Prepared by:
Modeling, Mapping, and Consequences

Appendix 3.1.4

Application of Simplified Physical Breach Method

FY2023 Standard Operating Procedure for Dams

June 2022

Date	Principal Author	Comments
12/02/2016	Corby Lewis, MMC	Initial Draft
10/16/2018	T. Barto, MMC	Annual Update
08/29/2019	T. Barto, MMC	Annual Update/Technical Edit
02/15/2022	D. Moree, MMC	Complete re-write
05/05/2022	D. Moree, MMC	Addressing Technical Comments
06/01/2022	M. Durham, MMC	Annual Update
08/05/2022	T. Hesseldenz, MMC	Finalized

SECTION 1

Application of Simplified Physical Breach Method in HEC-RAS

The simplified physical breach method within the Hydrologic Engineering Center-River Analysis System (HEC-RAS) allows for the calculation of breach parameters based on the physical conditions at the breach location. The simplified physical method can be applied to any breach (e.g., levees, dams, roadways) and is recommended for Modeling, Mapping, and Consequences (MMC) Levee Breach studies. The method requires an input of a breach widening rate versus velocity and down-cutting rate versus velocity relationships (erosion rates). Although there are currently no widely accepted erosion rates for use with this method, the U.S. Army Corps of Engineers (USACE) is making progress toward this goal. The guidance for selecting appropriate erosion rate inputs is provided below.

In all cases, the resulting breach dimensions should be carefully inspected after the HEC-RAS simulation to ensure the method produces reasonable results for all scenarios and adjustments should be made as necessary. Currently, there are two methods that can be used to determine erosion rates—the historic breach method (Section 1.1) and the velocity-erosion rate calculation based on soil properties method (Section 1.2). A consistent method should be used for both the widening and down-cutting rates.

1.1 HISTORIC BREACH INFORMATION

Direct historic breach information for the embankment being studied, if available, is considered the most accurate estimate of hypothetical future levee breach parameters. If historic breach parameters are available, the simplified physical inputs should be adjusted manually in order to match the historic information as a calibration step.

1.2 VELOCITY-EROSION RATE CALCULATION BASED ON SOIL PROPERTIES

The paper, Calculation of Levee-Breach Widening Rates, April 2022, written by Bryant Robbins and Maureen Corcoran, is primarily used to support the MMC application of the simplified physical breach method. This paper builds upon a 2016 Engineering Research and Development Center (ERDC) Report written by Johannes Wibowo.

The 2022 ERDC Paper simplifies the erosion rate widening rates using Equation 1, and assuming the levee is 15 feet high, depth of flow is equal to the height of the levee, and the Manning's "n" value to represent roughness though the breach is equal to 0.034.

$$\frac{dW}{dt} = 2k_d(0.0132V^2 - \tau_c) \quad (1)$$

Where:

$\frac{dW}{dt}$=the erosion rate in feet per hour

k_d=an erodibility parameter with SI units of (mm/hr)/Pa and English units of (ft/hr)/psf

V=velocity in feet per second

τ_c=shear stress with SI units of pascals or English units of pounds per square foot.

Figure 1-1 illustrates the sample erosion rates this equation produces when paired with the average coarse- and fine-grained soil properties as taken from the National Cooperative Highway Research Program (NCHRP) database (Briaud et al. 2019). For this purpose, coarse-grained soils were defined as those with predominately sandy soils, which includes 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. This utilized an erodibility parameter of 296.6 (mm/hr)/Pa and a shear stress 17.6 Pa. The fine-grained soils were classified as those of predominately silt and/or clay, which included the USCS categories of CH, (CH)s, CL, CL-CH, (CL)s, CL-SC, MH, (MH)s, ML, (ML)s, and ML-CL. This utilized an erodibility parameter of 16.6 (mm/hr)/Pa and a shear stress 86.5 Pa.

