# ERODIBILITY CHARACTERISTICS OF EMBANKMENT MATERIALS

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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 in which erosion and material erodibility have not been reliably defined in the past. Recent as well as past embankment failures have helped clarify that material erodibility is an essential geotechnical parameter for predicting embankment performance during overtopping, internal erosion, and breach failure events. There have been several methods, both field and laboratory, developed for characterizing earthen material erodibility including, large and small flumes, channel tests, submerged jets, rotating cylinders, hole erosion tests, slot tests, etc. Based on laboratory and field testing using the jet erosion test (JET), the erodibility of materials have been observed to vary over several orders of magnitude. Material texture and placement characteristics of soil materials have been observed to impact this variability. This paper describes the JET and the range of erodibility values measured, as well as the implications and importance of these measurements.

### Introduction

Simulating the failure of embankment dams is a key analysis step in the development of dam-failure flood inundation maps for emergency action plans, dam hazard classifications, and risk assessments. The prediction of geometric and temporal parameters of embankment dam breaches is widely recognized as one of the greatest sources of uncertainty affecting simulations of dambreak events and the resulting downstream flooding and associated consequences (Wahl et al. 2009). There is an ongoing effort to improve breach simulation technologies by focusing on applying physically-based models that simulate erosion processes and rates of breach development. The most significant fundamental improvement in physically-based breach models under development today is the incorporation of erosion process algorithms that rely on quantitative measures of material erodibility. This paper examines quantified measures of material erodibility and the resulting implications.

### Background

Hanson et al. (2008), Tejral et al. (2009) and Jamieson and Ferentchak (2008) conclude from their simulation studies of dam breach that in addition to the height of the embankment and reservoir storage volume, the rate of breach development has a significant impact on the peak discharge from a dam failure. Based on the study of 18 historical cases of earthen embankment dam failures, Walder and O'Connor (1997) provide some insight into the rate of breach development. They observed that the mean vertical erosion rate parameter ($k$) determined from the historical cases ranged from 1 to 1000 m/h. This study corroborates the significance of the rate of failure in determining the peak discharge but the shortcoming of the $k$ parameter as defined by

Walder and O'Connor is that it does not separate material property effects from geometry or hydraulic effects.

The simulations conducted by Hanson et al. (2008) and Tejral et al. (2009) utilized SIMBA (SIMplified Breach Analysis), a physically based computational research model. The model uses the excess stress equation as one of the algorithms that drives the rate of the erosion processes for the simulations.

$$E_r = k_d(\tau_e - \tau_c) \qquad [1]$$

Where

$E_r$ = the erosion rate,

$k_d$ = a detachment rate/erodibility coefficient,

$\tau_e$ = the hydraulically applied boundary stress, and

$\tau_c$ = the critical stress required to initiate detachment for the material,

The excess stress equation within the computational simulations separates the impact of material properties, $k_d$ and $\tau_c$, from the impact of geometry and hydraulic stresses. Hanson et al. (2008) and Tejral et al. (2009) varied the $k_d$ parameter as one of the key material properties to evaluate the importance of material erodibility in the erosion process. They concluded that although not exhaustive in study, variation of the $k_d$ parameter had an important influence on the rate of the predicted breach process and appeared to have even more relative influence for smaller dam embankments (less than 15 m). Smaller values of $k_d$ resulted in slower breach rates, and in some cases breach did not even occur. Because $k_d$ and $\tau_c$ impact computation breach simulations results, it is important to understand how these two parameters vary as material properties vary.

Hanson and Hunt (2007) and Wahl et al. (2009) conducted laboratory scale JET erodibility studies. As a part of both studies tests were conducted to investigate the impact of texture and compaction specifications on erodibility. They concluded that soil texture (i.e. % silt, sand, and clay) as well as compaction specifications influenced erodibility. Hanson and Hunt (2007) also compared the laboratory JET measurements of $k_d$ to values of $k_d$ determined from large scale embankment breach widening tests (Figure 1 and 2) for purposes of determining coherence of measurement to large scale erosion processes. They concluded that the small scale JET results were coherent and proposed a method of using laboratory results for specifying compaction for field construction. Because of the recognized importance of erodibility and the potential of using laboratory JET results for characterizing field performance of constructed embankments, additional tests have been conducted at the USDA-ARS HERU Laboratory and USBR Laboratory. The purpose of this paper is to describe the range of $k_d$ and $\tau_c$ values measured for different soil textures and compaction efforts.

