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Calculation of Levee-Breach Widening Rates

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Cover photo: Photo documents the Clear Creek Levee breach resulting from the 2019 runoff event along the Missouri River in Clear Creek, Nebraska, March 22, 2019. (Photo by USACE, Omaha District)

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Abstract

Inundation modeling is often conducted for levee systems to understand current flood risks. The extent of inundation caused by a breach in the levee is highly influenced by the widening rate of the levee breach. This study presents an approach for calculating levee-breach widening rates based on average flow velocity through the breach, embankment height, and erosion characteristics of the soil. Estimates of soil erodibility are derived through an analysis of the measurements of soil erodibility presented in the National Cooperative Highway Research Program (NCHRP) Report 915 database. Levee-breach widening rate curves are calculated based on these erosion properties to demonstrate the approach, and default curves are presented for typical levees built from coarse-grained soils and fine-grained soils. While the most accurate approach for a site is to calculate site-specific widening rate curves based on estimates of local soil erodibility, the default curves presented provide a suitable starting point for initial inundation modeling.

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Preface

This study was conducted for the U.S. Army Corps of Engineers, Headquarters, under Project "Surface Erosion of Coarse-Grained Material," Funding Account Code 8JGK75. The technical monitor was Dr. Julie D. Rosati, CZT.

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COL Teresa A. Schlosser was the Commander of ERDC, and Dr. David W. Pittman was the Director.

1 Introduction

1.1 Background

In order to adequately characterize risks associated with flooding, it is imperative to accurately analyze flood inundation due to overtopping and breaching of embankments. While modeling of flooding due to overtopping is relatively straightforward, modeling embankment breaching is quite complex and fraught with uncertainties. Decades of research into predicting the evolution of embankment breaches have been conducted, with the majority of this research focused on dams (e.g., West et al. 2018; Morris et al. 2018). As a result, numerous empirical equations have been developed for predicting dam breach geometries and times of development (e.g., von Thun and Gillette 1990; Froehlich 1995 and 2016; Xu and Zhang 2009), and many physics-based models have been developed for predicting breach evolution in embankment dams (e.g., Morris 2011; Hassan et. al 2002; Temple et al. 2005; Temple et al. 2006; Wang and Bowles 2006; and Wu 2013). Comprehensive reviews of the present body of knowledge on these predictive methods have been prepared by many authors. As such, a detailed review of these methods is not presented in this report. Instead, the authors refer the interested reader to Saucier et al. (2009); Zhenzhen (2015); Wang (2018); and West et al. (2018) for detailed treatments of the topic.

1.2 Purpose

While previous studies emphasized prediction of breach development for dams, the past decade in the United States has seen growing emphasis on modeling flood risk associated with levees. Unfortunately, very little research has been conducted specifically for analysis of breaching in levees. Even though the physics-based models developed for dams are sometimes applicable to levees, software that has been developed to date has targeted dams. Therefore, existing tools are quite difficult to apply to levee problems due to the many differences in hydraulic routing between dams and levee problems (Risher and Gibson 2016). Additionally, data sets used for development of empirical regression equations for dams are likely not directly applicable to levees (Saucier et al. 2009). As a result, levee breaches in the United States are most commonly assessed by using the Simplified Breach Analysis Method implemented in HEC-RAS 5.0

(Brunner 2016). This approach requires the user to specify the breach widening rate as a function of the mean velocity through the breach opening. Unfortunately, widening rates for levee breaches are not commonly available, and additional guidance is needed to aid users in the development of these widening rate functions used in HEC-RAS. An approach for calculating the widening rate function based on the levee soil erodibility and embankment height is presented herein. The approach presented can be used to calculate widening rate functions for use in HEC-RAS to predict flood inundation associated with levee breaches.