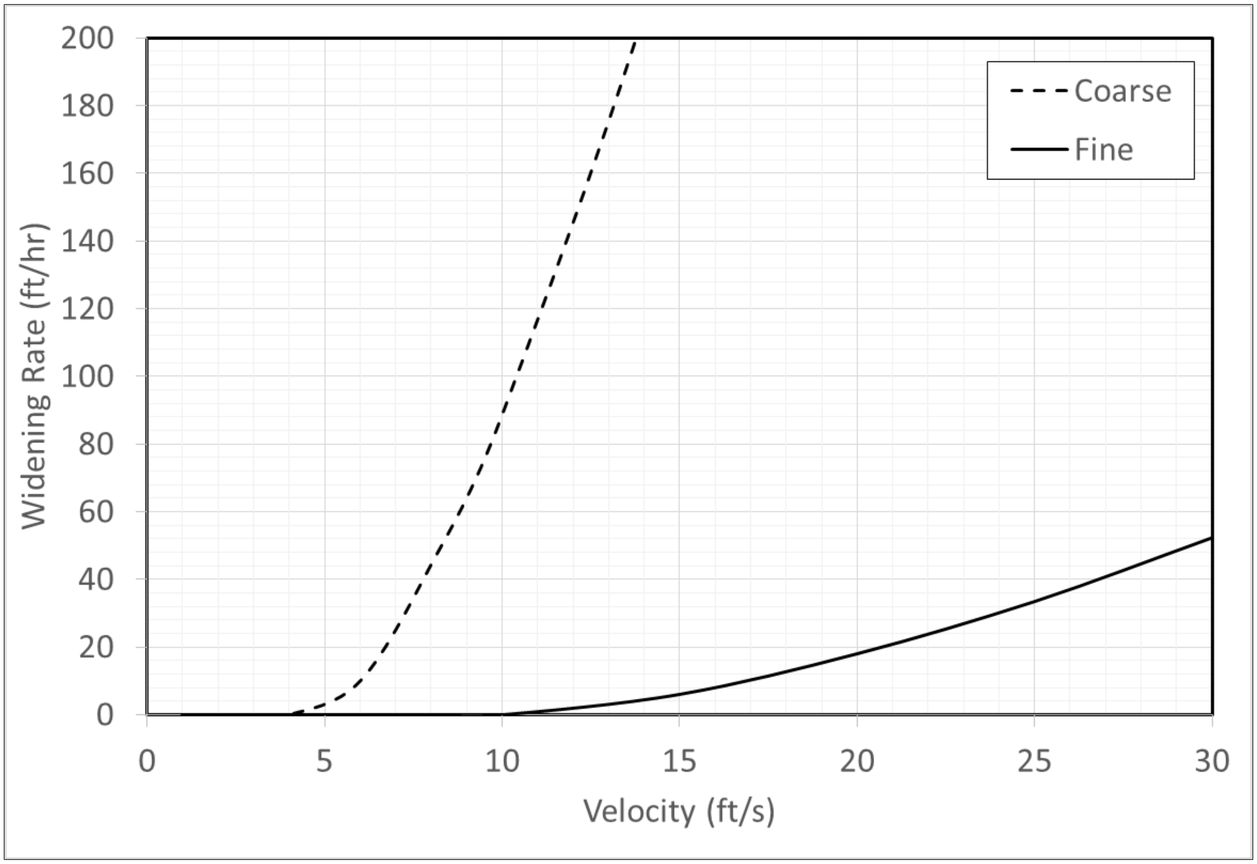

Figure 1-1. Robbin's Erosion Rates

1.2.1 Velocity Erosion Rate Methodology

The MMC uses Equation 2, where the variables simplified into the 0.0132 constant in the 2022 ERDC paper are individually calculated. A single relationship is created for each breach location. The relationship applies to both the widening and downcutting parameters. A calculator spreadsheet developed standardize this procedure is available in each MMC project folder.

