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Proposed USACE EM 1110-2-1913 Erosion Analysis Guidance

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ABSTRACT

The U.S. Army Corps of Engineers is updating EM 1110-2-1913, Design, Construction and Evaluation of Levees, including new guidance on how to conduct erosion analysis. This paper presents the two erosion models considered: erosion rate as a function of shear stress and an empirical relationship relating wave overtopping flow rate to erosion rate. The paper also suggests the current state-of-the-practice regarding factors to be considered when selecting erosion model parameters. Erosion design will be conducted in a risk-informed framework, using potential failure modes analysis and when possible, probabilistic limit state analyses to assess design reliability. Required design reliability will be selected based on levels necessary to achieve various life-safety, economic and other unspecified objectives, as appropriate for each flood risk mitigation system.

Keywords: *Army Corps of Engineers, erosion rate model, wave overtopping erosion model, critical shear stress, erosion coefficient, risk-informed design.*

1. INTRODUCTION

The U.S. Army Corps of Engineers (USACE) is moving towards risk-informed decision processes for all aspects of flood risk portfolio management, including design for levee erosion. Erosion is one of the principal causes of levee damage and can lead to both overtopping and prior-to-overtopping failures. The current version of Engineering Manual (EM) 1110-2-1913, Design, Construction and Evaluation of Levees is dated April 30, 2000, but is essentially an electronic version of the March 31, 1978 edition, with no updates in nearly forty years. This paper describes updates being made to the EM to evaluate and design features to manage erosion risk, focusing on the physical model that underlies most of the new analysis guidance and to suggest the current state-of-the-practice for selection of parameters in those analyses.

2. SURFICIAL EROSION ANALYSIS MODEL AND PARAMETERS

To evaluate waterside surficial current erosion, waterside wind wave erosion, and landside overtopping flow erosion, the EM proposes various analytical techniques that incorporate the widely used linear excess stress erosion model in which erosion rate is estimated as a function of hydraulic shear stress and soil erosion resistance (Hanson et al., 2011):

$$\varepsilon' = k_d\,(\tau-\tau_c) \tag{1}$$

where

ε' = the erosion rate, (ft/hr)
k_d = a detachment rate/erodibility coefficient (typically expressed in US units of ft^3/lb/hr),
τ = the hydraulically applied boundary stress (typically in US units of lb/ft^2 or psf), and

τ_c = the critical stress required to initiate erosion (typically in US units of lb/ft^2 or psf).

This erosion rate model is used in various computation schemes relating key processes of embankment and foundation erosion including riverine current flow, waterside wave action, overtopping flow headcut jet impingement, and overtopping flow headcut migration. The erodibility coefficient k_d and critical stress τ_c are properties of the soil material and are affected by various factors including soil composition, compaction characteristics, degree of cementation, etc., as discussed in the following sections.

2.1. Critical Shear Stress - τ_c

The critical shear stress can be estimated using empirical correlations between the critical shear stress and soil index properties. Several empirical correlations between critical shear stress τ_c and soil index properties such as grain size, plasticity index, and shear strength are available in the literature to estimate the value of τ_c. Typically, index properties are estimated based on laboratory tests on disturbed and undisturbed samples collected from the field.
For example, for coarse-grained soils Briaud et al. (2001) suggests that τ_c is related to median soil grain diameter, D_{50}, similar to Shields (1936) (Figure 1).

$$\tau_c\ [psf] = 0.53 D_{50}\ [in.] \qquad (2)$$

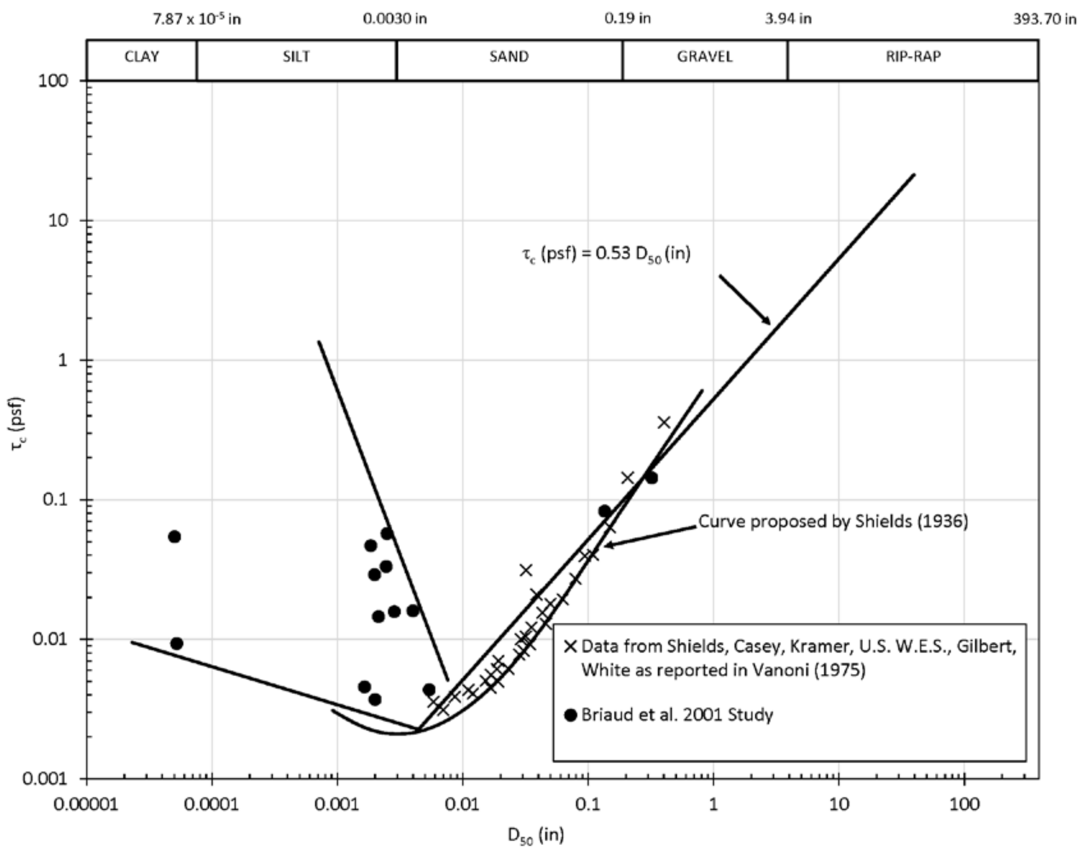


Figure 1. Critical Shear Stress versus Mean Soil Grain Diameter (after Briaud et al., 2001)

2.2. Erodibility Coefficient - k_d

In the United States, efforts by research hydraulic and geotechnical engineers to evaluate erodibility coefficients, k_d, have been progressing somewhat independently and for this article will be categorized in an oversimplified manner as:

- work by the US Department of Agriculture Natural Resources Conservation Service and the Agricultural Research Service ("Hanson"), primarily utilizing the submerged jet erosion test, which was developed for characterizing erodibility of cohesive soils, and
- work at Texas A&M University ("Briaud"), utilizing the Erosion Function Apparatus, a flume-type erosion test initially developed for characterizing cohesive soils encountered in bridge scour problems.