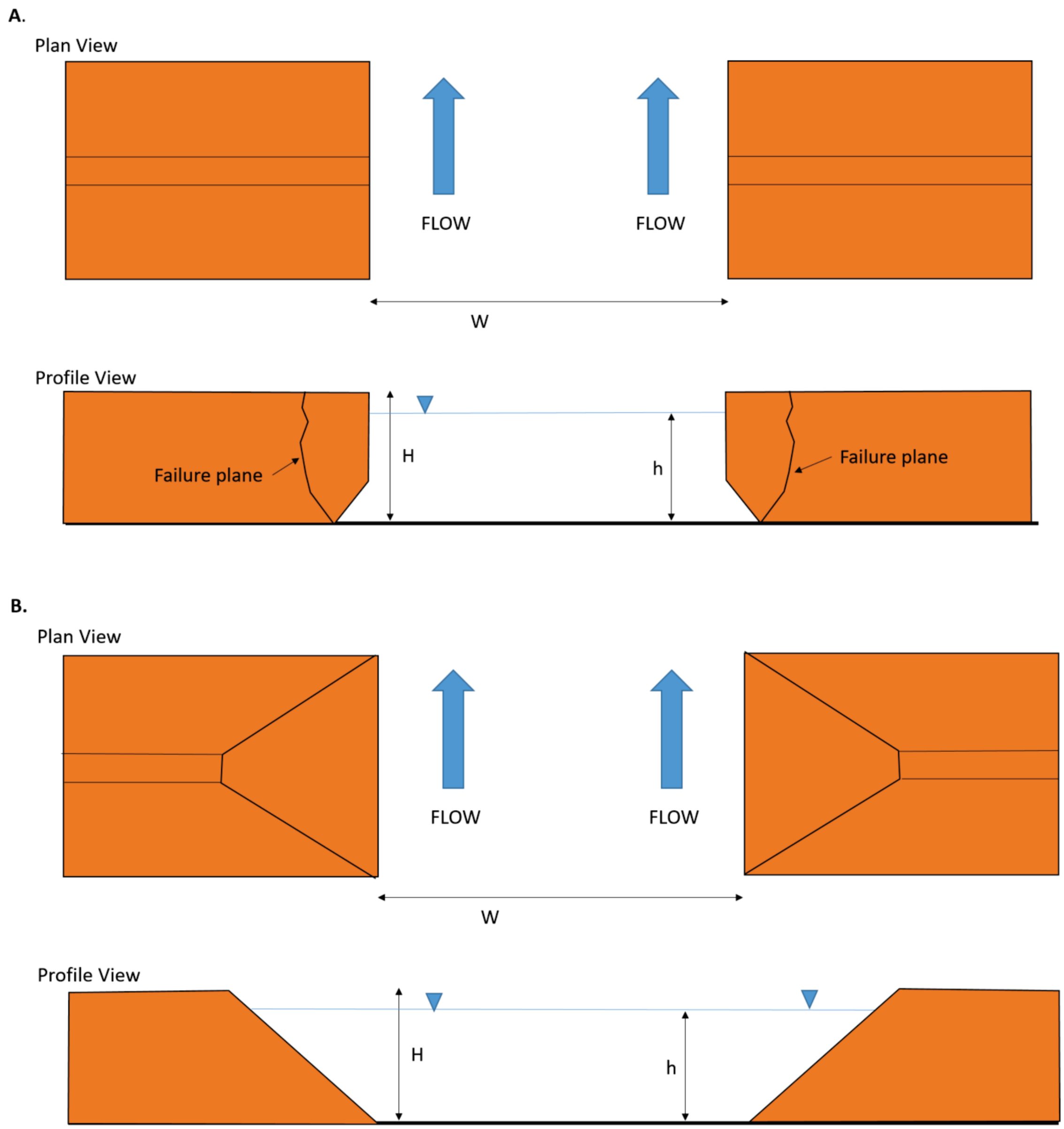
2 Calculation of Widening Rate

An illustration of a breach in a levee of height H is shown in Figure 1 in both plan view and profile view for a levee constructed of (A) cohesive material and (B) cohesionless material. Most levee breaches form due to either overtopping or internal erosion. Regardless of the mechanism, a complete breach will form at some point, as illustrated in Figure 1. Once a complete breach has formed, the mechanism for breach enlargement relies entirely on breach widening due to erosion of the exposed sides of the levee.

In the case of cohesive soils, as shown in Figure 1A, erosion at the bottom of the breach sides leads to undercutting of the soil mass. Once sufficient erosion has occurred, the sides of the breach collapse into the breach opening and are swept away by the swift currents through the breach. The toe of the slope must be gradually eroded again until the side of the breach is destabilized once more. In this manner, the erosion rate at the bottom of the breach sidewall controls the overall widening rate of the breach.

In the case of cohesionless soils, as shown in Figure 1B, the breach side slopes cannot support a vertical face. This condition is likely quite rare in nature as even sand levees will hold a vertical face when in a partially saturated state. Nevertheless, should a sloped face occur on a levee breach, the toe of the slope will be eroded such that the slope continuously sloughs into the breach opening. The continuous sloughing of the sloped surface will lead to the breach widening at the rate in which the toe erosion is occurring. Thus, it is readily seen that the erosion rate at the bottom of the breach sidewall again controls the breach widening rate. Despite the greatly differing erosion mechanisms for cohesive and cohesionless soils, the erosion rate near the bottom of the sidewall controls the overall widening rate. This was also noted by Morris (2011), who examined the influence of the block failure mechanism on the breach widening rate and found the influence to be negligible due to the material being quickly removed by the currents through the breach.

Figure 1. Illustration of levee-breach widening processes in (A) cohesive soil and (B) cohesionless soil.



The erosion of soil is commonly described by the expression

$$\epsilon = k_d(\tau - \tau_c) \quad (1)$$

where the erosion rate (ϵ) in length per unit time is a function of soil erodibility k_d (m^3/Ns), soil critical shear stress τ_c (Pa), and hydraulic boundary shear stress τ (Pa). The breach widening rate (dW/dt) is equal to twice the erosion rate at the toe, as erosion is occurring in both directions. The breach widening rate is thus defined as

$$\frac{dW}{dt} = 2k_d(\tau - \tau_c) \quad (2)$$

The soil erodibility k_d and critical shear stress τ_c are soil properties that can be measured through tests, such as the jet erosion test (Hanson and Cook 1997), or the erosion function apparatus (Briaud et al. 1999). If measurements are not available, general correlations for k_d and τ_c can be used (Briaud et al. 2019).

