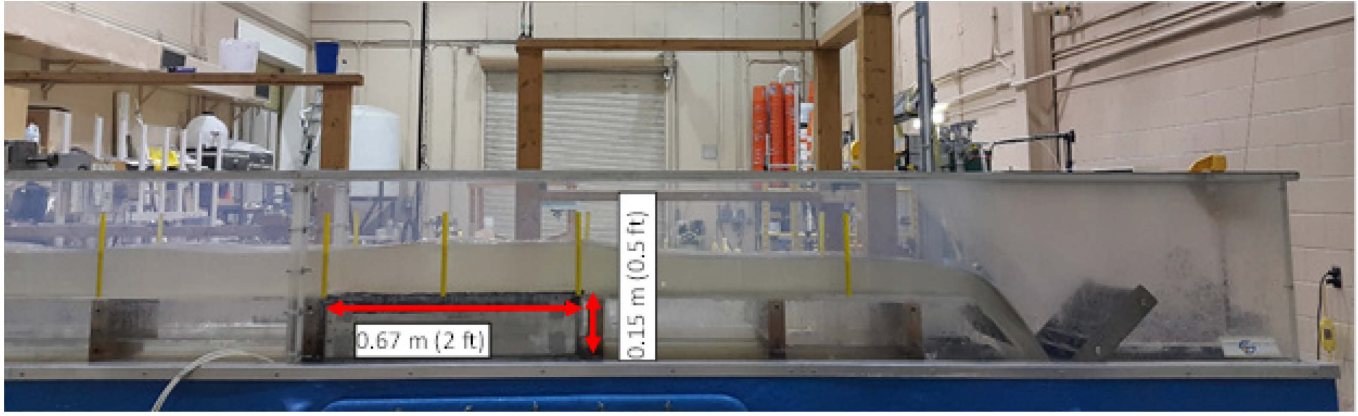
As shown in Figure 3.a, the small flume that was used in this study measured about 3.65 m (12 feet) in length, 0.33 m (1 foot) in width and 0.45 m (1.5 feet) in height. The sides of the flume were made from 12 mm (0.5 inch) thick plexiglass. The flow was enabled through a pump that circulates water from an underneath storage tank. The pump could be adjusted to give varying flow levels, and the flume bed could be tilted up to 10% (about 5 degrees) to achieve higher velocities at the same flow level. The box model (Figure 3.b) measures 0.33 m (1 foot) wide x 0.67 m (2 feet) long x 0.15 m (0.5 foot) high. The box was constructed from 6-mm

(0.25 inch) thick aluminum plates. The soil sample was compacted in the box in three lifts, with calculated volume and weight to match the corresponding density and water content for each mix as discussed above. The box was then inserted into a fitted space within the flume where it was epoxied overnight.

Before the test was started, the pump was adjusted to a selected flow level, and the flume bed to a tilting angle. The flow continued in each test for a duration of about 20 to 40 minutes after which sample erosion reached an almost equilibrium condition where the erosion progress stopped or very slow erosion occurred. The velocity was measured using a Pitot tube using the difference between the total and static head, and the water depth equaled static head. These measurements were taken at different locations along the flume as well as on top of the box. Manual readings using caliber and flow meter were taken as well. It was noticed that the continuous erosion of the soil in the box tended to cause the formation of a hydraulic jump and alter the hydraulic loading on top, upstream and downstream of the box.

Figure 3. Small Flume: a. Flume Dimensions, b. Test Box Dimensions





A solution for the energy equation in the form of a first-order ordinary differential equation (Hughes, 2017) was used to check these measurements assuming a Manning's n value. Equations 1, 2 and 3 show the solution for the water depth, velocity and shear stress, respectively. The calculations for the initial water depth and velocity used the unique relationship between the unit flow rate and the critical water depth. The bed shear was then calculated using a discrete form of the momentum equation (Hughes, 2017). After the test was stopped, the soil surface in the box was mapped using point gage measurements on a one-inch scale along the location where the maximum erosion occurred.

$$\frac{dy}{dx} = \frac{S - \left(\frac{n}{ku}\right)^2 \frac{q^2}{(y \cos \theta)^{10/3}}}{\cos^2 \theta - \frac{\alpha q^2}{g y^3 \cos^2 \theta}} \quad (1)$$

where, y = vertical flow depth [L], x = horizontal position [L], θ = angle of bed relative to horizontal [radians], S = bed slope (defined as $S = \tan \theta$) [-], n = Gauckler-Manning friction coefficient [$\text{s/m}^{1/3}$], ku = units conversion factor ($ku = 1$ for SI units, $ku = 1.486$ for English units), q = discharge per unit width [L^2/T], g = gravitational acceleration [L/T^2], α = velocity coefficient (normally taken equal to unity) [-].