Summaries are provided later in this paper of several studies by Hanson and others using the submerged jet test as a tool to investigate many factors that influence erodibility. A benchmark result is Hanson and Simon (2001), in which results from a study to measure the erosion resistance of streambed materials in the loess areas of the Midwestern USA were presented in a summary chart which included a five level characterization scheme for describing the erosion resistance of a material based on associated values of k_d and τ_c (Figure 2). These parameters were found to be loosely correlated and inversely proportional.

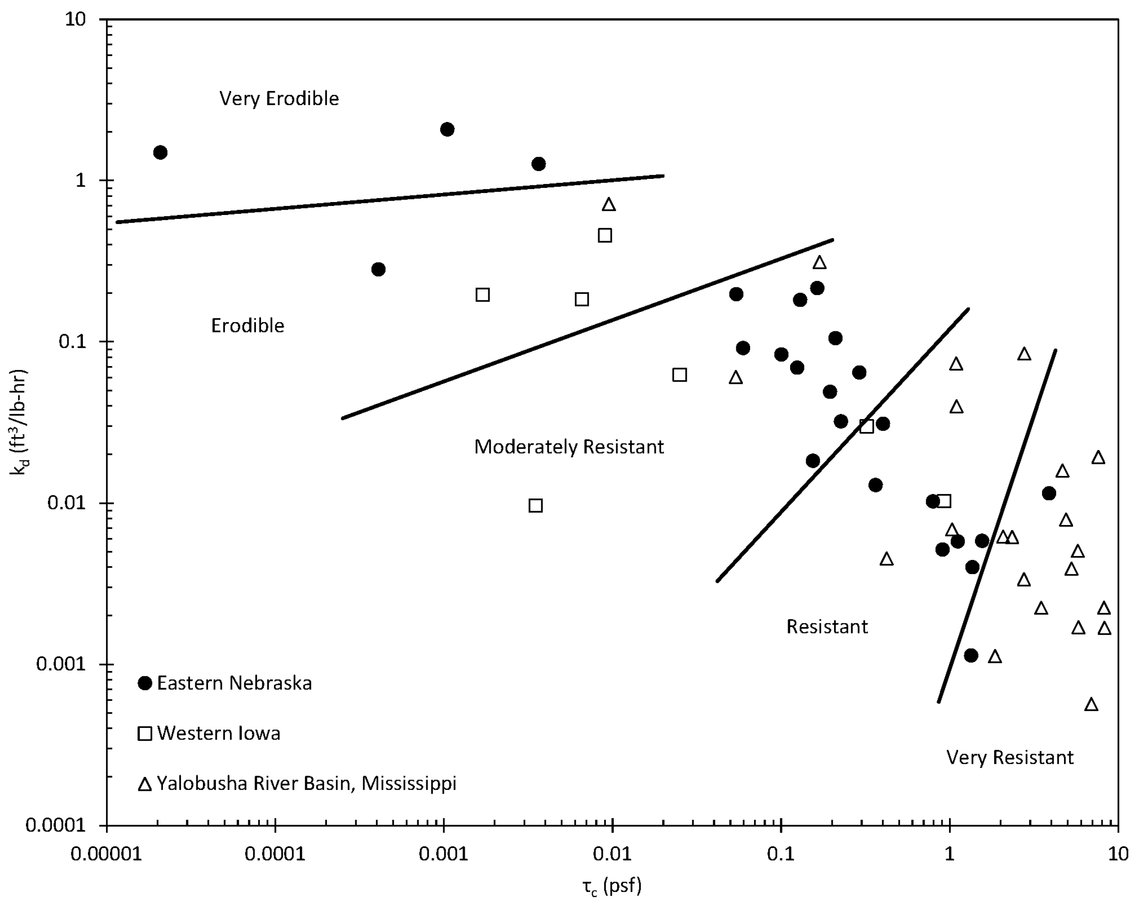


Figure 2. τ_c versus k_d from cohesive streambed submerged JET tests (after Hanson and Simon 2001)

In Briaud et al. (2001), a new test device, the Erosion Function Apparatus (EFA) is described and results from tests on various soils are presented. In a companion discussion, Hanson and Simon (2002) plot the Briaud et al. (2001) data on the Hanson and Simon (2001) erodibility classification scheme (Figure 3), again showing a similarly correlated relationship between k_d and τ_c.

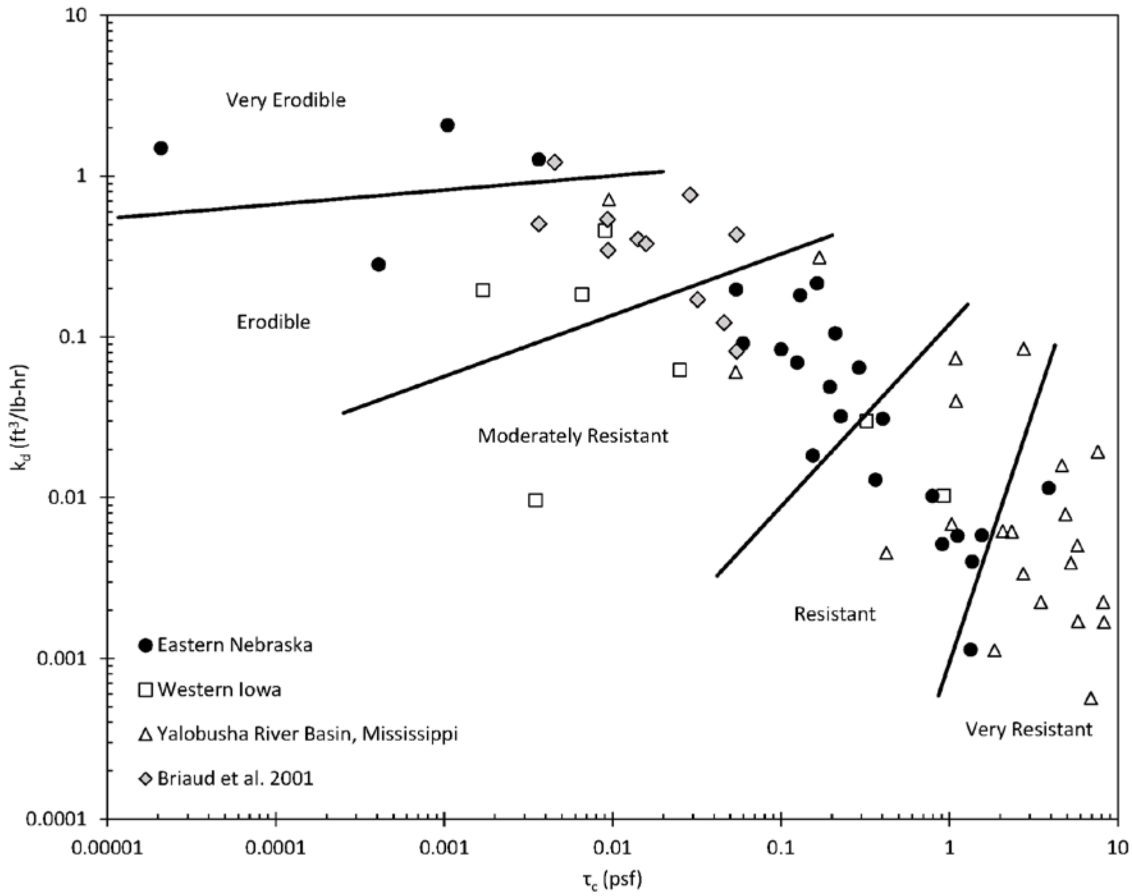


Figure 3 Briaud et al. (2001) Erosion Function Apparatus test results plotted on Hanson and Simon erodibility classification chart (after Hanson and Simon 2002)

In Briaud et al. (2008), results from a study to evaluate the erodibility of levees overtopped during hurricane Katrina were presented in a summary chart which included a new six level characterization scheme for describing the erodibility of a material based on associated values of erosion rate as a function of flow velocity. A similar six level scheme was presented based on erosion rate as a function of applied stress (Figure 4). The six levels were associated with a wide variety of materials ranging from cohesive and granular soils to jointed and intact rock.