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

Where

$\frac{dW}{dt}$=the erosion rate in feet per hour

k_d=an erodibility parameter with units of (ft/hr)/psf

γ_w=the unit weight of water in pounds per cubic foot

R=hydraulic radius (assumed to be height of the levee in feet)

n=the Manning's roughness coefficient

V=velocity in feet per second

τ_c=critical shear stress with units of pounds per square foot.

This equation was developed in English Units, however many of the inputs are provided in SI Units. The SI units for kd are typically found as ((mm/hr)/Pa and for τ_c as pascals. For the purposes of the MMC Levee Breach Erosion Rate Calculator Spreadsheet, these values are first converted, then entered into the equation.

The MMC calculator spreadsheet allows the option to adjust four parameters: k_d, τ_c, Manning's "n" values, and levee height. Additional information for each of these parameters is included in Sections 1.2.2 to 1.2.5.

1.2.2 Critical Shear Stress

For the purposes of MMC modeling efforts, and at the recommendation of the Risk Management Center (RMC) and MMC leadership, shear stress (τ_c) should be set to 0. This assumption is a conservative estimate selected in order to ensure erosion breach initiation and breach progression in areas of low velocity gradients. The lack of a modeled breach initiation has been a programmatic levee breach modeling issue for levees that have a soil makeup, compaction, and/or protection that would align with the less erodible erosion rates.

1.2.3 Manning's "n" Roughness Coefficient

The MMC recommends that the Manning's "n" value in the direction of the breach be set at 0.034 and not be adjusted unless site-specific data for the roughness condition during a breach is readily available. The Robbin's paper (Robbins 2022) selected this value as an appropriate value for a relatively rough earthen channel. This parameter could be assessed with considerations to soil type and turbulence impacts during a higher-level risk assessment.

1.2.4 Levee Height

The MMC recommends the levee height be estimated to the nearest foot at the levee breach initiation location. If the height at the breach location varies greatly, take care to ensure the levee height is representative of the breach area.

1.2.5 Erodibility Parameter

Expect in most cases that a single k_d Value will be appropriate for the whole levee system. Some level of conservatism is introduced with the shear stress assumption, therefore it is recommended that the best estimate, instead of a conservative k_d value, be chosen. There are three options for selecting a k_d value, (listed in order of preference).

1. The district levee safety program manager (LSPM) or geotechnical lead provides a $k_d$value from direct testing done on structure.
2. The district LSPM or geotechnical lead provides an estimated k_d value from known soil and compaction properties. This can be a specific value or a selection from the preselected MMC values.
3. The modeler may estimate a k_d value from the preselected MMC values based on known soil and compaction properties.

Table 1-1 provides preselected values based off an evaluation of values found in the Texas Agricultural and Mechanical University (TAMU) database developed by Briaud et. al. This evaluation was completed by RMC technical leads.

Table 1-1. Preselected Modeling, Mapping, and Consequences Production Center Values

Recommended k_d Values if district information is not available		
k_d (mm/hr)/Pa	**k_d (ft/hr)/psf**	**Descriptor**
1	0.16	Moderately Resistant
25	3.93	Erodible
100	15.7	Very Erodible
500	78.5	Extremely Erodible

1.2.6 Erodibility Parameter Selection Rationale

A summary of the selection rationale for erodibility parameter (k_d) are presented below. These values were selected though a review of the TAMU database by RMC Leads. These selections are generally based on lumped measured erodibility of various soil types as described with the USCS. Table 1-2 provides a sample of the supporting data produced through the review of the TAMU database.