Figure 1. Large scale embankment widening tests.

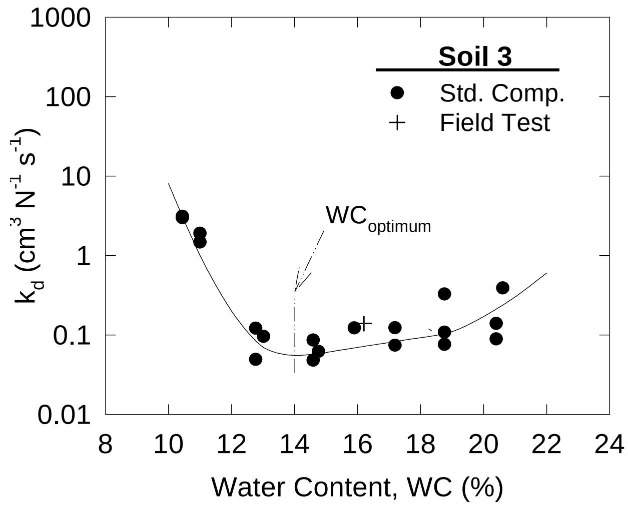


Figure 2. Large scale field test and laboratory JET results (Hanson and Hunt 2007).

**Jet Test Results**

In order to understand the range of anticipated erodibilities (i.e. $k_d$ and $\tau_c$) for compacted soils in earthen embankments a series of 183 laboratory JET tests were conducted on seven soils at the USDA-ARS HERU laboratory in Stillwater, OK and 43 tests were conducted on 8 soils at the USDI-BR Hydraulic laboratory in Denver CO. The JET testing procedure used is described in detail in Hanson and Cook (2004) and Hanson and Hunt (2007). The soil properties are reported in Table 1 and Table 2. The first 5 soils in Table 2 were obtained from stockpiles in the laboratories of the USDI-BR, while the last 3 were provided by the USDA-ARS HERU and although somewhat different measured parameters are from the same stockpiles as A, C, and F in Table 1.

Figure 3 provides a comparison of $k_d$ vs $\tau_c$ for the tests conducted at both laboratories over a range of compaction efforts and water contents. It can be concluded from this plot that $k_d$ and $\tau_c$ are inversely related which was also an observation noted by Hanson and Simon (2001). The other important observation from this plot is that values of $k_d$ and $\tau_c$ can vary over several orders of magnitude for compacted soils.

Soil samples were compacted in both laboratories using the standard 101.6 mm diameter compaction mold described in ASTM D698. Compaction efforts applied to samples varied from 1.2 kg-cm/cm$^3$ to 27.5 kg-cm/cm$^3$ using a 4.54-kg rammer with a 457-mm drop or a 2.49-kg rammer with a 305-mm drop. Figure 4 shows a plot of the $k_d$ values for the seven soils tested at the USDA-ARS HERU for a compaction effort of 6.0 kg-cm/cm$^3$. A compaction effort of 6.0 kg-cm/cm$^3$ is equivalent to the standard compaction prescribed in ASTM D698. Concluding observations from this plot are: 1)The soil texture (%Clay) and Plasticity Index (PI) have a strong influence on the erodibility; and 2) The compaction water content also has a strong influence with steep

Table 1. Property of tested soils at the USDA-ARS Laboratory.

| Soil Sample Designation | USCS Classification | Atterberg Limits | | Texture | |
|---|---|---|---|---|---|
| | | Liquid Limit(%) | Plasticity Index (%) | % Sand >0.074 mm | % Clay < 0.002 mm |
| A | SM | NP | NP | 73 | 6 |
| B | SM | NP | NP | 64 | 9 |
| C | ML | 23 | 3 | 32 | 15 |
| D | CL | 26 | 15 | 35 | 25 |
| E | CL | 31 | 15 | 24 | 26 |
| F | CL | 37 | 19 | 20 | 28 |
| G | CL | 37 | 17 | 13 | 35 |