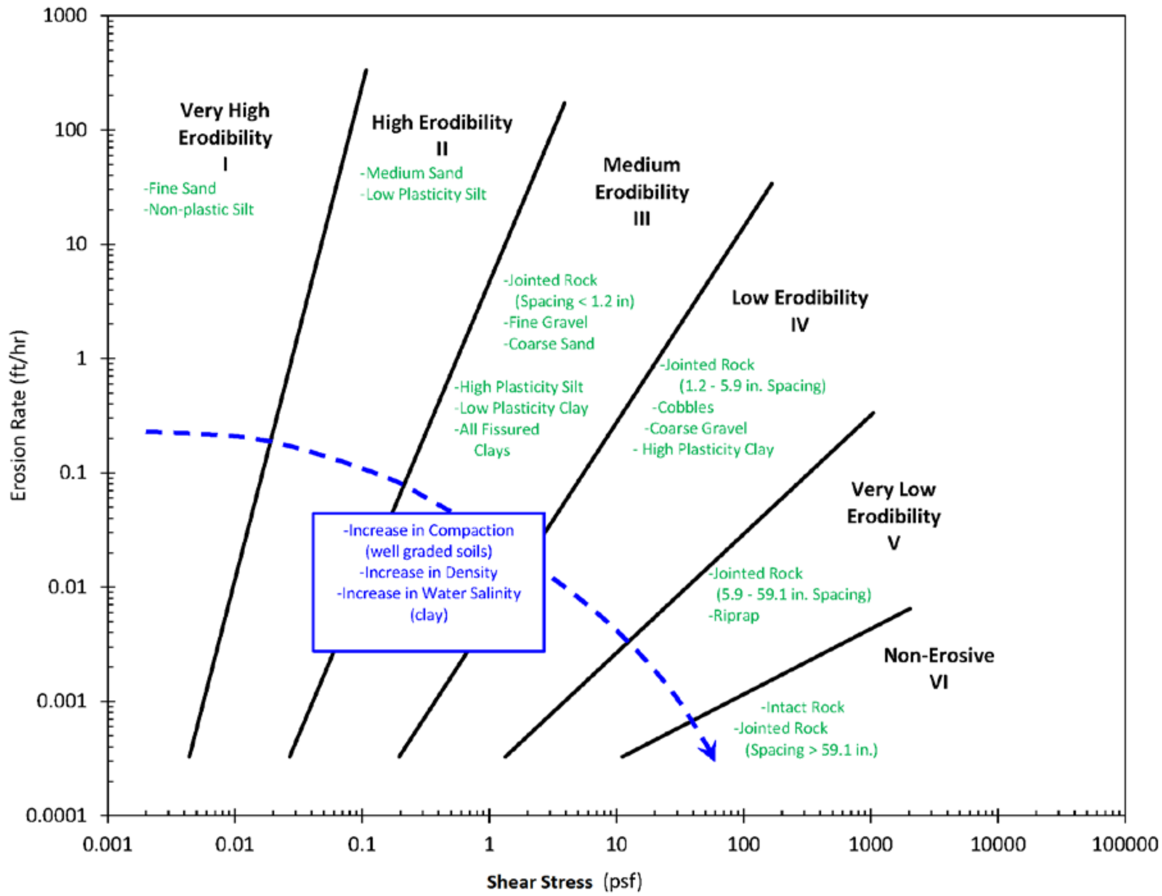


Figure 4. Proposed erosion categories for soils and rocks based on shear stress (after Briaud 2008)

Figure 5 presents an overlay of the "Hanson" erosion resistance classification (Figure 2 above), a proposed transformation of the "Briaud" erodibility classification together with Briaud associated materials (Figure 4 above), and URS/USACE Levee Erosion Toolbox (URS 2007) default erosion parameters k_d and τ_c based on mean grain size, D_{50}, from Briaud 2001 (Figure 1 above). The "Hanson" and "Briaud" classification schemes appear to be complementary, with each erosion class having similar ranges of values for k_d and associated τ_c. In the new EM, analysts will be encouraged to continue using the classification scheme and nomenclature of Hanson and Simon (Figure 2) when describing the erosion resistance of materials.

