COHERENCE OF ERODIBILITY FOR EROSION PROCESSES AND DIFFERENT SCALES

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Abstract Erosion is one of the least reliably defined elements of many hydraulic projects. Earthen embankments (i.e. dams and levees) are an example of hydraulic projects for which erosion and erodibility have not been reliably defined in the past. Characterizing material erodibility is one of the essential requirements for predicting erosion of earthen embankments. The jet erosion test (JET) is a test method that has been developed for the purpose of characterizing erodibility of soils materials in both the laboratory and field. This paper provides a comparison of erodibility measurements based on JET results and erodibility based on large scale flume and embankment tests. The purpose of this paper is to compare the coherence of erodibility characterization at the JET scale with large scale test results. Coherence of erodibility measurement at the different scales is essential for predicting erodibility of earthen embankments.

INTRODUCTION

Floodwaters overtopping dam embankments are one of the main causes of failure (Wan and Fell 2004). The study of 18 historical cases of embankment dam failures by Walder and O'Connor (1997) provides some insight into the rate of embankment erosion. The mean vertical erosion rate parameter (*k*) that they used for overtopping was based on dam height divided by breach formation time. The *k* value in the 18 historical cases was determined to range from 1 to 1000 m/h. The study conducted by Walder and O'Connor (1997) was significant because it pointed out the importance of the rate of failure in determining the peak discharge but the shortcoming of the *k* parameter as defined by Walder and O'Conner is that it does not separate material property effects from geometry or hydraulic effects. In order for future modeling to address the appropriate rates, it is necessary to provide algorithms appropriate for the key erosion processes that include rate parameters that separate material property effects from geometry and hydraulic effects.

The erosion processes during flood overtopping and the rate of erosion are dependent on the hydraulic stresses that occur and the erosion resistance characteristics of the compacted embankment soil material. The excess stress equation, which is commonly used to characterize the erodibility of soil materials (Hutchinson, 1972; Foster et al., 1977; Dillaha and Beasley, 1983; Temple, 1985; Hanson, 1989; Stein and Nett, 1997; Wan and Fell, 2004) relates hydraulic stress and erosion resistance parameters to predicted erosion rates.

$$E_r = k_d(\tau_e - \tau_c) \tag{1}$$

where E_r = the erosion rate, k_d = a detachment rate/erodibility coefficient, τ_e = the hydraulically applied boundary stress, and τ_c = the critical stress required to initiate detachment for the material,

The excess stress equation has been a basis for development of key erosion process algorithms related to several aspects of embankment erosion including embankment breach widening (Hunt et al. 2005), headcut jet impingement scour (Hanson et al. 2002), and headcut migration (Hanson et al. 2001).

The embankment breach widening algorithm used by Hunt et al. (2005) used the excess stress equation directly for predicting breach widening.

$$\frac{dW}{dt} = 2k_d(\tau_e - \tau_c) \tag{2}$$

Where W = breach width.

The equation includes a factor of 2 to account for both sides of the breach widening. Measurement of the soil parameters, k_d and τ_c, from the excess stress equation is essential to predicting the rate of erosion processes in

earthen embankments. The jet erosion test (JET) (Hanson and Cook, 2004) is a method of measurement that has recently been developed to characterize erosion resistance of earthen embankment materials. One of the questions that must be addressed in the use of the JET or any other measurement method is whether the measurements at the smaller scale are coherent with the erosion resistance at the larger scale erosion processes observed during overtopping failure and breach of an earthen embankment. Hanson and Hunt (2007) conducted a comparison study of coherence of scales for breach widening erodibility, and laboratory scale JET erodibility measurements. The results from the study showed that small scale laboratory JET testing could be used to characterize materials and compaction specifications for embankment breach widening. Two soil materials, referred to as Soil 2 and Soil 3, were tested by Hanson and Hunt (2007). Soil 2 was a non-plastic SM silty-sand material with 6% clay and Soil 3 was a plastic CL-lean clay with 26% clay. Samples were compacted in the laboratory at three compaction efforts over a range of compaction water contents and k_d measurements were compared (Figure 1a and 1b). They observed that soil texture has an important influence on erodibility but compaction water content and compaction energy are also important factors. Hanson and Hunt compared the erodibility results from three field embankment breach tests to the laboratory JET tests results for samples prepared at standard compaction efforts (Figure 2a and 2b). The results provided confirmation that the JET test measurements are coherent with the erodibility determined for the large scale breach widening erosion process.