Table 2. Property of tested soils by the USDI-BR Laboratory (Wahl et al., 2009)

| Soil Sample Designation | USCS Classification | Atterberg Limits | | Texture | |
|---|---|---|---|---|---|
| | | Liquid Limit(%) | Plasticity Index (%) | % Sand >0.074 mm | % Clay < 0.002 mm |
| 55T-160 | CL | 34 | 23 | 37 | 24 |
| TE | CL-ML | 29 | 4 | 12 | 11 |
| MF | CL | 47 | 34 | - | - |
| MP | CH/CL | 51 | 30 | 9 | 40 |
| TF | CH | 55 | 40 | 6 | 42 |
| P1 | SM | NP | NP | 76 | 4 |
| P2 | CL | 25 | 9 | 31 | 16 |
| P3 | CL | 36 | 24 | 20 | 25 |

gradients in the change of $k_d$ on the dry side of optimum compaction water content and less influence with flatter gradients of change on the wet side of optimum.

Figure 5 shows the influence of changes in compaction effort on the relationship of unit dry weight and water content, and Figure 6 show the corresponding influence on erodibility for soil D. A similar response was observed for other soils tested in this manner. There are two significant conclusions from Figure 6: 1) Increased compaction effort tends to increase the resistance of the soil material at the optimum water content; and 2) the resistance based on the erodibility coefficient $k_d$ tends to become independent of compaction effort on the wet side of the optimum water content for equivalent compaction water contents. Figure 7 shows the relationship of $\tau_c$ versus WC% for soil D which is consistent with the observation the $k_d$ and $\tau_c$ tend to be inverse in relationship as indicated in Figure 3.

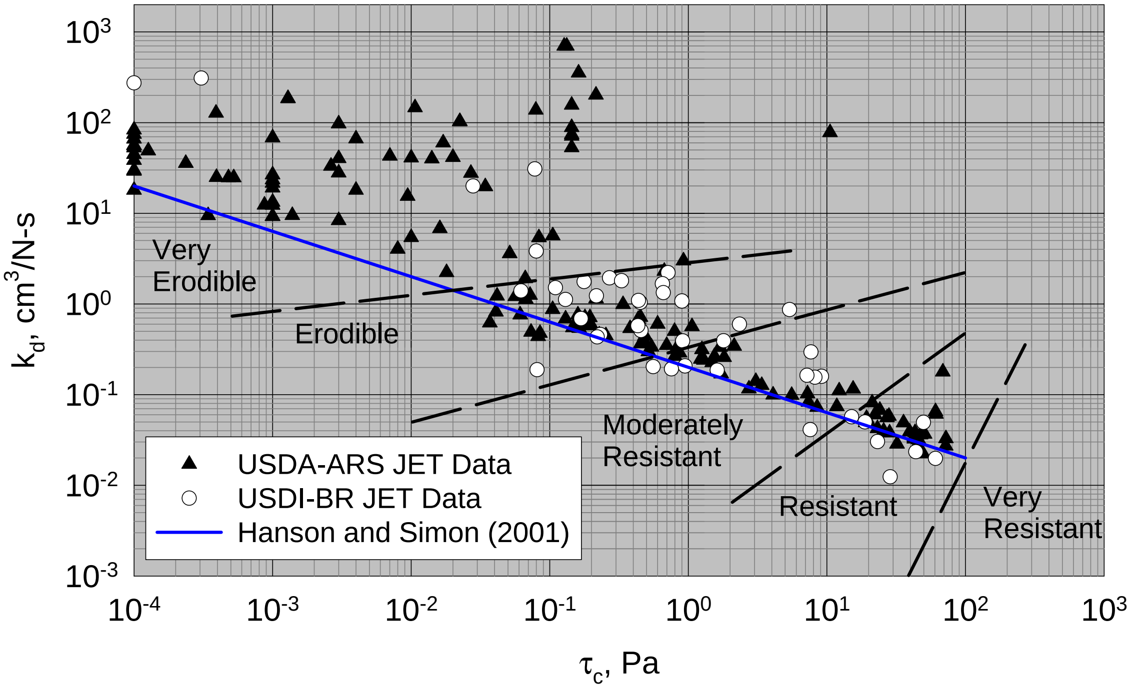


Figure 3. Relationship of $k_d$ and $\tau_c$ from JET tests on soil at the USDA-ARS HERU and USDI-BR Hydraulic Laboratory. (Note:1 Pa = 0.02089 lb/ft$^2$; 1 cm$^3$/N-s = 0.5656 ft$^3$/lb-h)