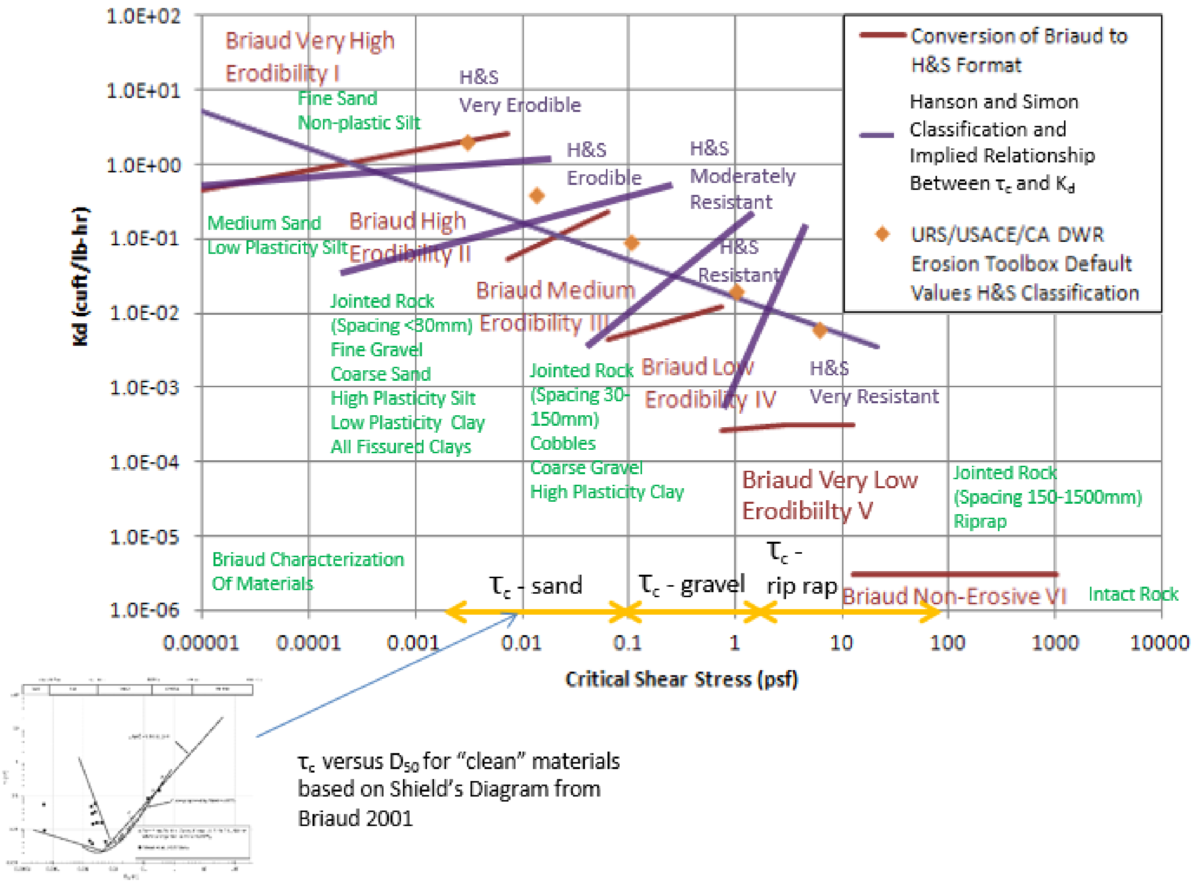


Figure 5. “Hanson” erosion resistance, “Briaud” erodibility, and Levee Erosion Toolbox (URS 2007) default values for k_d and associated τ_c for the various “Hanson” erosion resistance classifications and Shield’s Diagram τ_c from Briaud (2001) to be cited as the primary source for analysis parameters in Engineering Manual 1110-2-1913.

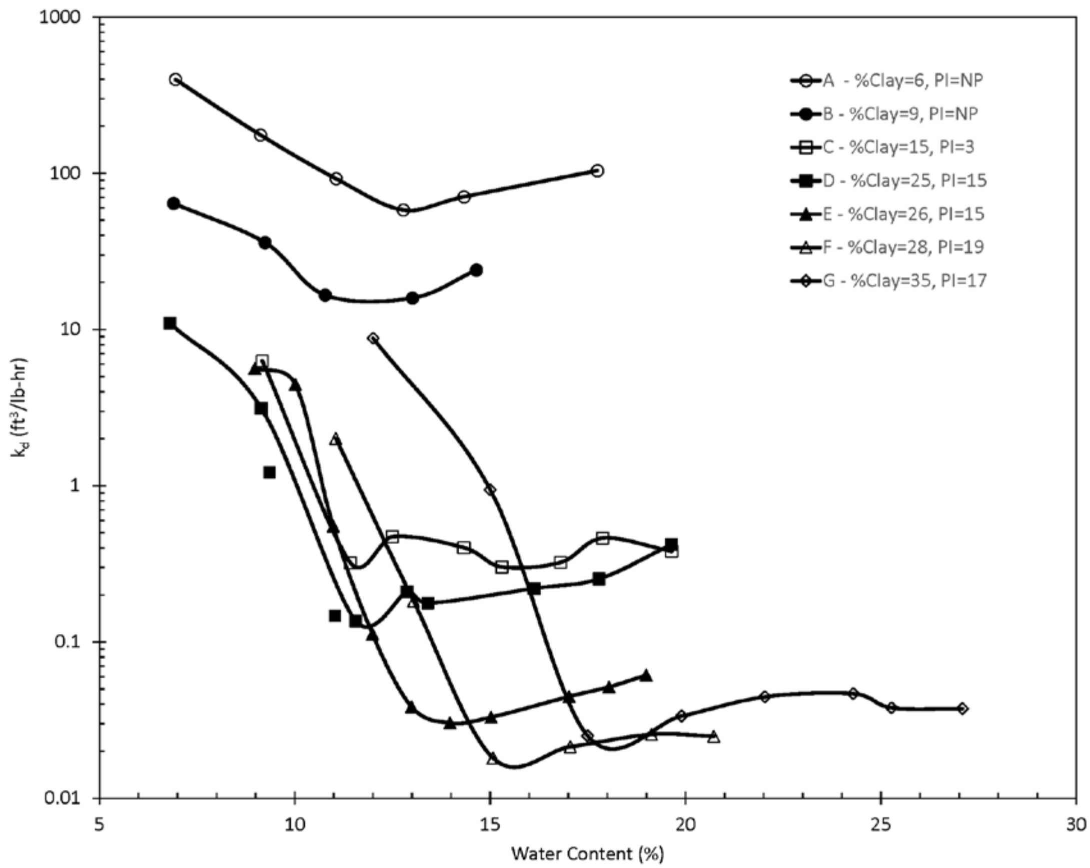
3. PHYSICAL TESTS AND FACTORS AFFECTING SOIL EROSION RATE PARAMETERS

3.1. Physical Tests

Several test methods have been developed for evaluating erodibility coefficient, k_d and critical stress, τ_c. Representative examples from the literature (Hanson et al., 2011) include flume tests, jet erosion test (JET), rotating cylinder test (RCT), small samples inserted in the bottom of flumes (e.g., Erosion Function Apparatus, EFA), and the hole erosion test (HET). At this time, the standard JET test (ASTM D 5852) is considered the best understood with the most confirmation of coherence between small scale test results and the larger scale erosion processes modelled in overtopping analyses. HET tests have gained some popularity for evaluating internal erosion potential (scour/crack erosion), but typically indicate greater erosion resistance than JET tests when numerically comparing k_d-τ_c values (typically one order of magnitude lower k_d and up to 2 orders of magnitude greater τ_c). (Wahl et al. 2008). This may be due to a host of factors, including simplified modelling of the stress environment created by each test, different erosion mechanisms, and oversimplification of the basic erosion modelling equations (i.e., applying the linear excess stress equation to an inherently nonlinear process). Unfortunately, most of these tests are not at all suited to purely granular or rocky materials. Large flume tests and potentially large-scale JET devices might be applicable, but large flume tests are difficult and expensive to carry out and available JET devices are too small to test samples of rockfill materials (e.g., coarse sands, gravels and cobbles). As a result, values of k_d for gravels are an area of uncertainty and continuing research.

3.2. Factors Affecting Soil Erosion Rate Parameters

Hanson et al. (2011) presents JET erosion test results from low plasticity clayey materials compacted at different compactive efforts and moisture contents, showing that compaction moisture content can have a significant impact on both k_d (Figure 6) and τ_c.



Soil Sample	USCS Classification	Atterberg Limits: Liquid Limit (%)	Atterberg Limits: Plasticity Index (%)	Texture: % Sand > 0.0030 in	Texture: % Clay <7.87 x 10⁻⁵ in
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

Figure 6 Change in k_d versus compaction water content for seven low plasticity soils compacted at Standard Proctor (ASTM D698). Lowest values of k_d are generally achieved near optimum water content. (after Hanson et al., 2011)

Figure 7 presents the measured values of k_d from Hanson et al. (2011), indicating that for the low plasticity CL soil tested, k_d decreases with increasing compactive effort.