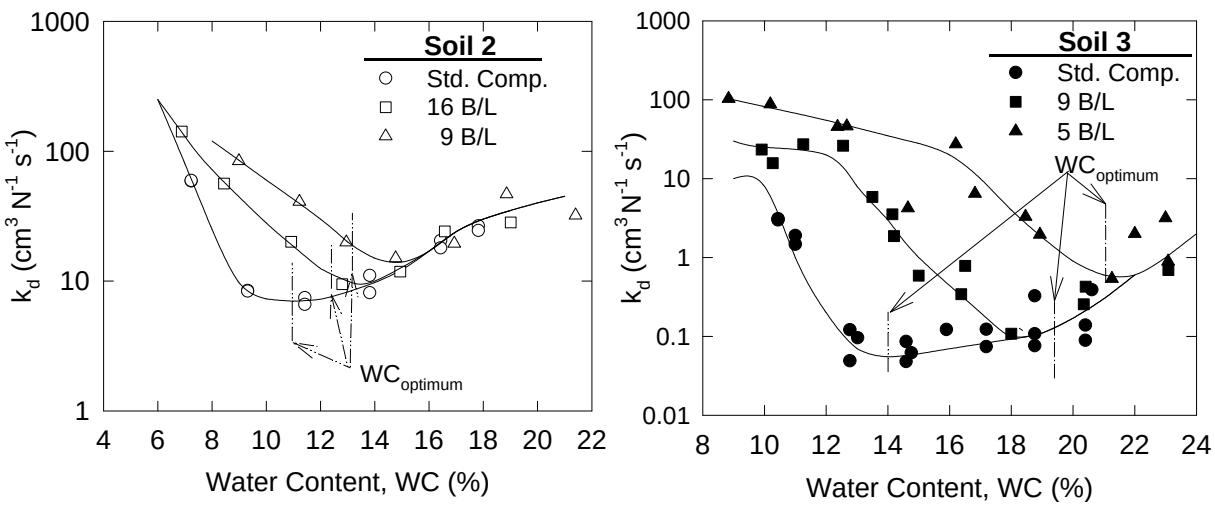

Figure 1 Relationship of the erodibility coefficient to changes in compaction effort and compaction water content for a) Soil 2 and b) Soil 3 (Hanson and Hunt, 2007).

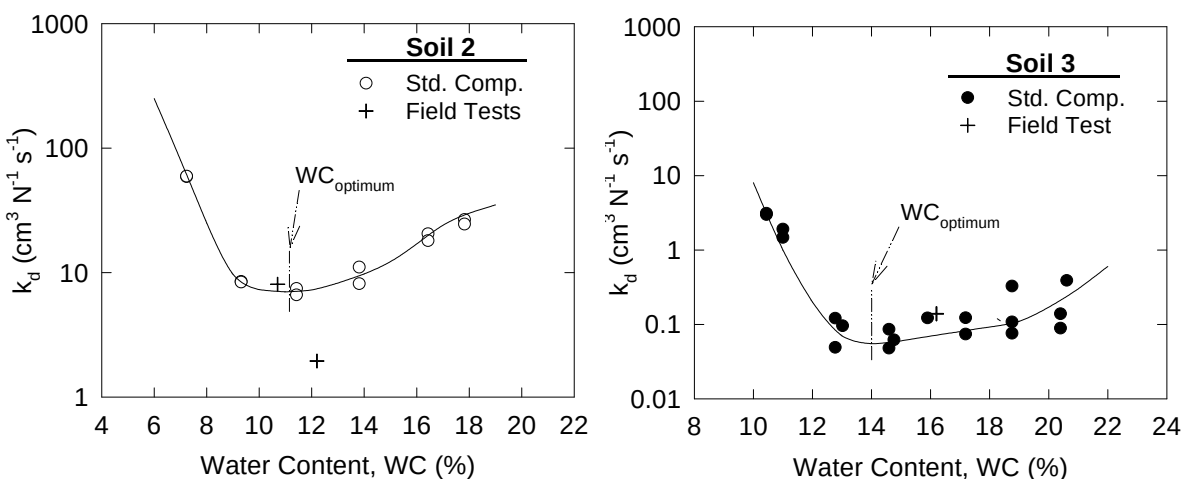

Figure 2 Coherence of JET erodibility coefficient, k_d measurements and embankment breach widening field test results for a) Soil 2 and b) Soil 3 (Hunt and Hanson, 2007).