The applied boundary shear stress τ must also be determined to find the breach widening rate. The shear stress at the toe of the breach sidewall can be estimated by the equation

$$\tau = \gamma_w R_h S_o \quad (3)$$

where γ_w denotes the unit weight of water, R_h is the hydraulic radius of the breach cross section, and S_o is the friction slope through the breach. Approximating the breach as being rectangular in cross section with width W and flow depth h, the hydraulic radius is given by the expression

$$R_h = \frac{Wh}{W+2h} \quad (4)$$

For $W \gg h$, Equation 4 becomes

$$R_h = h \quad (5)$$

Making this assumption is convenient, as it allows the widening rate to be calculated independently from the breach dimensions.

Finally, to relate the widening rate to the velocity through the breach, Manning's equation is used to relate the average velocity to the friction slope through the breach. Manning's equation is

$$V = \frac{k}{n} R_h^{\frac{2}{3}} S_o^{\frac{1}{2}} \quad (6)$$

where V denotes the average velocity through the breach, k is a constant dependent on system of units (k=1.49 in English units and 1.0 in SI units), and n is the Manning's roughness factor. Solving Equation 6 for S_o, substituting into Equation 3, and subsequently substituting into Equation 2 yields the following expression for the breach widening rate

$$\frac{dW}{dt} = 2k_d(\gamma_w R_h^{-\frac{1}{3}} \left[\frac{n}{k} V\right]^2 - \tau_c) \quad (7)$$

The same assumptions made here were also made by Van Damme (2020) for calculating widening rate. However, Van Damme used a different approach for determining soil erodibility and also incorporated the weir equation into the widening rate expression rather than leaving it in terms of V. By using Equation 2 for soil erodibility, Equation 7 for the breach widening rate makes use of soil erosion properties commonly used on USACE risk assessments. Additionally, by leaving Equation 7 in terms of the average velocity through the breach, widening rate curves can be computed from Equation 7 that are directly compatible with the Simplified Breach Analysis Method in HEC-RAS 5.0. A review of soil erosion parameters is presented in the following section. These parameters will then be used to demonstrate how to calculate erosion widening rate curves using Equation 7.

3 Erosion Characteristics of Soils

The NCHRP database of erosion parameters developed by Briaud et al. (2019) represents the most comprehensive data set of soil erodibility available. This database was therefore used to estimate reasonable values of soil erodibility (k_d) and critical shear stress (τ_c). Only two soil categories were evaluated: coarse-grained soils and fine-grained soils common in levee construction.

For the coarse-grained soil category, the NCHRP database of 975 samples was filtered down to only those samples categorized as predominantly sandy soils. This included the Unified Soil Classification System (USCS) categories of SC, (SC)g, SC-SM, SM, SM-SC, SP, SP-SC, SP-SM, SW, and SW-SM (ASTM D2487 2017). These USCS groups essentially include all soil types that are 50 percent or more sand with up to 49 percent fines of any type (low plasticity or high plasticity). Only database entries that reported a single measurement value were included in this analysis. The NCHRP database contained 209 measurements of k_d and 207 measurements of τ_c for this soil category. The resulting distributions for each parameter are shown in Figures 2 and 3, respectively. For this cursory look at breach widening rates, the mean values of the data (Table 1) will be used as the representative values in the calculations.

For the fine-grained soil category, the NHCRP database was filtered down to only those samples categorized as predominantly clay or silt. This included the USCS categories of CH, (CH)s, CL, CL-CH, (CL)s, CL-SC, MH, (MH)s, ML, (ML)s, and ML-CL. Once again, only database entries that reported a single measurement value were included in this analysis. The NHCRP database contained 553 measurements of k_d and 552 measurements of τ_c for this soil category. The resulting distributions for k_d and τ_c are shown in Figures 4 and 5, respectively. Once again, mean values of the data (Table 1) will be used as representative values in calculations of the widening rate curves that follow.

Table 1. Average erosion parameters for coarse- and fine-grained soil categories.

Soil Category	Avg. k_d (mm/hr-Pa)	Avg. τ_c (Pa)
Coarse Grained	296.6	17.6
Fine Grained	16.6	86.5

Figure 2. Histogram of measurements of k_d for coarse-grained soil category.