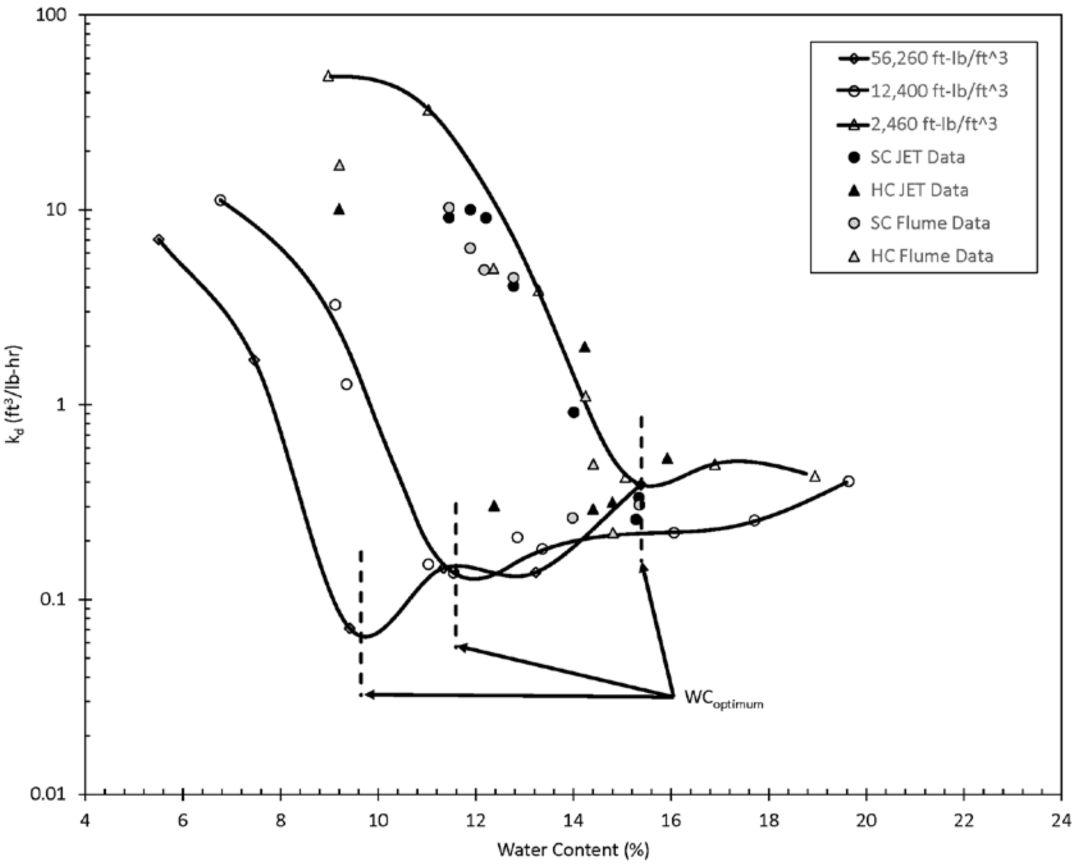
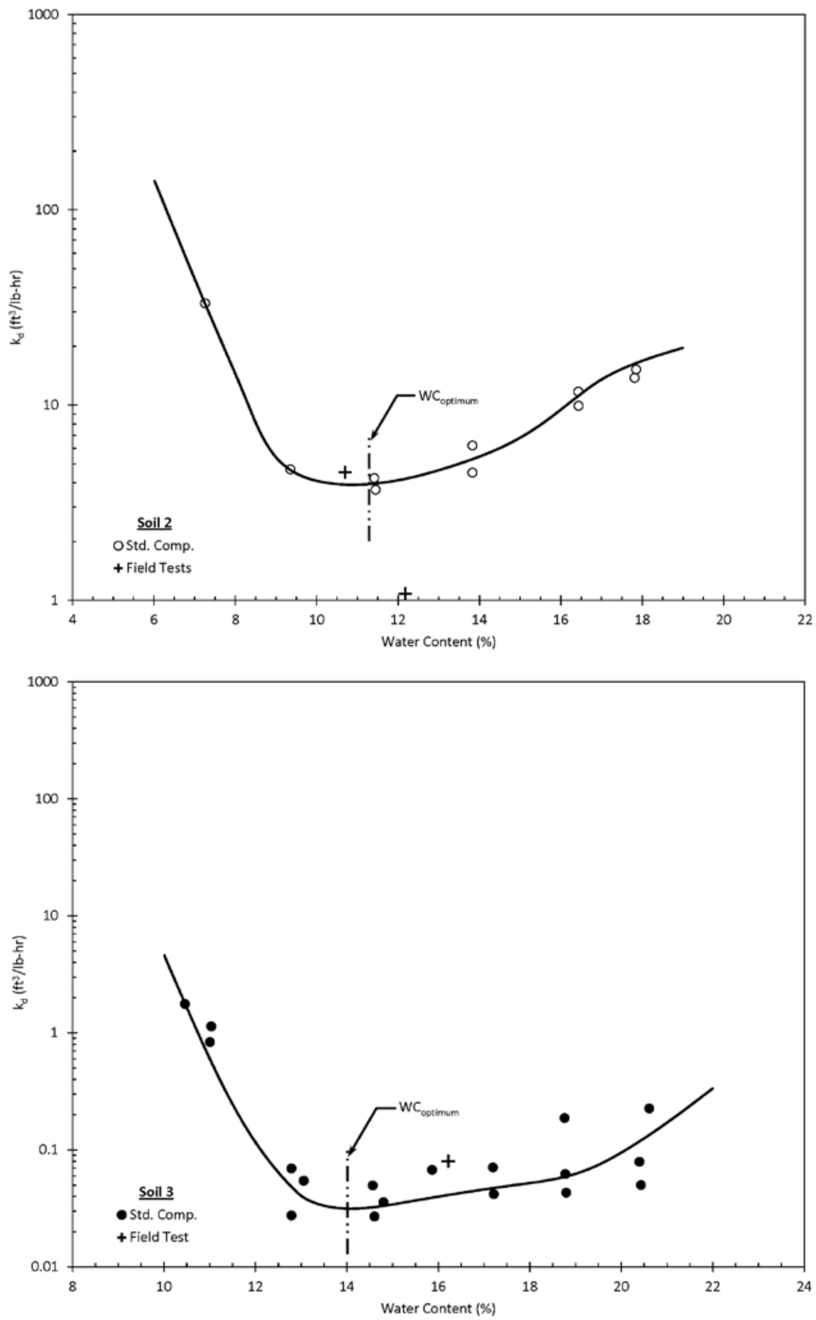


Figure 7. k_d versus Compaction Water Content for Different Compactive Efforts (low, "Standard", and "Modified" Proctor, based on energy level in Kg-cm/cm^3) for a low plasticity clay (after Hanson et al., 2011). SC indicates testing performed in conjunction with flume tests that measured scour rates, and HC indicates testing associated with flume tests of headcut advance rates.

Figure 8 presents results from Hanson and Hunt (2007) indicating a slightly different relationship for the SM and slightly dispersive CL materials tested in their study, with these materials showing less immediate increase in k_d than materials presented in Figure 7 when compacted dry of optimum. Similar results were found in Wahl (2009).