The headcut jet impingement scour (Hanson et al. 2002), and headcut migration (Hanson et al. 2001) studies not only included use of the excess stress equation in predicting erosion but also included large scale erosion process flume testing and small scale JET measurements. One soil material was the same in both studies and several of the tests were placed with similar field compaction effort. The results from these two studies along with a series of laboratory studies on this same material provide an opportunity for determining the coherence of two additional large scale erosion processes and small scale laboratory JET measurements. Therefore, the purpose of this paper is to take a similar approach as described by Hanson and Hunt (2007) and determine the coherence of large scale test results and laboratory JET results for two additional erosion processes; 1) headcut impingement scour, and 2) headcut migration.

BACKGROUND

Erosion Algorithms **Jet impingement Scour** The headcut jet impingement scour algorithm used by (Hanson et al. 2002) was based on the work by Stein and Nett (1997). Stein and Nett (1997) used the excess stress equation directly including jet diffusion parameters for characterizing the effective hydraulic stress of a planar jet:

$$\frac{dJ}{dt} = k_d\left[\frac{\tau_o J_p}{J} - \tau_c\right] \tag{3}$$

where J = distance along the jet centerline from the point of pool entry to the eroding bed (Figure 3), J_p = length of the jet potential core (Figure 3), τ_o = the maximum potential applied shear stress within the potential core of the jet (Figure 3), and t = time.

Headcut Migration The headcut migration algorithm developed by Hanson et al. (2001) incorporates the excess stress equation as part of the process based algorithm:

$$\frac{dX}{dt} = \left(\frac{H}{2E_v}\right)k_d[\tau_e - \tau_c] \tag{4}$$

where X = headcut location, H = headcut height (Figure 4), and E_v = erosion on the vertical face required to cause the headcut to become unstable and fail (Figure 4).

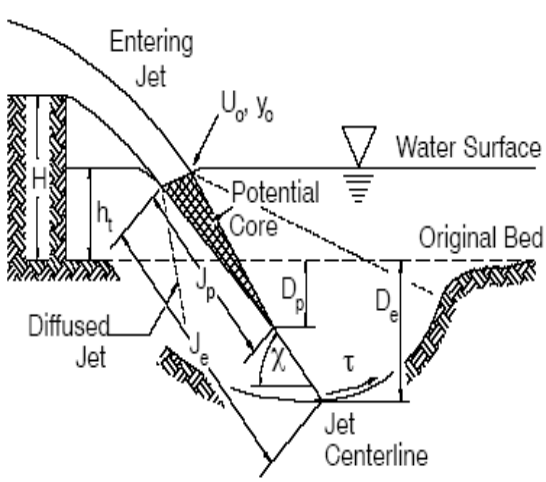

Figure 3. Schematic of headcut jet impingement scour parameter definitions (Hanson et al. 2002).

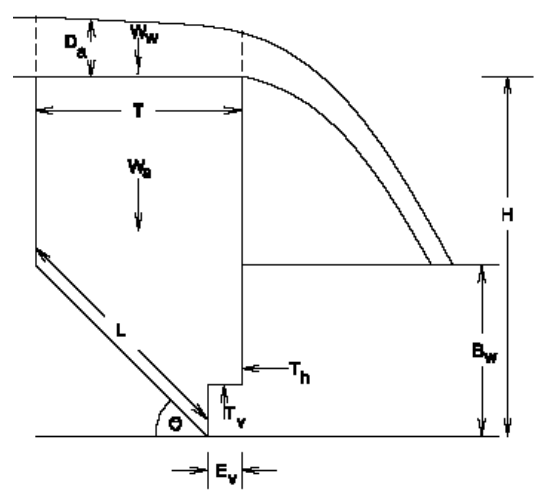

Figure 4. Schematic of headcut migration forces (Hanson et al. 2001).