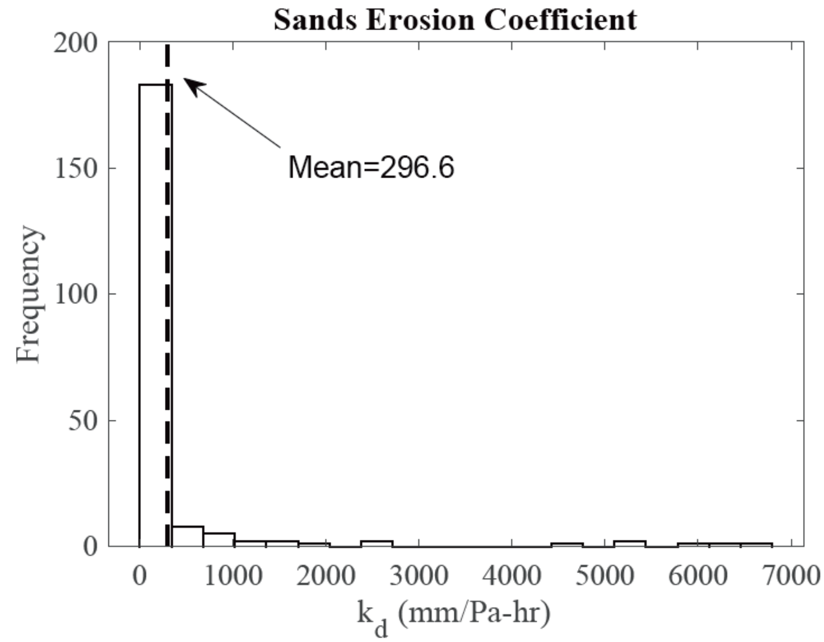


Figure 3. Histogram of measurements of τ_c for coarse-grained soil category.

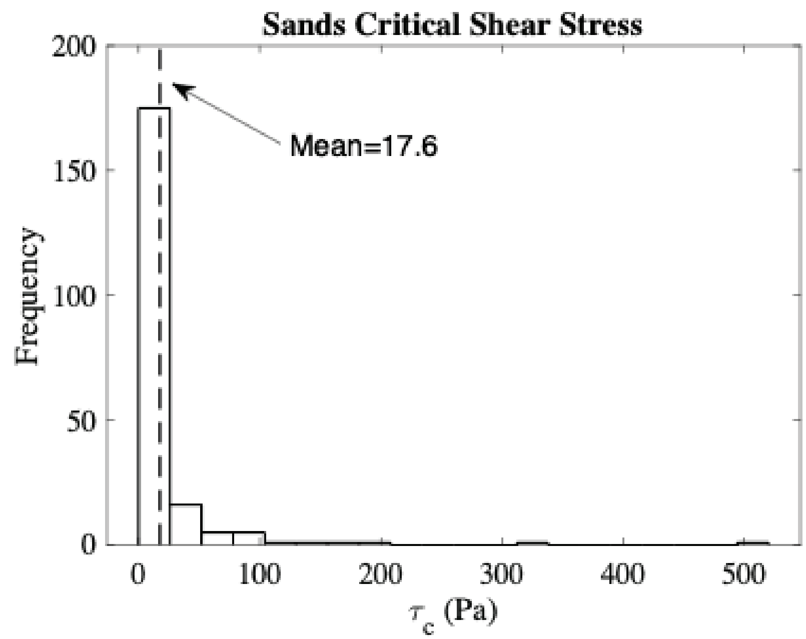


Figure 4. Histogram of measurements of k_d for fine-grained soil category.

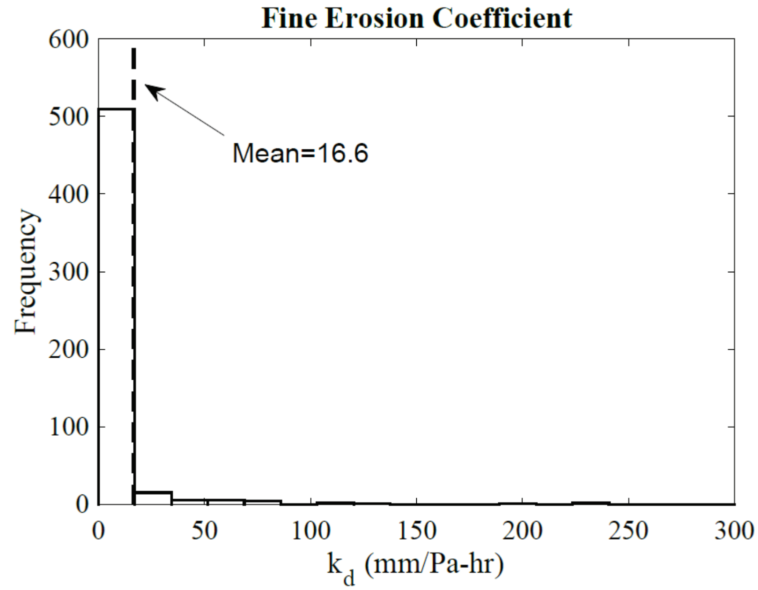
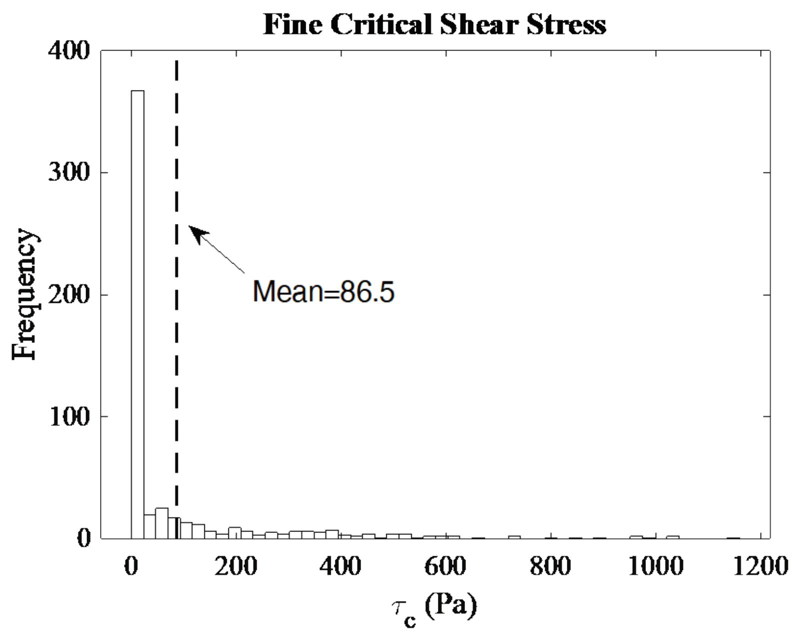