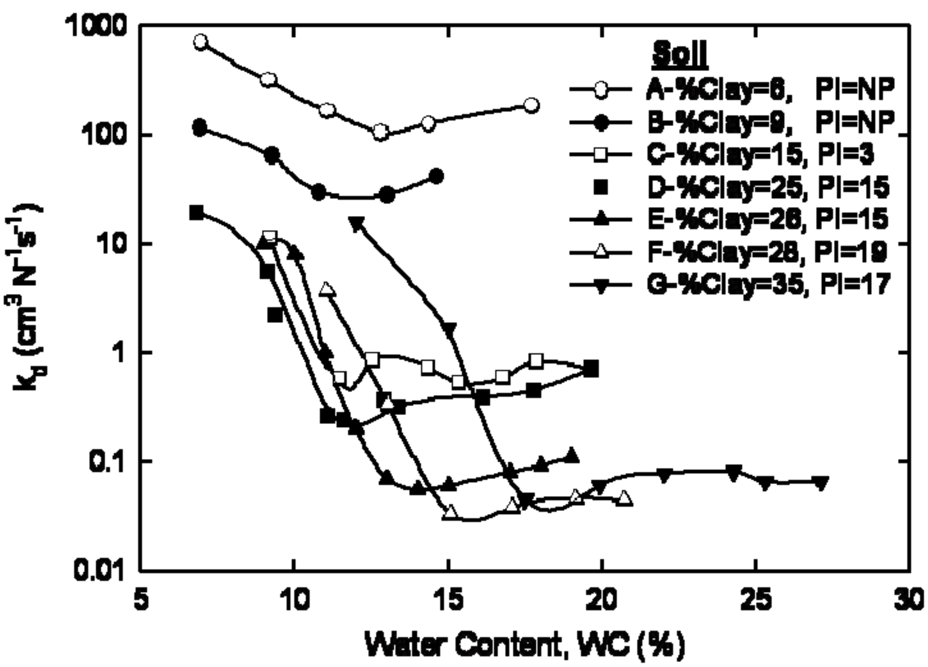


Figure 4. Resulting $k_d$ curves for soils tested at USDA-ARS HERU at standard compaction effort, 6.0 kg-cm/cm$^3$.

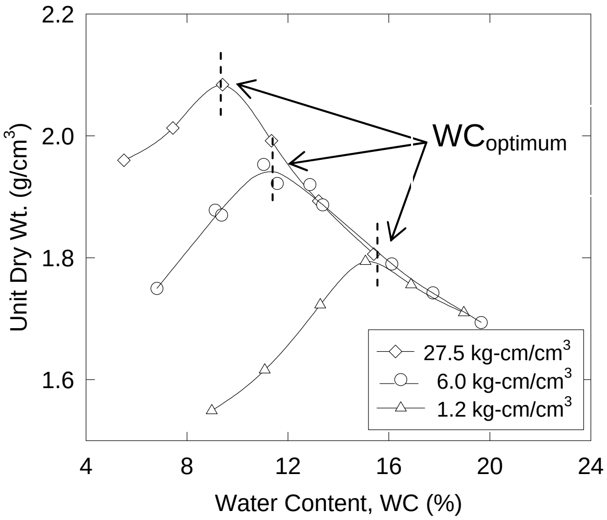


Figure 5. Compaction curves for soil D at three compaction efforts.

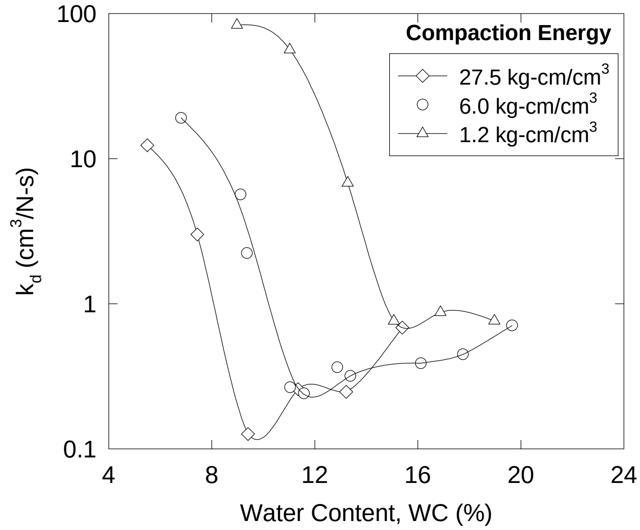


Figure 6. Compaction curves for soil D three compaction efforts.