Erosion Process Flume Studies Jet Impingement Scour Study The headcut jet impingement-scour tests (Hanson et al. 2002) were conducted in a 1.8–m wide, 29.3–m long flume, with 2.4–m high sidewalls. The test fill, a soil with 25% clay and a plasticity index of 15, was placed in the flume in horizontal loose lift layers of 150-mm thickness. Water was added, as necessary to achieve the desired soil moisture and then the lifts were compacted using a walk behind compactor. Variation of compaction energy was achieved by number of passes, passes with and without vibration compaction of the roller, and lift thickness (Hanson et al. 2002). Layers were placed until a total depth of approximately 1.2 m was achieved. After soil samples were extracted, an overfall was excavated in the surface of the fill and water was run over the overfall. Both bed and water surface profiles were measured as the scour occurred (Figures 5 & 6).

Tests 1-5 of the scour study were tests conducted in the same soil material placement with variations in overfall height, therefore for comparison of erodibility parameter coherence these test results were considered the same test. Tests 6 and11 were compacted at considerably less compaction effort in comparison to the other tests and were not used for comparisons in this study. Hanson et al. (2002) reported erodibility parameters results based on analysis of the flume scour test results (Table 1 and Figure 7). Samples were also tested for erodibility using the JET and reported later in the JET section of the paper. The results in Figure 7 show that there is a very steep gradient in the relation between the erodibility coefficient k_d and the compaction water content for the large scale tests.

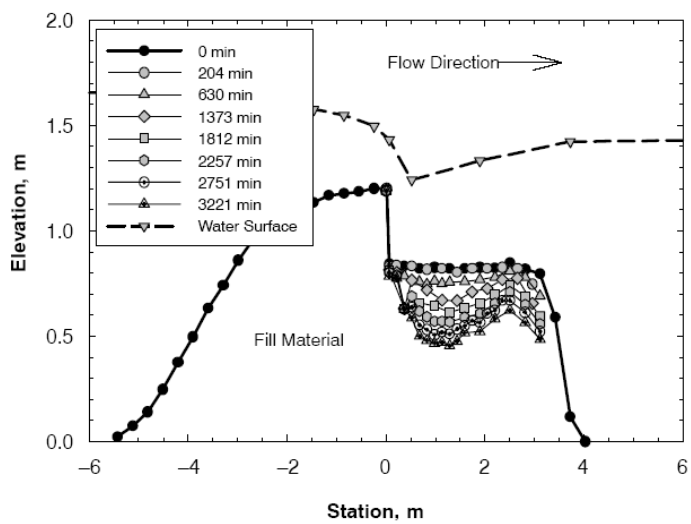

Figure 5 Observed scour for selected intervals for test 13.

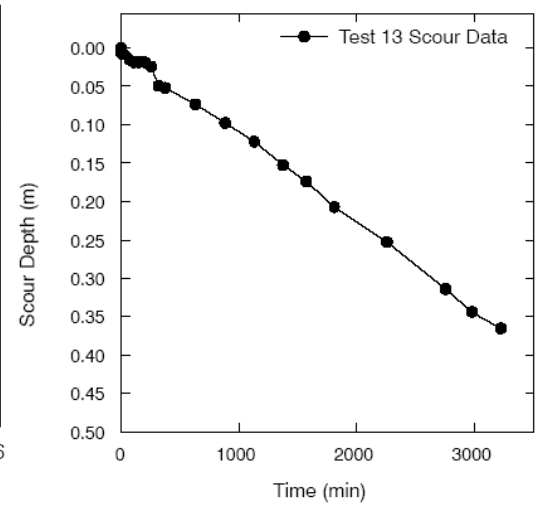

Figure 6 Maximum scour depth vs. time.

Table 1 Scour Test Results (Hanson et al. 2002).

Test	Water Content WC (%)	Dry Unit Weight (Mg/m^3)	Scour Test Results	
			k_d (cm^3/N-s)	τ_c (Pa)
1-5	15.4	1.75	0.62	0.55
7	11.9	1.72	11.0	0.14
8	12.2	1.73	8.56	2.36
9	12.8	1.66	7.68	6.37
10	14.0	1.71	0.46	0.89
12	11.5	1.70	17.75	0.06
13	15.3	1.80	0.52	8.91

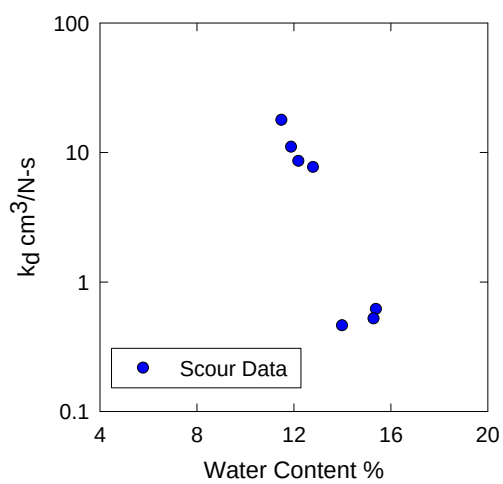

Figure 7 k_d from scour test results vs. WC%.