Figure 5. Histogram of measurements of τ_c for fine-grained soil category.



4 Sample Widening Rate Curves

To demonstrate the calculation of breach widening rate curves for use in HEC-RAS, the average soil erosion characteristics for fine- and coarse-grained soils from Table 1 are used to calculate sample widening rate curves. For these calculations, it was assumed that the levee was 15 ft in height. It was also assumed that the depth of flow through the breach was equal to the height of the levee (i.e., $h = H$), and Equation 5 was used for the hydraulic radius. The Manning's n-value was assumed to be 0.034, as it seemed to be an appropriate value for a relatively rough earth channel (Phillips and Tadayon 2006). Under these assumptions, Equation 7 for the widening rate becomes

$$\frac{dW}{dt} = 2k_d(0.0132V^2 - \tau_c) \tag{8}$$

where k_d is expressed in units of ft/hr/psf, and τ_c is in units of psf. Equation 8 can be used with soil erosion properties of any soil to determine the widening rate curves for a levee 15 ft in height. Using the mean values of k_d and τ_c from Table 1 yields the levee-breach widening rate curves illustrated in Figure 6. The calculated widening rates are also tabulated in Table 2. While these sample curves may be used for breach analysis, it must be recognized that the variability in erosion properties is extremely large (Figures 2-5). Large errors will result from using these curves if the erosion properties of the levee material being modeled deviate substantially from the mean values shown in Table 1.

The sample widening rate curves illustrated in Figure 6 will be used as a baseline for sensitivity analyses in the following section.

Figure 6. Sample widening rate curves for H = 15 ft using mean soil erosion properties.

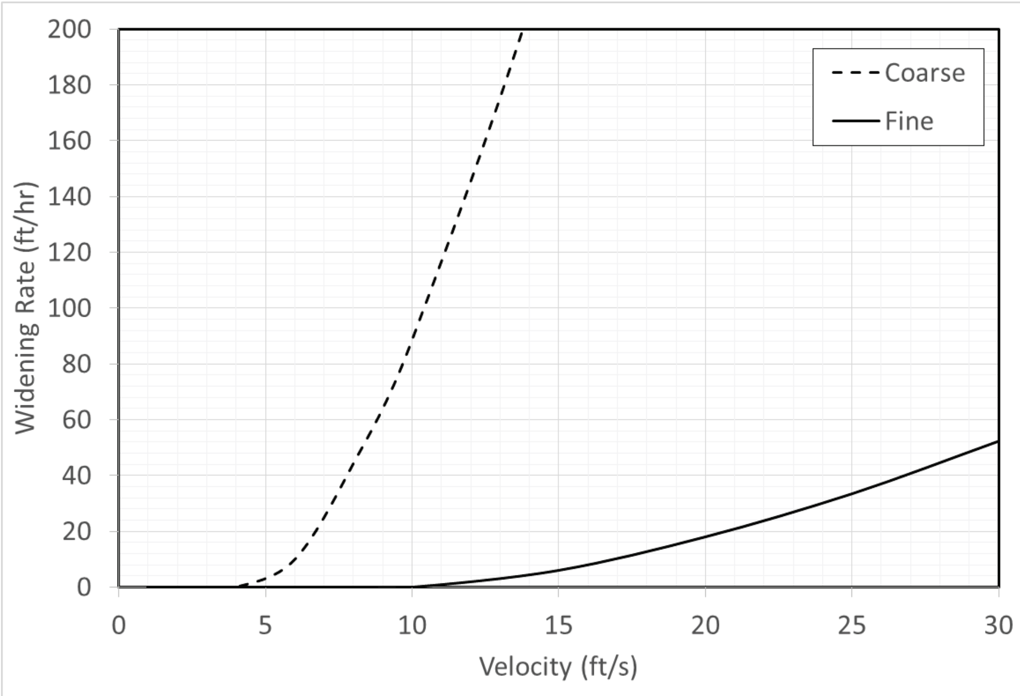


Table 2. Sample widening rate curves for H = 15 ft using mean soil properties.