- An erodibility parameter of 500 (mm/hr)/Pa was selected to represent an extremely erodible erosion-velocity relationship. This value was selected as it is slightly higher than the mean of all coarse-grained samples within the TAMU database. The coarse-grained samples of all types are also slightly higher than the coarse-grained samples of compacted embankments, such as dams or levees. This value is likely lowered by samples with appreciable fines. However, it is slightly more conservative than using the median erodibility parameter of all of the poorly-graded sand (SP) samples where all values with a k_d less than 5 (mm/hr)/Pa were excluded. This erodibility parameter produces results very similar to the upper end of the very erodible curve (as defined by the 2016 ERDC paper) identified in previous versions of this appendix and is intended to be an infrequently used upper bound (the lower bound is affected by the shear stress equals zero assumption).
- An erodibility parameter of 100 (mm/hr)/Pa was selected to represent a very erodible erosion-velocity relationship. This value was selected because it represents a number that is slightly higher than the median erodibility of all silty sand (SM) samples in the database with k_d less than 5 (mm/hr)/Pa excluded and is similar to the mean erodibility value for Silt (ML). This erodibility parameter produces results very similar to the upper end of the erodible curve recommended by previous versions of the MMC Technical Manual for Levees and this appendix and as defined by the 2016 ERDC paper.
- An erodibility parameter of 25 (mm/hr)/Pa was selected to represent an erodible erosion-velocity relationship. This value was selected as it is slightly less than the median kd of all silty sand (SM) and silt (ML), where any value with a k_d less than 5 (mm/hr)/Pa is neglected. This curve agrees

with the mean kd values for clayey sand (SC), clayey sand with silty sand (SC-SM), and well-graded sand with silty sand (SW-SM) embankment materials in the database. This erodibility parameter produces results between the 2022 very erodible and moderately resistant curves that is slightly higher than the upper bounds of the moderately resistant curve recommended by prior versions of the MMC SOPs as defined by the 2016 ERDC paper.

- An erodibility parameter of 1 (mm/hr)/Pa was selected to represent a moderately resistant erosion-velocity relationship. This value was selected because it represents a number that is slightly higher than the median k_d of all lean clay (CL), elastic silt (MH), and fat clay (CH) samples in the database (see Figure 4-1 for zoomed view). The curve allows for less erosion than the previous moderately resistant curve recommended by prior versions of the MMC SOPs as defined by the 2016 ERDC paper. However, as this curve provides very limited erodibility, this curve is intended to be an infrequently used lower bound for MMC production simulations. Higher level studies may consider use of this or a similar erodibility parameter after thoroughly assessing soil type and construction methods for possible flaws. Consideration should be given on the likelihood of swaying the risk calculation using consequences from a breach that is not fully developed combined with a low probability of failure.

Table 1-2. Soil Sample Statistics—Preselected Modeling, Mapping, and Consequences Production Center Values (sheet 1 of 2)

All Soil Samples–k_d ((mmh/hr)/Pa)					
Soil Type (USCS)	**Sample Count**	**Mean k_d**	**Median k_d**	**Minimum k_d**	**Maximum k_d**
CH	127	9.09	0.59	0.00	496.8
CH-without outliers	75	0.33	0.30	0.00	1.00
MH	12	11.93	0.76	0.10	111
MH-without outliers	7	0.31	0.11	0.01	0.81
CL	348	12.12	0.63	0.00	1,362.31
CL-without outliers	216	0.34	0.26	0.00	0.99
CL-ML	25	2.90	1.57	0.07	13.32
SC	76	26.08	2.58	0.02	486.17
SW	1	19.45	19.45	——	——
ML	40	90.14	4.55	0.02	1,718.02
ML-without outliers	19	188.23	26.23	5.52	422.33
SM	106	277.50	27.70	0.10	5,802.96

Table 1-2. Soil Sample Statistics—Preselected Modeling, Mapping, and Consequences Production Center Values (sheet 2 of 2)

All Soil Samples–k_d ((mmh/hr)/Pa)					
Soil Type (USCS)	**Sample Count**	**Mean k_d**	**Median k_d**	**Minimum k_d**	**Maximum k_d**
SM-without Outliers	76	386.13	76.80	5.14	5,802.96
SP	26	1,176.04	306.15	0.11	6,690.26