Headcut Migration Study A headcut is a vertical or near–vertical drop or change in elevation of a concentrated flow channel. Headcuts migrate upstream due to hydraulic stresses at the overfall, seepage at the base of the headcut, and weathering processes, as well as gravitational forces on the soil mass. A total of 35 headcut migration tests (Hanson et al. 2001) were performed using the same soil and flume as the jet impingement scour study. Prior to testing, a near–vertical overfall was pre-formed in the material at the downstream end of the test section. Compactive effort and water content, flow discharges, overfall heights, and backwater levels were varied in these tests. Six tests representing compaction efforts similar to the scour study were evaluated from the headcut migration study for comparison purposes. Figure 8 shows water surface and material surface profiles during test 4 of the headcut migration tests. Figure 9 provides a view of the headcut location versus time during test 4. An estimation of k_d was made for the six tests in Table 2 based on equation 4 assuming that the critical stress was of minor importance and could be assumed equivalent to zero (Table 2 and Figure 10). The results in Figure 10 show that there is a very steep gradient in the relation between the erodibility coefficient k_d and the compaction water content for the large scale tests.

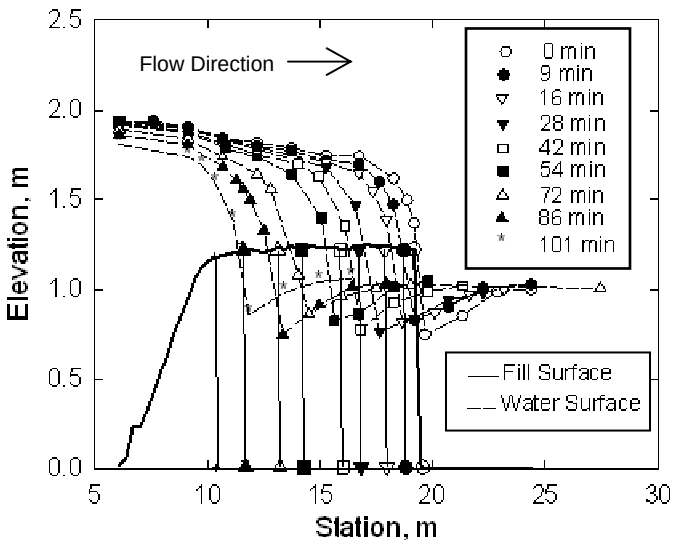

Figure 8 Water and fill material surface profile for test 4. (Hanson et al. 2001)

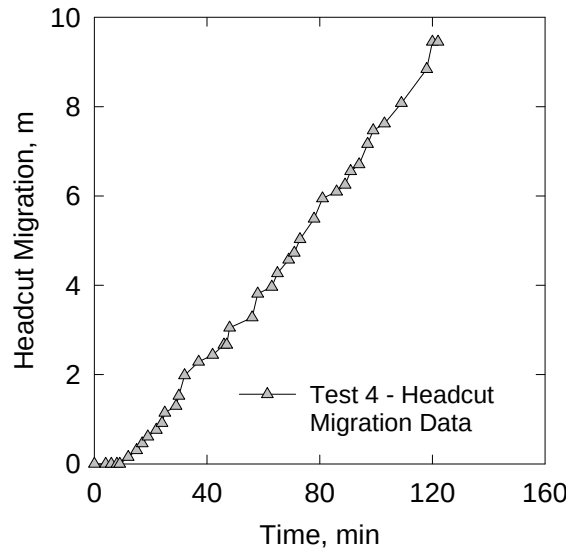

Figure 9 Headcut location vs. time for test 4. (Hanson et al. 2001).