	Coarse Soil	Fine Soil
V(ft/s)	dW/dt (ft/hr)	dW/dt (ft/hr)
1	0	0
1.5	0	0
2	0	0
3	0	0
4	0	0
6	10	0
8	44	0
10	89	0
15	242	6
20	457	18
25	733	33
30	1,071	52

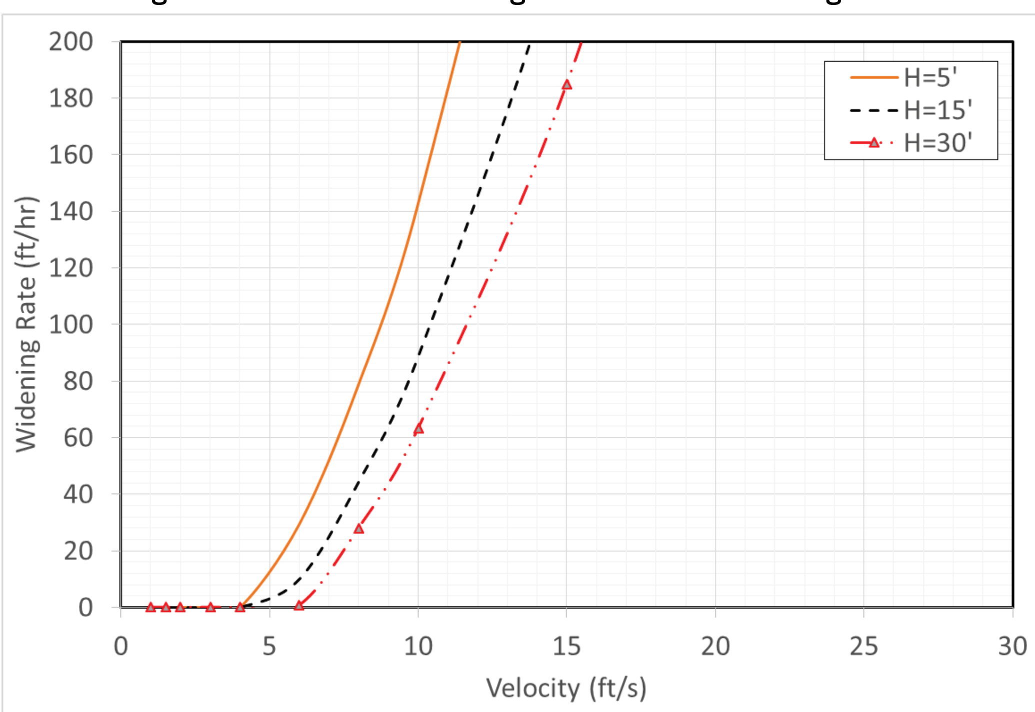
5 Sensitivity Analyses

The baseline widening rate curves presented in the previous section were calculated by using the mean soil properties and a levee height of 15 ft. The authors expect that many scenarios will deviate substantially from the baseline presented due to the variability in levee heights and soil properties that may be encountered. To provide insight into how these variables may alter the baseline curves, the following sections present sensitivity analyses in which the levee height and soil properties are independently varied. Only the coarse-grained baseline curve was used for the purposes of the analyses in this section.

5.1 Influence of levee height

The height of the levee influences the calculated breach widening rate as it determines the hydraulic radius of the breach opening. To demonstrate the influence of levee height, the base case was rerun using levee heights of 5 ft and 30 ft. The results are illustrated in Figure 7. As shown, the widening rate increases as the levee height decreases for a given average velocity through the breach opening. Conceptually, this can be explained by the proportionality of boundary shear stress to the average fluid shear rate. As the levee height decreases, the shear rate in the fluid increases. This results in an increased boundary shear stress and higher breach widening rates.