$$v = \frac{q}{y \cos \theta} \quad (2)$$

where, v = mean flow velocity [L/T]

$$\tau_o = \frac{\gamma}{2} (y_1 + y_2) \cos \theta \sin \theta + \frac{\gamma \cos^4 \theta}{2 \Delta x} (y_1^2 - y_2^2) + \frac{\gamma q^2}{g \Delta x} \left(\frac{1}{y_1} - \frac{1}{y_2} \right) \quad (3)$$

where, y_1, y_2 = vertical flow depth at locations 1 and 2 [L], Δx = horizontal distance between locations 1 and 2 [L], γ = specific weight of water [F/L^3].

4 Results and discussion

An average Manning's n value of 0.024 was selected to match the measured velocity and water depth to the energy equation solution described above. That was performed for all the twelve conducted tests (three mixes and four hydraulic loadings each). A judgement call was used when discrepancies appeared between measured and calculated values. It was noticed that the velocity measurements were in general closer to the expected trend than the water depth. That could be attributed to uncertainty in the static head measured by the Pitot tube. Figure 4 shows an example of the measurements and the calculated curves for water depth, velocity and bed shear for a test conducted on mix 1-3 at a flow rate of about $0.1 \text{ m}^3/\text{sec}/\text{m}$ ($1.0 \text{ cfs}/\text{ft}$) and a slope of 8 percent.

Figure 5.a and 5.b show the calculated average bed shear along the box for each of the twelve tests versus the maximum erosion depth and erosion rate, respectively. Erosion rate was calculated by dividing the maximum erosion depth as measured after the stop of the test by the test duration. It should be noted that the measured erosion was observed to be uniform in some cases where the acting bed shear was small, however, as the flow rate increased or the flume bed was tilted resulting in a higher velocity and higher bed shear, the profile of the erosion became concentrated in some areas. Figure 6 shows the erosion profile of the test on mix 1-3 presented in Figure 4.

Figure 4. Energy equation comparison with measured data points a) water depth, b) velocity, c) bed shear