SP-without Outliers	21	1,455.58	567.93	15.70	6,690.26
All Embankment Samples with Reasonable* Results–k_d ((mmh/hr)/Pa)					
Soil Type (USCS)	**Sample Count**	**Mean k_d**	**Median k_d**	**Minimum k_d**	**Maximum k_d**
CH	14	0.84	0.28	0.02	3.39
MH	1	0.09	0.09	——	——
CL	16	0.17	0.09	0.03	0.84
CL-ML	8	4.52	4.33	1.57	7.38
SC	3	0.37	0.05	0.02	1.05
ML	2	0.63	0.63	0.62	0.63
SM	20	95.89	15.14	0.41	623.64
SP	2	210.43	210.43	133.71	287.16
All Natural (non-pre-processed) Embankment Samples with Reasonable Results–k_d ((mmh/hr)/Pa)**					
Soil Type (USCS)	**Sample Count**	**Mean k_d**	**Median k_d**	**Minimum k_d**	**Maximum k_d**
CH	14	0.84	0.28	0.02	3.39
MH	1	0.09	0.09	——	——
CL	15	0.14	0.09	0.03	0.84
CL-ML	0	——	——	——	——
SC	3	0.37	0.05	0.02	1.05
ML	2	0.63	0.63	0.62	0.63
SM	12	137.24	39.21	0.41	623.64
SP	2	210.43	210.43	133.71	287.16

*Reasonable results are defined as all values not unreasonably low per soil type as defined by the RMC Lead.

**Pre-processed refers to the fact that sample is disturbed prior to the testing methodology. An example includes drying and recompression.

1.3 PREVIOUS BREACH RATE METHODOLOGY

1.3.1 2013 Technical Memorandum for Record-West Consultants

The MMC applied the information summarized in the 2013 Technical Memorandum for Record by West Consultants in previous USACE levee breach studies. The memo incorporated much of the available literature and provided a set of suggested erosion rate relationships for use in HEC-RAS. The relationships were also verified with an HEC-RAS breach analysis of two historic levee breaches in the central valley of California. The useful relationships from the memo for direct use in MMC studies are shown in Table 2-1 of the FY2020 Breach Appendix 3.1.4.

1.3.2 2016 Engineering Research and Development Center Report: Estimating Levee Erosion Rates (Under development as of December 2016)

The ERDC completed a draft report regarding breach widening rates based on an analysis of shear-stress induced erosion at the toe of the breach opening, which drives slope failures that widen the breach. The study looks at a large range of embankment heights and levee material types, and also provides uncertainty ranges for material types. The ERDC developed rates assume the same erosion rates for the widening and downcutting. The average erosion rates for a 15-foot-high embankment are included in Table 3-1 of the FY2016–2021 Breach Appendix 3.1.4. In general, the 2016 report methodology produces somewhat smaller breaches for erodible and very erodible soils.

1.4 COMPARISON OF BREACH RATE METHODOLOGIES

Figures 1-2 and 1-3 provide a comparison of the previous erosion rates, the 2016–2022 SOP Rates, and the 2022 ERDC Paper erosion rates. Both curve sets are based on an estimated 15-foot levee for consistency. In general, these new curves are expected to produce a larger percentage of breach initiations, and better control over the erosion rate at each breach site.