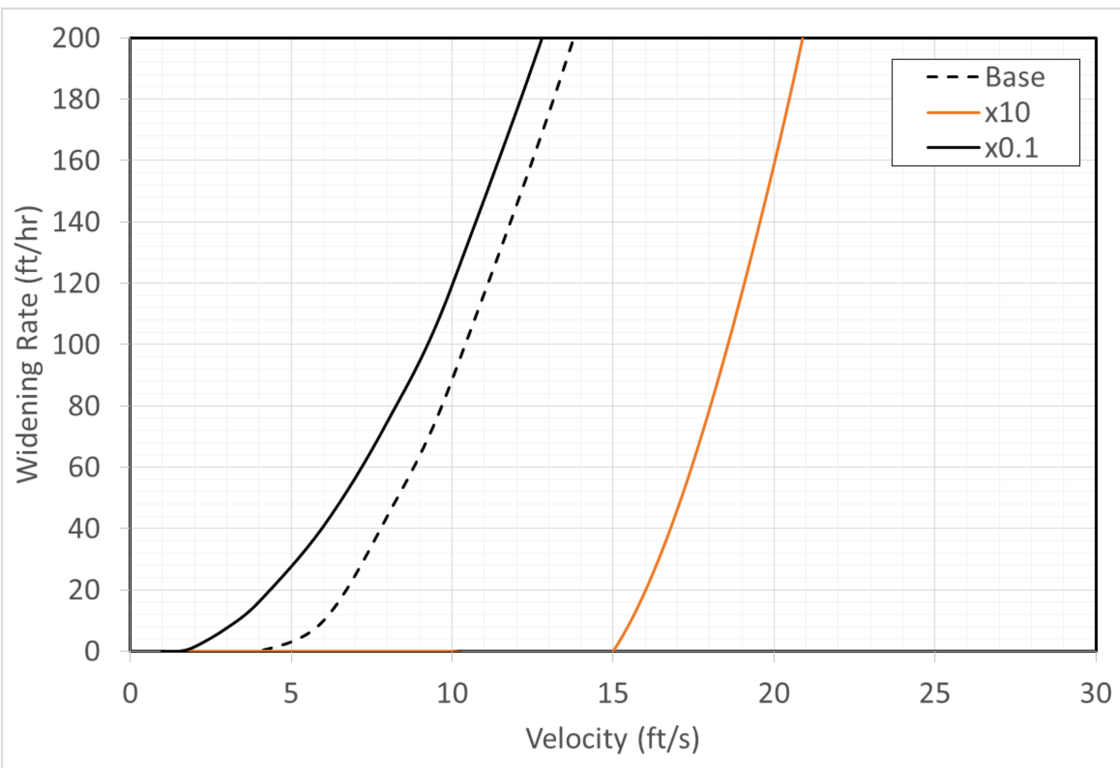
Figure 7. Influence of levee height on calculated widening rates.



5.2 Influence of critical shear stress (τ_c)

The critical shear stress of the soil dictates the threshold velocity at which erosion initiates. As such, the critical shear stress has a large influence on the breach widening rates. To illustrate the relative influence, the base curve for the coarse soil was recalculated using multipliers on τ_c of 0.1 and 10. The results are illustrated in Figure 8. As shown, an increase in τ_c causes the widening rate curve to shift to the right. As a high value of critical shear stress will yield no breach growth until the critical velocity is reached, high values of τ_c should be used with caution. Using a value of τ_c that is too high will prevent breach growth, leading to unconservative inundation model results.

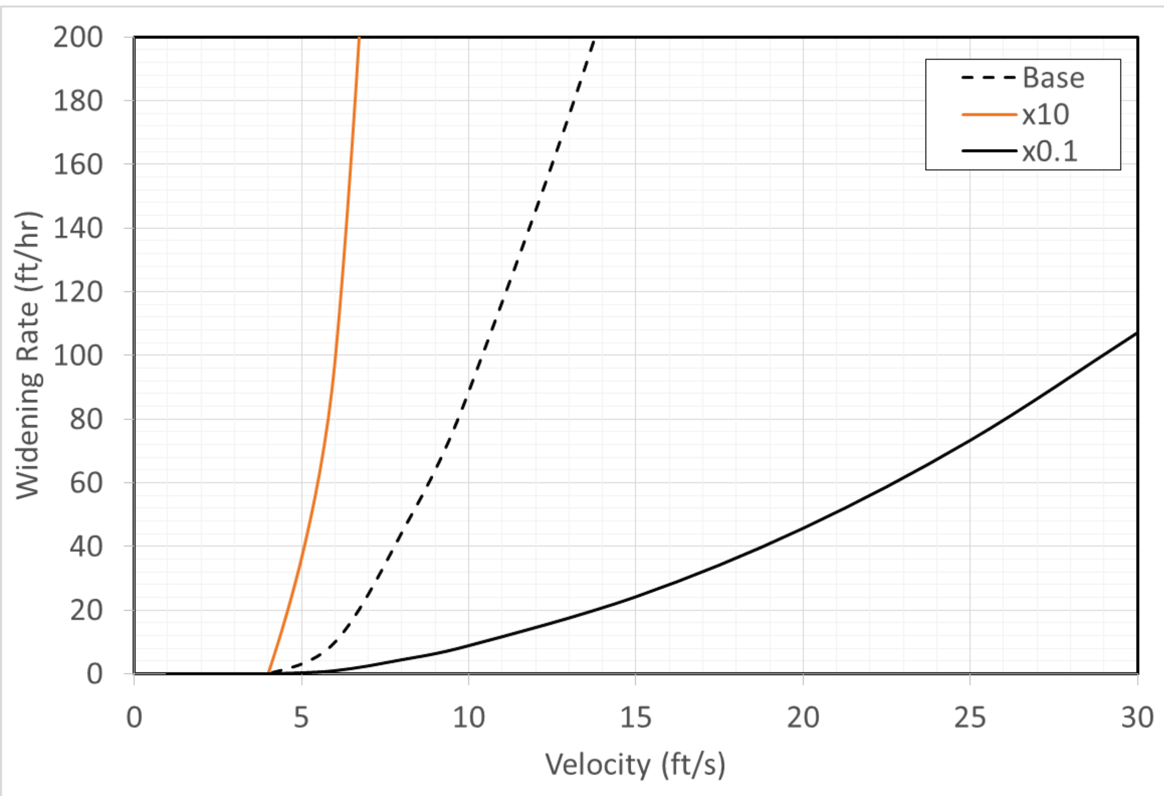
Figure 8. Influence of critical shear stress τ_c on breach widening rates.