	Grain Size					Standard Compaction		
Soil	% Sand > 2.95 x 10^{-3} in	% Fines > 7.87 x 10^{-5} in	% Fines < 7.87 x 10^{-5} in	Plasticity Index PI	% Dispersion	γ_{dmax} (psf)	WC_{opt} (%)	Soil Classification
2	63	31	6	NP	0	116.80	11.0	SM-Silty Sand
3	25	49	26	17	20	111.06	13.9	CL-Lean Clay

Figure 8. Variation of k_d with variation in compaction moisture content (after Hanson and Hunt 2007)

Figure 9 presents the measured values of k_d from Hanson et al. (2010 and 2011), Wahl (2009) and Shewbridge et al. (2010), suggesting that k_d may also vary with plasticity index, decreasing with increasing plasticity, consistent with the erosion classification chart of Briaud (2008). Unfortunately "paired" samples for "dry" and "wet" comparisons of many of the higher plasticity materials are not available to confirm higher erodibility if compacted and tested with water content dry of optimum.

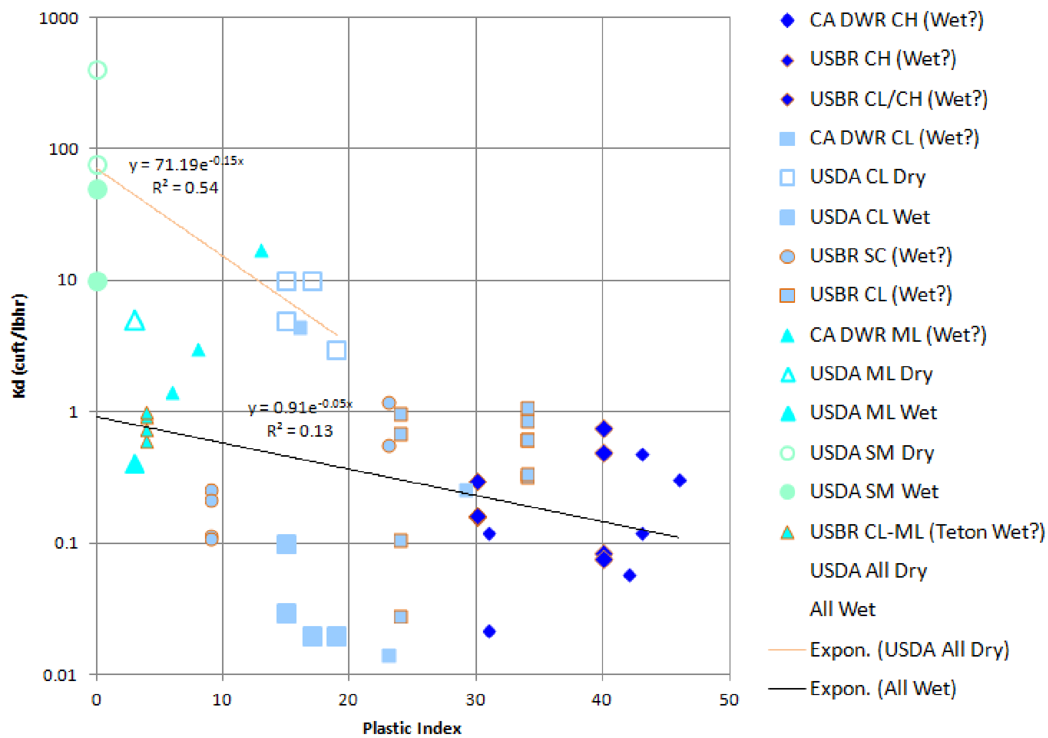


Figure 9. k_d versus Plastic Index from tests by Hanson et al. (2010 and 2011), Wahl et al. (2009) and Shewbridge et al. (2010).

While Briaud (2008) suggests that gravels have medium to low erodibility and thus lower expected values of k_d and τ_c, unfortunately there is little to no test data available at this time to confirm this supposition. Nevertheless, it seems reasonable to presume that both parameters are sensitive to the amount and type of finer grained materials surrounding the gravel (when a sufficient fraction of fines is present to fill the voids between the gravel and allow the fines to experience compaction), as well as the inclination of the eroding surface. Steep erosion surfaces (i.e., inclined near the friction angle of the gravels), comprised of poorly graded gravels with little sand and little to no fines, might have high erodibility until the eroding surface flattens below the angle of repose. In contrast, relatively flat erosion surfaces (i.e., inclined at say 70% of the friction angle of the soil), with appreciable sand and fines (e.g., GW-GC or GC) may have very low erodibility, approaching that of jointed rock. In a review of the breach parameter regression equations of Xu and Zhang (2009), Wahl (2014a) suggests, based on review of dam breach case studies, that medium erodibility may be an appropriate designation for rockfill dams. Unfortunately there is little empirical evidence to support the above speculations and until more research data becomes available, the analyst will have to apply judgment when selecting values for k_d and τ_c to model breaches in embankments comprised of these types of materials.

Estimating representative modelling values for k_d and τ_c for soils with variable constituents compacted at various water contents requires some consideration of the relative proportions, magnitudes and scales of the discontinuities. Relatively heterogeneous mixtures of low, medium and high erodibility materials may have relative low erodibility if the low and medium erodibility materials provide "protection" for the highly erodible materials. In contrast, mixtures with extensive areas of high erodibility materials may not experience any benefit from a small proportion of low erodibility materials (Figure 10) if the more erodible materials undermine the more resistant ones. Direct weighted averaging of constituent concentrations is unlikely to give appropriate estimates of average erodibility;

some consideration of spatial distribution is likely necessary. Wahl (2014b) suggests that in some cases, JET testing of reconstituted samples stripped of larger materials (e.g., gravels) may give reasonable estimates of average properties. Again, at this time the literature does not provide complete guidance and the analyst must apply judgment to develop a good estimate of the expected behavior.