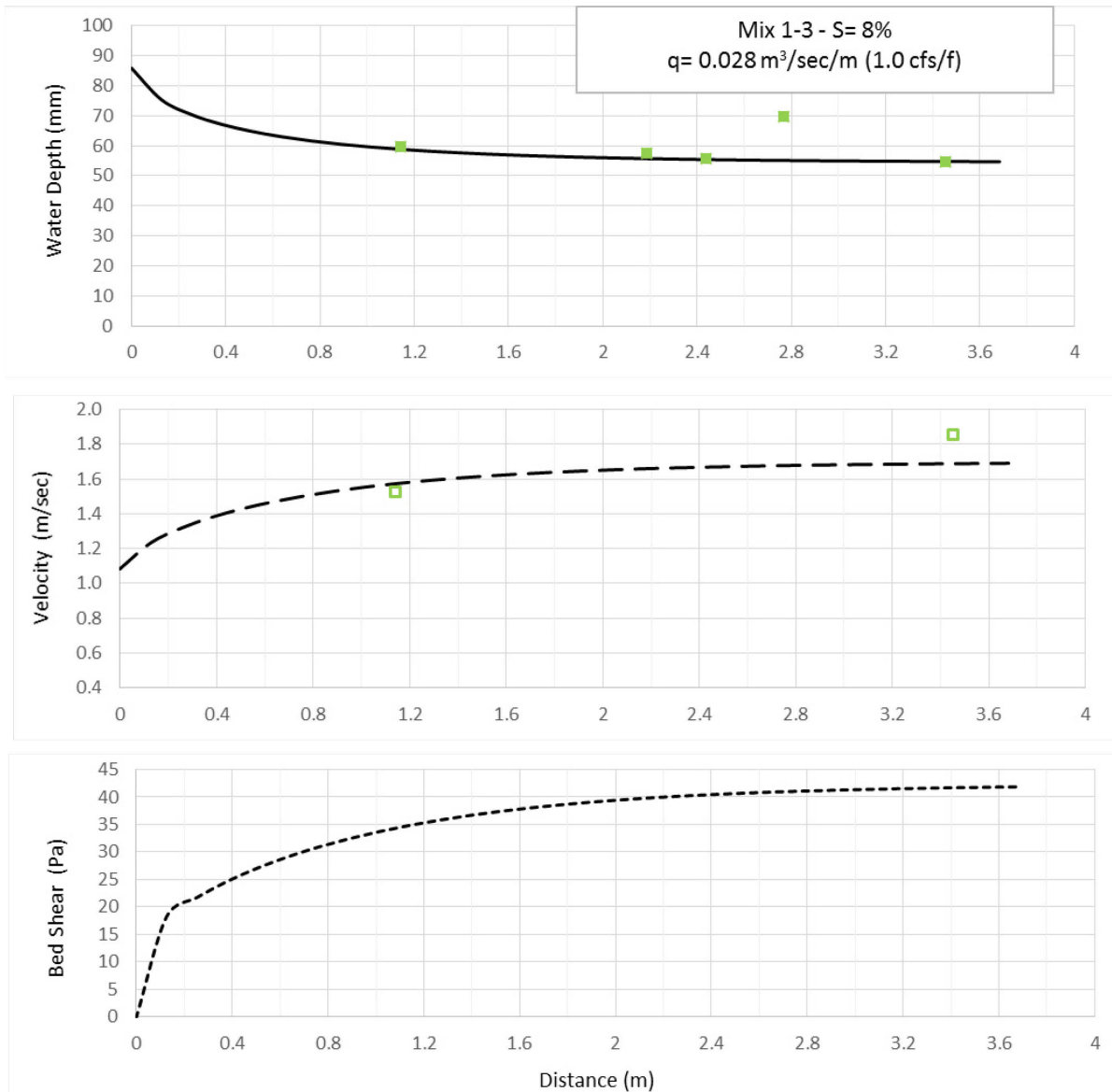
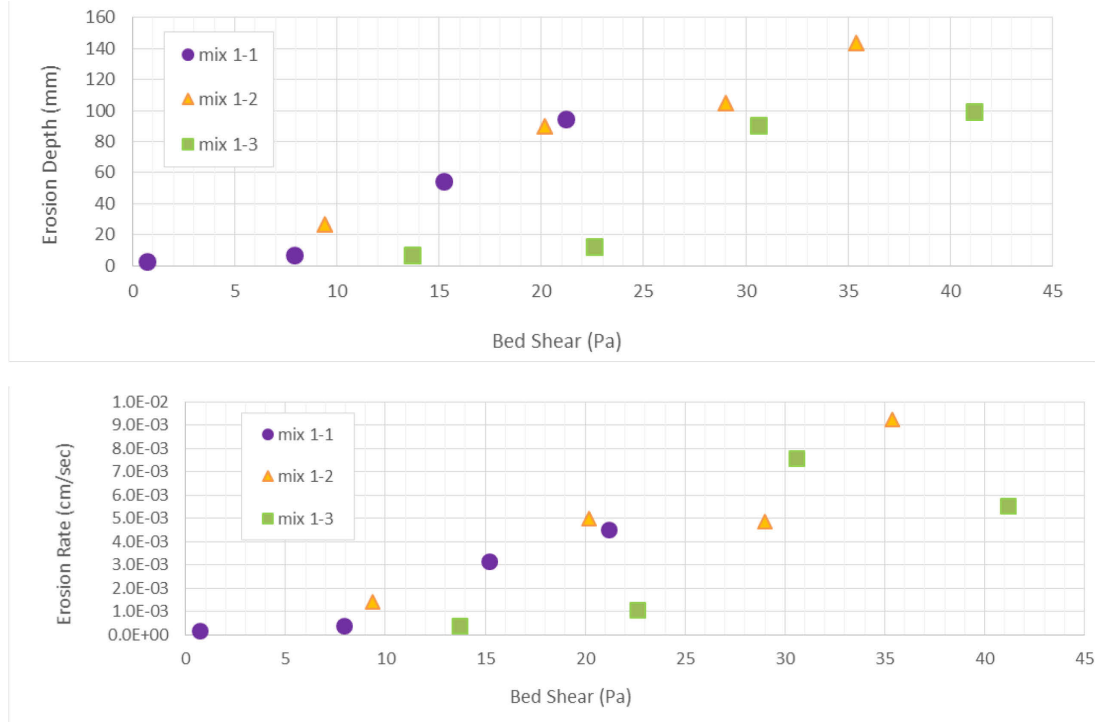
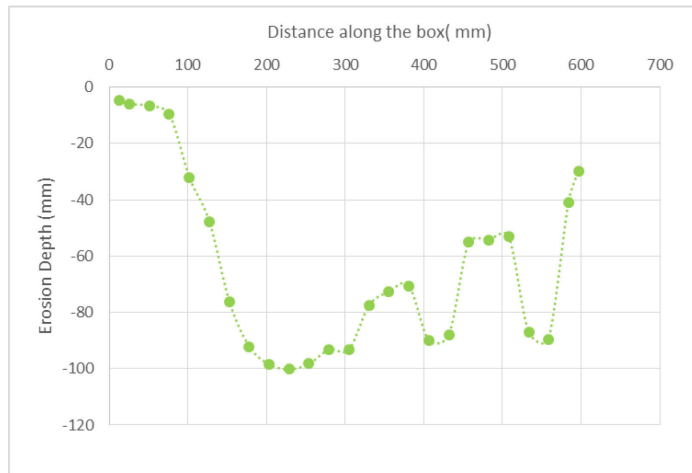