5.3 Influence of erosion coefficient (k_d)

While the value of critical shear stress dictates the threshold velocity at which erosion initiates, the value of the erosion coefficient k_d determines how quickly the erosion rate changes with increases in velocity. The base case for coarse soil was once again modified by altering the value of k_d using multipliers of 0.1 and 10. The resulting breach widening rate curves are illustrated in Figure 9. The breach widening rate curves are incredibly sensitive to k_d values with 1 order of magnitude representing the difference between the coarse-grained and fine-grained soil data sets.

Figure 9. Influence of soil erodibility k_d on breach widening rates.



6 Discussion

This study developed an approach for calculating levee-breach widening rates directly from the average velocity through the breach, levee height, and soil erosion properties. As demonstrated by the sensitivity analysis, breach widening rates are influenced slightly by the levee height but are extremely sensitive to the values of τ_c and k_d used in the analysis.

While the review of the NHCRP data set revealed an extremely broad range of soil erosion parameters, it must be recognized that this data set is for all types of soil (natural stream bank deposits to deep bridge foundations). As such, it should be expected to find substantial variability in the soil erosion parameters. It is entirely possible that the typical range of soil erodibility for levee fills is much narrower than the data set of all soils in general. The authors highly encourage investigations into this particular topic to aid in development of standard breach widening rate curves.

Lastly, the proposed approach is based on sound engineering principals, and the concepts have been validated by others through comparisons with laboratory breach data (Van Damme 2020). Nevertheless, the proposed approach has not been rigorously tested through breach modeling of previous failures. It is highly recommended that this approach be trialed through hindcasting of historical breaches using the Simplified Breach Analysis Method in HEC-RAS 5.0 (Brunner 2016). Back calculation of soil erodibility parameters and comparison to laboratory test results for the same levee materials is the only rigorous manner in which the proposed calculations can be tested.

7 Conclusions

Widening rate curves that specify levee-breach widening rates as a function of mean flow velocity through the breach are required inputs for the Simplified Breach Analysis Method used in HEC-RAS. In this study, a method for calculating these widening rate curves based on levee height and soil properties was developed. Average values of soil erosion properties from nearly 1,000 erosion tests were used to calculate base widening rate curves for coarse-grained soils and fine-grained soils. While these base curves may serve as a suitable starting point for inundation models, it was also demonstrated that the curves are highly sensitive to soil erosion properties. Proper engineering judgment must be used to ensure the erosion parameters used for the base curves are similar to soils being assessed. Failure to do so will result in substantial error, leading to erroneous inundation model results.

While the approach presented provides a much-needed scientific basis for calculating levee-breach widening rates, additional research is needed. Future research should evaluate the validity of the assumptions made for determining the boundary shear stress from the mean flow velocity through the breach. Additionally, the database of soil erosion characteristics used is not specific to engineered fills. Additional research to evaluate the distribution of erosion characteristics for solely levee fill materials would be helpful.

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Unit Conversion Factors

Multiply	By	To Obtain
feet	0.3048	meters
inches	0.0254	meters
pounds (force)	4.448222	newtons
pounds (force) per square foot	47.88026	pascals
pounds (force) per square inch	6.894757	kilopascals
square feet	0.09290304	square meters
square inches	6.4516 E-04	square meters

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14. ABSTRACT

Inundation modeling is often conducted for levee systems to understand current flood risks. The extent of inundation caused by a breach in the levee is highly influenced by the widening rate of the levee breach. This study presents an approach for calculating levee-breach widening rates based on average flow velocity through the breach, embankment height, and erosion characteristics of the soil. Estimates of soil erodibility are derived through an analysis of the measurements of soil erodibility presented in the National Cooperative Highway Research Program (NCHRP) Report 915 database. Levee-breach widening rate curves are calculated based on these erosion properties to demonstrate the approach, and default curves are presented for typical levees built from coarse-grained soils and fine-grained soils. While the most accurate approach for a site is to calculate site-specific widening rate curves based on estimates of local soil erodibility, the default curves presented provide a suitable starting point for initial inundation modeling.

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