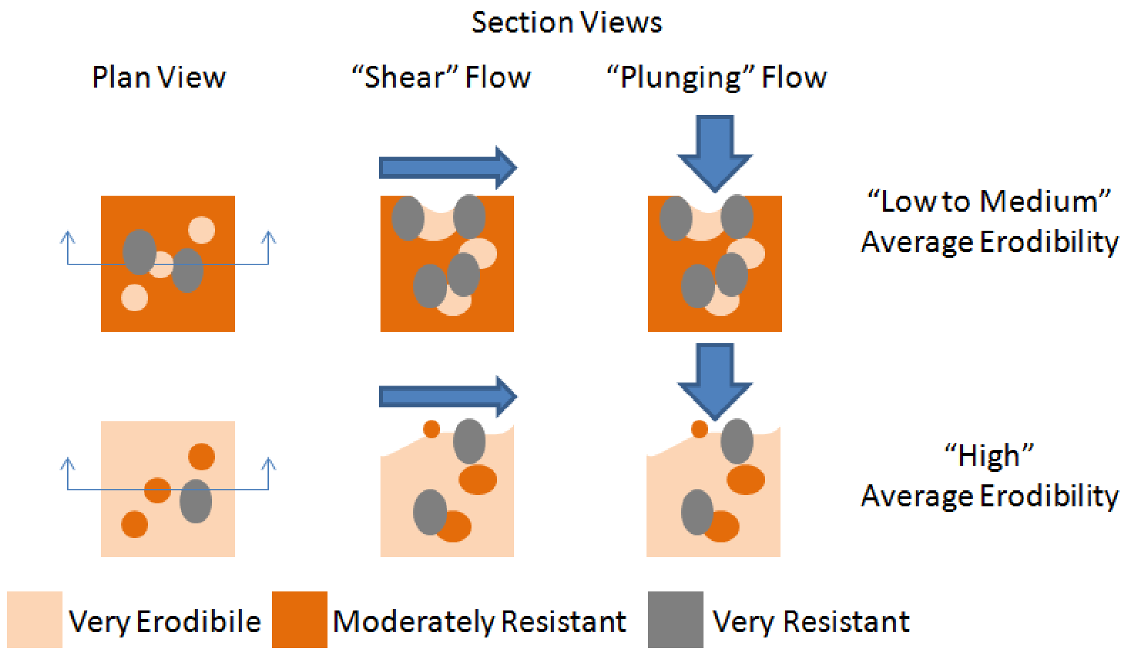


Figure 10. Material composition affects average erodibility for modelling different composite materials such as a gravelly clay (CL - upper material) and a gravelly silt (ML - lower material). Distribution and relative proportions are both important.

“Native” materials may also need to be considered in erosion and breach analysis and are affected by many of the same factors discussed above, but may also be affected by geologic processes that will increase or decrease the erosion resistance. In general, materials that have experienced high stresses in the past, such as glaciated foundation clays and well-consolidated claystones, will behave like materials that have been compacted under very high compactive effort, resulting in lower erodibility. Similarly, older deposits often will have some amount of natural cementation, which can impart considerable erosion resistance, but may also be vulnerable to degradation through solutioning water flows and/or through slaking or other wetting/drying processes. Wahl (2014b) (Figure 11) found a trend of increasing erosion resistance in compacted specimens that were cured at their compaction moisture content for extended times before testing and may have experienced cementation.

Furthermore, both native and engineered fill materials are subject to various processes, such as shrinking and swelling with seasonal variations in moisture; this may result in cumulative change in erosion characteristics over time, with deeper material being less and shallower material being more susceptible to those changes. Finally most erosion tests are conducted on samples that are compacted and tested at the same water content, immediately after compaction, which may not reflect in situ conditions. Based on limited anecdotal evidence, in some situations, it is possible that moisture conditioning over time and at relatively high confining stresses in situ could diminish the flocculated clay structure that may form in plastic clays compacted dry of optimum, resulting in an increase in erosion resistance with time (Wahl 2015). This may explain in part why undisturbed samples of saturated silts and clays retrieved from levees in California and tested in the EFA device (Shewbridge et al. 2010) have lower erodibility than laboratory compacted samples of many of the compacted, unsaturated silts and clays tested in the JET apparatus by USDA and USBR. Again, at this time the literature does not provide complete guidance and the analyst must apply judgment.

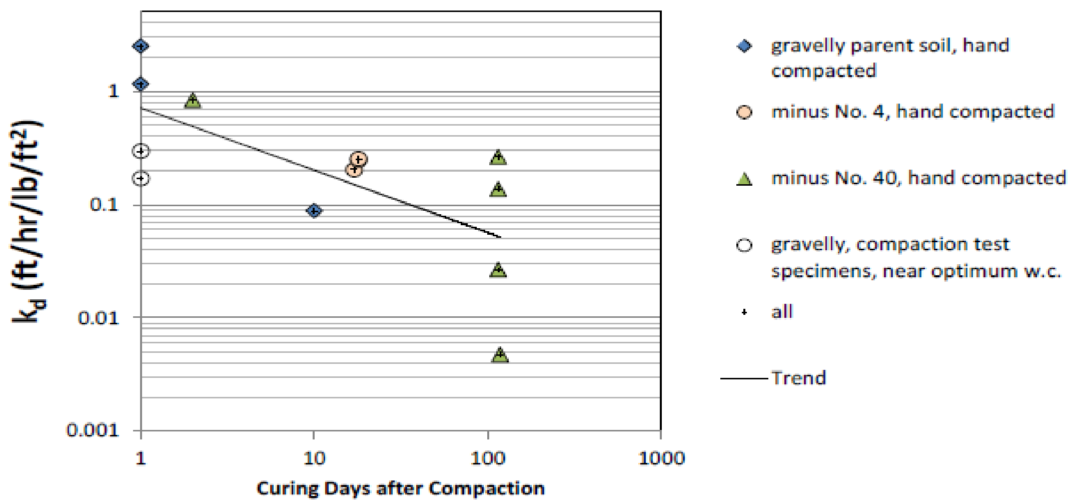


Figure 11. Jet erodibility test results versus specimen curing time after compaction.

4. OVERTOPPING WAVE EROSION RATE ESTIMATES

At this time, physically based methods, such as those described above for river currents against the levee face and steady overtopping flow, are inadequate for capturing the dynamic, erosional process involved under unsteady flow wave overtopping conditions. Often using the above equations, the erosion rate will be significantly underestimated. Therefore, empirical relationships developed during testing by Colorado State University (CSU) under contract with the USACE, New Orleans District (Thornton et al., 2010) for the post-Katrina reconstruction of New Orleans were used to develop interim guidance until further research and development can be completed. The testing program evaluated proposed levee erosion control materials on the landward (protected) side of levees during wave overtopping conditions resulting from extreme storm surge events (greater than a 0.01 annual chance exceedance). Example wave overtopping erosion rates for bare clay estimated using the CSU tests results are presented in Table 1.

Table 1. Overtopping Wave Erosion Rates

Bare Clay	q = 0.1 cfs/ft	q = 0.2 cfs/ft
3:1 (H:V) Slope	1 ft/hr	2 ft/hr
25:1 (H:V) Slope	0.5 ft/hr	-

5. RISK INFORMED DESIGN PROCESS

Designs that will allow no erosion generally require that the critical shear stress limit of the armoring material not be exceeded. At this time there is no standard "factor of safety" and local practice and engineering judgment are required to select an appropriate value. Designs that allow some amount of erosion will require trade-offs between amount of erosion allowed in various scenarios, reliability and long-term maintenance costs; again there are no specific design criteria. Instead, design alternatives will be evaluated in a risk-informed process.

In general, the erosion mitigation system components are evaluated using Potential Failure Modes Analyses, in which the conditional probability of various "events" occurring that will lead to inundation due to the system component failure or poor performance are evaluated in an event tree framework using a variety of methods, including probabilistic analyses and expert elicitation (Figure 12). These event tree analyses are done for all potential loading frequencies and are combined, yielding system response or "fragility" curves which are functions of load frequency and associated load level. Integration over all loadings yields an estimate of the expected performance and is portrayed in a number of different ways, including estimates of average annual probability of failure. Combined with the estimate of consequences for each loading level, the flood risk of the system can be evaluated. Using a combination of traditional planning processes and newer life-safety evaluation methods, the "tolerability" of the reliability of the system can be evaluated. If inadequate, the same process can then be used to evaluate the risk reduction that can potentially be achieved through structural and non-structural measures. In general, system reliability requirements will be greater for areas of high population and high potential consequences. See Shewbridge et al. (2015) for more information.