The distinction in erodibility resistance for fine grained soils, although influenced by, is not strictly correlated to clay percentage or plasticity. Other complicating factors such as compaction effort, compaction water content, as well as additional factors play a role in erodibility of soil materials. Therefore based on these JET results Tables 3 and 4 provide an estimate of expected values for $k_d$ and $\tau_c$ for ranges of % clay, wet and dry of optimum water content, and compaction effort.

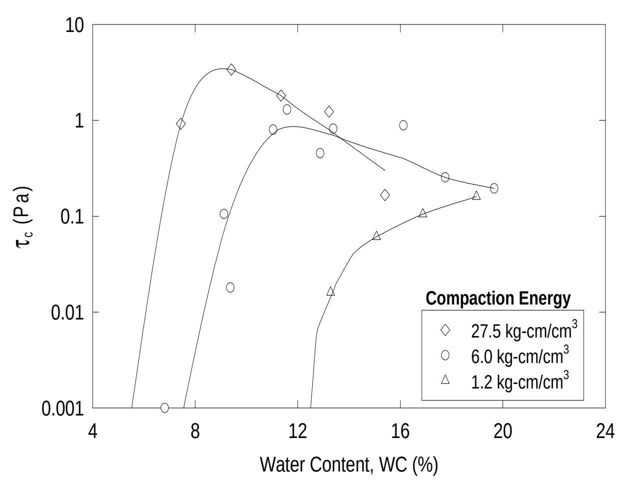


Figure 7. Compaction curves for soil D at three compaction efforts.

Table 3. Approximate values of $k_d$ ($cm^3$/N-s) relative to compaction and % clay.

| Clay % | Modified Compaction (27.5 kg-cm/cm$^3$) | | Standard Compaction (6.0 kg-cm/cm$^3$) | | Low Compaction (1.2kg-cm/cm$^3$) | |
|---|---|---|---|---|---|---|
| | ≥Opt WC% | <Opt WC% | ≥Opt WC% | <Opt WC% | ≥Opt WC% | <Opt WC% |
| | Erodibility, $k_d$ (cm$^3$/N·s) | | | | | |
| >25 | 0.05 | 0.5 | 0.1 | 1 | 0.2 | 2 |
| 14-25 | 0.5 | 5 | 1 | 10 | 2 | 20 |
| 8-13 | 5 | 50 | 10 | 100 | 20 | 200 |
| 0-7 | 50 | 200 | 100 | 400 | 200 | 800 |

Table 4. Approximate values of $\tau_c$ (Pa) relative to compaction and % clay.

| Clay % | Modified Compaction (27.5 kg-cm/cm$^3$) | | Standard Compaction (6.0 kg-cm/cm$^3$) | | Low Compaction (1.3kg-cm/cm$^3$) | |
|---|---|---|---|---|---|---|
| | ≥Opt WC% | <Opt WC% | ≥Opt WC% | <Opt WC% | ≥Opt WC% | <Opt WC% |
| | Critical shear stress, $\tau_c$ (Pa) | | | | | |
| >25 | 16 | 0.16 | 4 | 0 | 1 | 0 |
| 14-25 | 0.16 | 0 | 0 | 0 | 0 | 0 |
| 8-13 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0-7 | 0 | 0 | 0 | 0 | 0 | 0 |

## Summary

The erodibility of compacted soils is an important parameter for determining the anticipated performance of an earthen embankment during overtopping. In-order for the model simulations to be useful for field application, the process based algorithms used in the models must use soil parameters that properly predict the rates of the process and the soil parameters must be reasonably obtained from field measurements or estimated from information provided. The excess stress parameters, $k_d$ and $\tau_c$ measured using the JET are coherent with the large scale erosion processes observed in the embankment breach processes. This paper shows, based on JET measurements, that $k_d$ and $\tau_c$, range over several orders of magnitude. The results also provide insight into the importance of not only material texture but also compaction specifications. Tables 3 and 4 are provided as guidance for expected ranges and variation of $k_d$ and $\tau_c$ values expected for gradation and compaction. Because of the variability and many factors that influence erodibility the authors do recommend measuring erodibility rather than using these estimates but these estimates can be useful to conduct preliminary breach revaluations or when erodibility measurements are not available.

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