Table 2 Headcut migration erodibility results based on JET

Test	Water Content WC (%)	Dry Unit Weight (Mg/m^3)	Headcut Migration Results	
			k_d (cm^3/N-s)	τ_c (Pa)
4	9.2	1.68	29.6	-
13	12.4	1.84	8.7	-
8	14.2	1.79	2.0	-
6	14.4	1.79	0.9	-
15	14.8	1.81	0.4	-
11	15.9	1.78	0.5	-

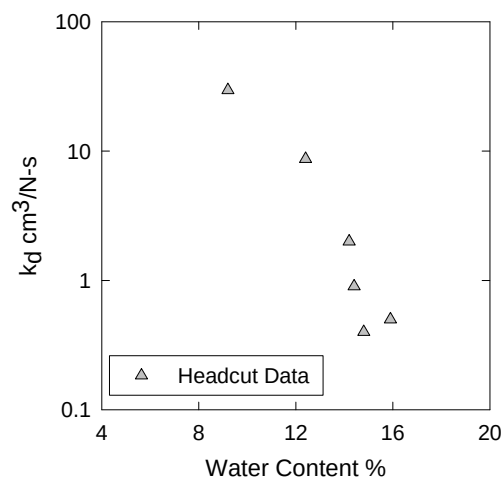

Figure 10 k_d from headcut migration test results vs. WC%.

JET TEST STUDIES

In addition to the large scale flume tests, erodibility measurements were also determined from JET tests conducted on samples taken from the jet impingement scour and headcut migration flume tests (Hanson et al. 2001, 2002). JET tests were also conducted in the laboratory on remolded samples of the same soil material used in the flume tests as part of this study for comparison and relationship to compaction effort. The samples were prepared over a series of compaction efforts and compaction water contents. The JET results represent measurements of erodibility at a smaller scale.

The samples prepared in the laboratory were air dried and then passed through a screen with openings equivalent in size to a number 4 sieve (4.75 mm). The soils were thoroughly mixed with water to achieve the desired compaction water contents. The soils were stored for a minimum of 48 h to allow time for the soil particles to hydrate. The samples reported in this study were compacted at three compaction efforts over a range of compaction water contents. The soil was compacted in the standard mold described in ASTM D698, with a diameter of 101.6 mm, a height of 116.4 mm, and a capacity of 944 cm^3. The three compaction efforts were; 1) a compaction effort of 27.5 kg-cm/cm^3 was administered in accordance with ASTM D1557 using a 4.54 kg rammer with a 457 mm drop, 5 layers and 25 drops per layer; 2) a compaction effort of 6.0 kg-cm/cm^3 was administered in accordance with ASTM D698 using a 2.49 kg rammer with a 305 mm drop, 3 layers and 25 drops per layer; and 3) a compaction effort of 1.2 kg-cm/cm^3 was administered similarly to number 2 with 3 layers but with 5 blows/layer. The resulting compaction curves for each compactive effort are shown in Figure 11a. It is important to note that as the compaction effort is decreased the optimum dry unit weight decreases and the corresponding optimum water content increases.