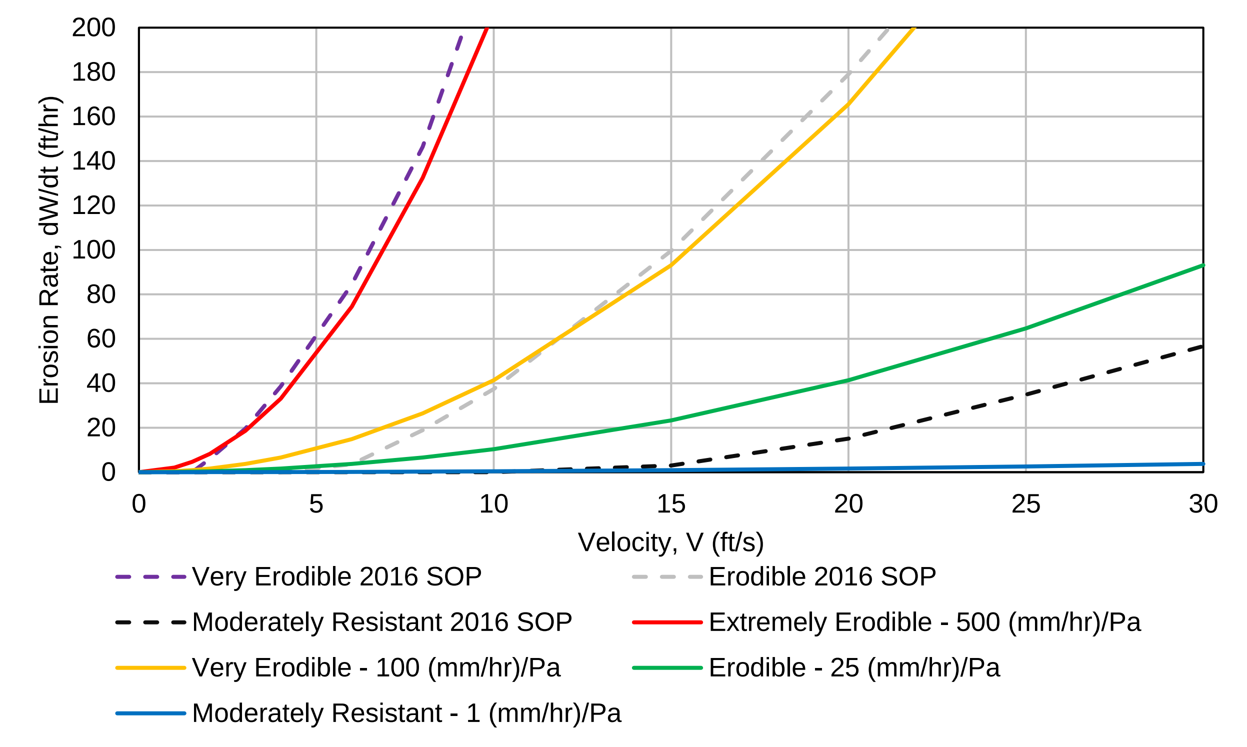

Figure 1-2. 2016 versus 2023 Modeling, Mapping, and Consequences Production Center Erosion Rate Curves, 15-foot levee height