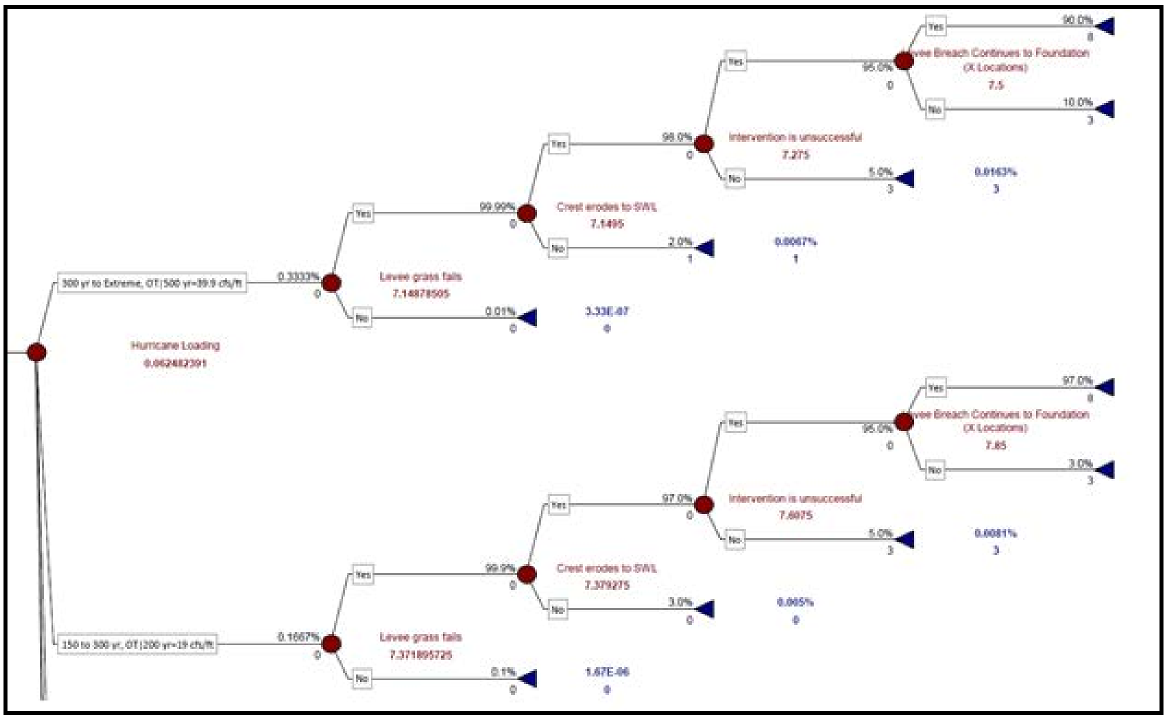


Figure 12. Example Wind Wave Overtopping Failure Event Tree.

6. CONCLUSION

After nearly forty years, the USACE is updating design guidance for levees, retaining the knowledge and performance experience gained from traditional design, construction and operations processes and incorporating it into a risk-informed evaluation, decision and design process to improve levee system erosion reliability commensurate with the evolving needs of society.

7. REFERENCES

Briaud, J.-L., Ting F., Chen, H.C., Cao Y., Han S. -W., Kwak K. 2001. Erosion Function Apparatus for Scour Rate Predictions. Journal of Geotechnical and Geoenvironmental Engineering. ASCE, Vol. 127, N. 2, pp. 105-113.

Briaud, J.-L., Chen, H.C., A.V. Govindasamy, and R. Storesund 2008 "Levee Erosion by Overtopping in New Orleans During the Katrina Hurricane" J. Geotech. Geoenviron. Eng. 2008.134:618-632.

Briaud, J.-L., 2008, “Case Histories in Soil and Rock Erosion: Woodrow Wilson Bridge, Brazos River Meander, Normandy Cliffs, and New Orleans Levees”, The 9th Ralph B. Peck Lecture, Journal of Geotechnical and Geoenvironmental Engineering, Vol. 134, ASCE, Reston Virginia, USA.

Hanson, G. J., and A. Simon, 2001, “Erodibility of cohesive streambeds in the loess area of the midwestern USA” Hydrol. Process. 15, 23–38 (2001)

Hanson, G. J., and A. Simon, 2002, “Discussion of ‘‘Erosion Function Apparatus for Scour Rate Predictions’’ by J. L. Briaud, F. C. K. Ting, H. C. Chen, Y. Cao, S. W. Han, and K. W. Kwak” J. Geotech. Geoenviron. Eng. 2002.128:627-628.

Hanson, G.G. and S. Hunt, 2007 “Lessons Learned Using Laboratory JET Method to Measure Soil Erodibility of Compacted Soils” ” Applied Engineering in Agriculture Vol. 23(3): 305-312

Hanson, G.J., T. Wahl, D. Temple, S. Hunt, and R. Tejral, 2010, “Erodibility Characteristics of Embankment Materials” Proceedings Association of State Dam Safety Officials Annual Conference

Hanson, G.J., D.M. Temple, S.L. Hunt, and R.D. Tejral, 2011, “Development and Characterization of Soil Material Parameters for Embankment Breach” Applied Engineering in Agriculture Vol. 27(4): 587-595

Shewbridge, S.E., Perri, J., Millet, R., Huang, W., Vargas, J., Inamine, M., Mahnke, S., (2010) “Levee Erosion Prediction Equations Calibrated with Laboratory Testing”, Proc, V International Conference on Scour and Erosion, San Francisco, CA

Shewbridge, S.E., M. Navin, N. Schwanz, N. Vroman (2015) Upcoming Changes for EM 1110-2-1913: Design Construction and Evaluation of Levees”, Proc Association of State Dam Safety Officials Annual Conference

Shields, A. (1936). ‘‘Anwendung der Aenlichkeitsmechanik und der Turbulenzforschung auf die Geschiebebewegung (Application of “similarity” mechanics and turbulence research on the glacial movement.’’ Mittleilungen der Preussischen Versuchsanstalt fur Wasserbau und Schiffbau, W. P. Ott and J. C. Van Uchelen, translators, California Institute of Technology, Pasadena, Calif

Thornton CI, Scholl BN, Abt SR (College of Engineering, Colorado State University, Fort Collins, CO). 2011 Jun. Wave overtopping simulator testing of proposed levee armoring materials. New Orleans: US Army Corps of Engineers. 302 p.

URS. 2007. Erosion Toolbox: Levee Risk Assessment Methodology: Users Manual. Report prepared for the United States Army Corps of Engineers. 113p.

Wahl, T.L. 2009 “Quantifying Erodibility of Embankment Materials for the Modeling of Dam Breach Processes” ASDSO Conference Proceedings

Wahl, T.L., 2014a, “Evaluation of Erodibility-Based Embankment Dam Breach Equations,” Hydraulic Laboratory Report HL-2014-02, U.S. Bureau of Reclamation

Wahl, T.L., 2014b “Measuring Erodibility of Gravelly Fine-Grained Soils” Hydraulic Laboratory Report HL-2014-05, U.S. Bureau of Reclamation

Wahl, T.L., 2015 Personal Communication

Xu, Y. and L.M. Zhang, 2009. Breaching parameters for earth and rockfill dams. *Journal of Geotechnical and Geoenvironmental Engineering*, 135(12):1957-1970.