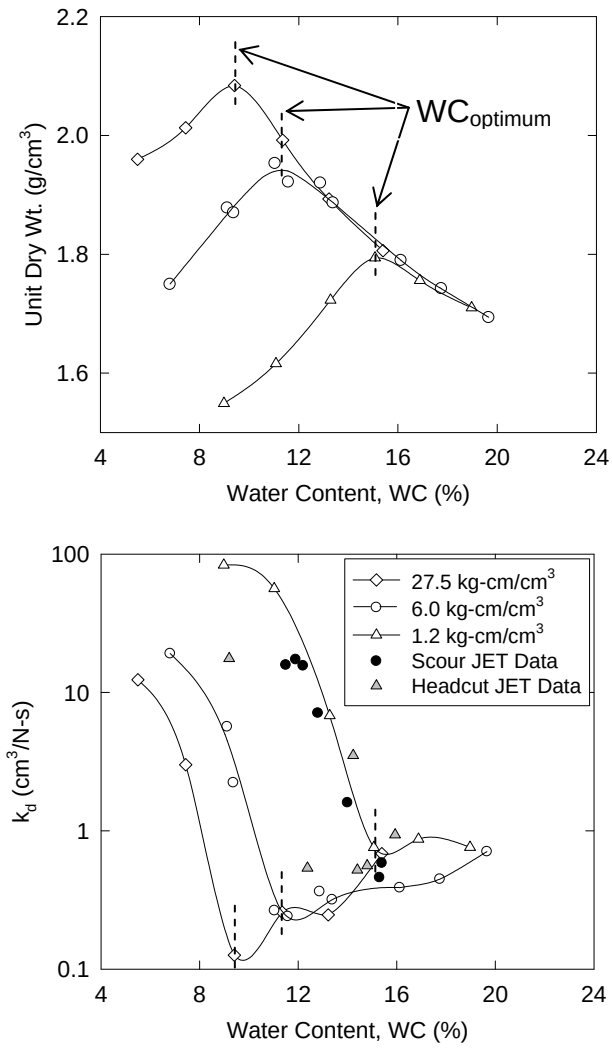

Figure 11 Comparison of a) compaction dry unit weight, and b) k_d curves for three compaction efforts.

Corresponding erodibility parameter measurements were made using laboratory jet test apparatus as described by (Hanson and Hunt, 2007). Figure 11b shows the k_d relationship for the corresponding compaction curves in Figure 11a. The Figure also shows the laboratory jet test results obtained on samples taken from corresponding scour and headcut migration studies described in the previous sections of this paper. The JET results from the scour study and the headcut migration study are similar and are comparable to the laboratory samples prepared at a 1.2 kg-cm/cm^3 compaction effort. The tests concur with the large scale tests in that a very steep gradient in change in k_d does occur. The gradient curve is influenced by compactive effort and water content. The gradient is very steep on the dry side of optimum in each case of compaction effort. The gradient is flatter on the wet side of optimum water content and the curves join together at comparable water contents on the wet side of optimum.

CONCLUSION: COHERENCE OF SCALES

The results from the large scale flume scour tests (Figure 7) and headcut migration tests (Figure 10), and the JET (Figure 11b) provide evidence of the coherence of erodibility measurements at the large and small scales (Figure 12). The results at the different scales also consistently indicate the magnitude and range of erodibilities, dependent on compaction water content and effort. The JET method of erodibility measurement is a viable approach for determining erodibility of materials for prediction of headcut scour and headcut migration at the larger scale based on the comparison of erodibility measurements. These results also indicate that erodibility testing of laboratory prepared samples may be a useful tool for characterizing materials and compaction specifications for construction of embankments for dams and levees. It is important to note that the erosion measurements in the laboratory and flume were taken at time of compaction and that weathering and time effects were not a part of this research. This is important because it should be recognized that environmental effects such as weathering (i.e. freeze, thaw, drying, and wetting) can alter erodibility of materials and impact material performance over the history of an embankment.

Even though laboratory-scale compaction may not perfectly duplicate the field scale heavy equipment compaction, laboratory results are presently used to specify field compaction for density, shrink swell, permeability, and strength. In some environments it may be important to add erodibility to the reasons for testing and for construction specifications. Hanson and Hunt (2007) proposed specification methods for erodibility related to breach widening and the results from this paper lead to the conclusion that this could also be used for other erosion processes related to embankment erosion during overtopping. The other point of consideration is that erodibility is not the only performance parameter of interest. Therefore, acceptable zones of compaction need to also be taken into account for other performance parameters (i.e. strength, shrinkage, and conductivity).

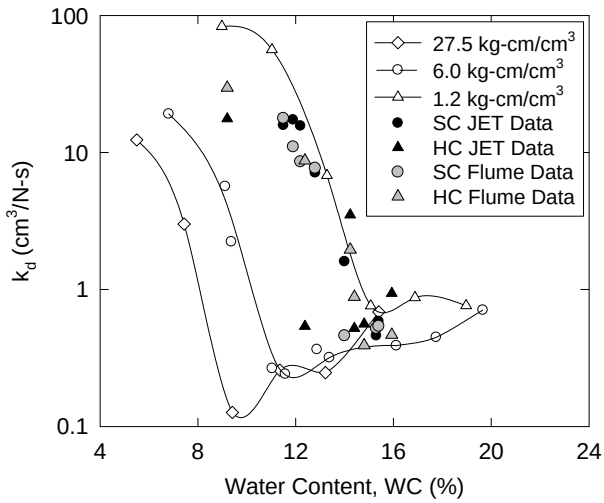

Figure 12 Coherence of k_d for large scale erosion process test results and small scale JET flume and laboratory sample results.

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