Figure 5 indicates that, in general, the presence of fines and clay in the sand mixes resulted in an increase in the critical shear τ_c and decrease in the erodibility coefficient k_d as a trend line passing all the data points for each mix as shown in Figure 5. However, it could be noticed that the rate of erosion is not uniform throughout the acting bed shear levels. This indicates that a bi-linear or nonlinear relationship between erosion rate and acting shear stress could be more representative of

the erosion of coarse-grained materials. The critical shear stress, τ_c , and erodibility coefficient, k_d as measured by the JET are conservative compared to the results shown in Figure 5. The Same conclusions were shown in Ellithy et al 2017, and it was noted that the perpendicular jet could change the hydrodynamics acting on the soil especially with coarser particle sizes.

Figure 5. Acting bed shear versus a. maximum erosion depth, b. erosion rate

Figure 6. Erosion profile, mix 1-3, $q = 0.0283 \text{ m}^3/\text{sec}/\text{m}$, slope 8%

5 Summary and conclusions

This paper presents the results of twelve box erosion tests conducted on sand samples in a 0.33-m wide flume. The box measures 0.3 m wide x 0.6 m long x 0.15 m deep. The sand samples consisted of three mixes that have a median grain size D_{50} of about 2 mm with varying fines content of zero, 5 percent, and 20 percent, and clay content of zero, 2 percent and 10 percent, respectively. The samples were compacted in the box near optimum water content and density as determined from standard Proctor test. The erodibility of the soil mixes were initially measured using the JET, and

followed by the box tests where the erosion rate was calculated by dividing the maximum erosion depth by the duration of the test. The acting bed shear stress was calculated using a discrete form of the momentum equation (Hughes, 2017) after matching the calculated water depth and velocity with a measured data point. The JET measurements in general overestimated the degree of erodibility of all three sand mixes. The small flume box tests showed that the presence of fines and clay in the sand mixes increased the critical shear stress and decreased (slowed down) the erosion process of the mixes. The results showed that the erosion rate is

not constant throughout the applied shear stresses, indicating that a bilinear or nonlinear relationship could be more representative of the erosion of coarse-grained materials.

References

- ASTM. (2012). "Standard test method for Laboratory Characteristics of Soil Using Standard Effort (12,400 ft-lbf/ft³ (600 kN-m/m³)." American Society for Testing and Materials Standard Designation D 698-12, West Conshohocken, PA.
- ASTM. (2007). "Standard test method for erodibility determination of soil in the field or in the laboratory by the Jet Index method." American Society for Testing and Materials Standard Designation D 5852-07, West Conshohocken, PA.
- Ellithy, G.S., Savant, G., Wibowo, J.L. 2017. "Effect of Soil Mix on Overtopping Erosion", *ASCE EWRI*, Sacramento, CA 21-25 May.
- Hanson, G.J., and Simon, A. (2001). "Erodibility of cohesive streambeds in the loess area of the Midwestern, USA". *Hydrological Processes*, p 23-38.
- Hanson, G.J., Robinson, K.M., and Cook, K.R. (2001). "Prediction of headcut migration using a deterministic approach," *Transaction of the ASAE*, 44(3), 525-531.
- Hughes, S.A. (2017). "Review of Proposed Physical Model to Evaluate Overtopping Erosion of Coarse-grained Materials". Report prepared for ERDC, water resources infrastructure technical program.
- May, J.H. (1989). "Geotechnical Aspect of Rock Erosion in Emergency Spillway Channels." Report 4; Geologic and Hydrodynamics Controls on the Mechanics of Knick-point Migration. Technical Report REMR-GT-3. Corps of Engineers, Waterways Experiment Station, Vicksburg, MS.
- van Rijn, L.C. (1984). "Sediment pick-up functions." *Journal of Hydraulic Engineering* 110(10), 1494-1502.
- van Rijn, L.C. (1993). "Principle of sediment transport in rivers, estuaries, coastal seas." Aqua Publications, Amsterdam, The Netherlands.
- Visser, P.J., Ribberink, J.S., and Kalkwijk, J.P.Th. (1986). "Development of the breach and flow discharge in a dike-burst". Rep. 8-86, Hydraulic and Geotechnical Eng. Div., Dept. Civ. Eng., Delft Univ. Tehn., Delft, The Netherlands.
- Yalin, M.S. (1977). "Mechanics of sediment transport". Pergamon Press, Oxford, England.