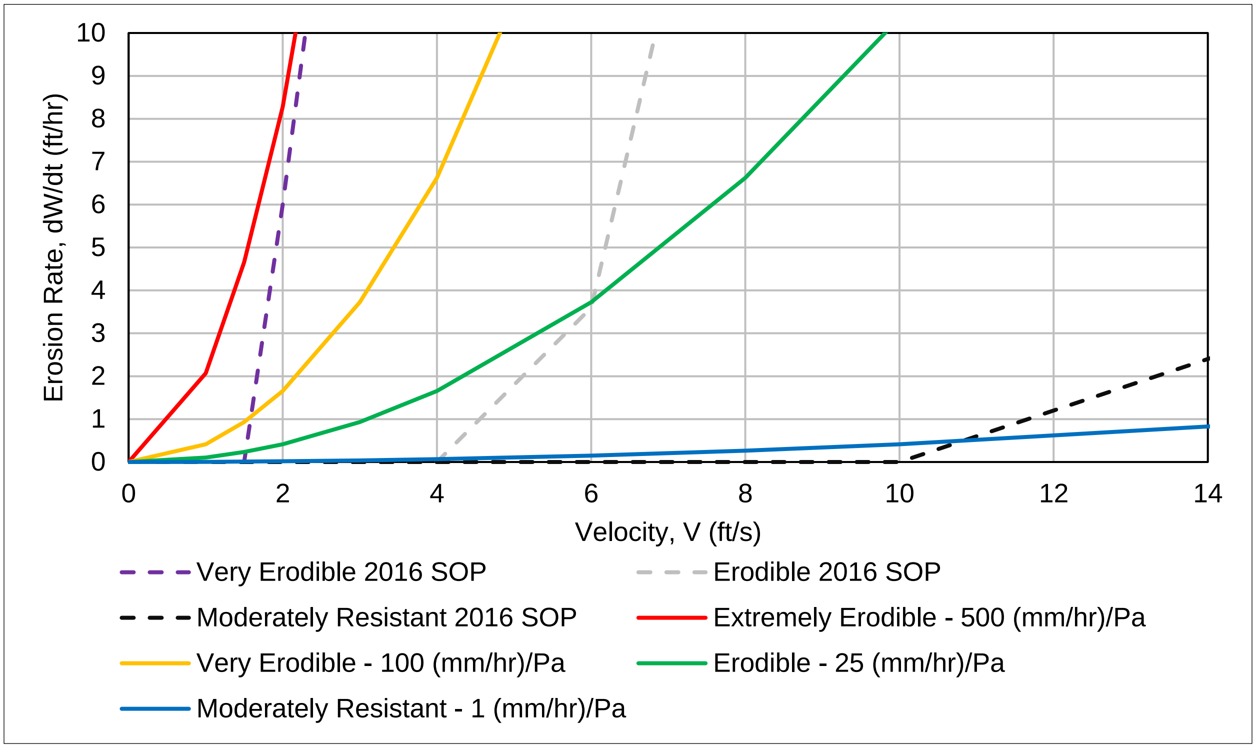

Figure 1-3. 2016 versus 2023 Modeling, Mapping, and Consequences Production Center Erosion Rate Curves at Lower Velocities, 15-foot levee height

There is a range of expected results from the updated breach erosion equations as the new velocity relationships do not always produce higher or lower results as compared to the previous rate curves. This is due to the τ_c=0 assumption, which allows slower but continuing erosion at lower velocity profiles and faster initiation of the initial breach widening, as well as a gradual expansion of the eroded area during the recession of the hydrograph with the evacuation of waters from the protected area. For the very erodible curve in the 2016–2022 SOPs the breach erosion relationship was capped at 10 cfs, where the current methodology allows this to expand faster at higher velocities. The relationship between the curves is further affected by the additional levee height adjustment factor. However, generally the new breach methodology produces a larger breach for a similar erosion rate relationship from previous methodologies.

References

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List of Acronyms and Abbreviations

A&M	Agricultural and Mechanical
BL	breach location
CH	heavy clay
(CH)s	heavy clay with some sand
CL	lean clay
CL-CH	lean clay with heavy clay
(CL)s	lean clay with some sand
CL-SC	clay with clayey sand
ERDC	Engineering Research and Development Laboratory
HEC-RAS	Hydrologic Engineering Center River Analysis Software
LSPM	levee safety program manager
MH	heavy silt
(MH)s	heavy silt with some sand
ML	lean silt
(ML)s	lean silt with some sand
ML-CL	silty clay
MMC	Modeling Mapping and Consequences Production Center
NCHRP	National Cooperative Highway Research Program
RMC	Risk Management Center
USACE	United States Army Corps of Engineers
USCS	Unified Soil Classification System
SC	clayey sand
(SC)g	clayey sand with some gravel
SC-SM	clayey sand with silty sand
SM-SC	silty sand with clayey sand
SM	silty sand
SP	poorly-graded sand
SP-SC	poorly-graded sand with clay
SP-SM	poorly-graded sand with silt
SW	sands

SW-SM	well-graded sand with silt
TAMU	Texas Agricultural and Mechanical (A&M) University

CONVERSIONS

This paper is presented in metric units. However, there are several standard sets of units for k_d Erosion Coefficient. Therefore, the most common conversions are listed below.

1 (ft/hr)/psf=6.366 (mm/hr)/Pa=1.768 $cm^3/(N \cdot s)$
1 (mm/hr)/Pa=0.1571 (ft/hr)/psf=0.2778 $cm^3/(N \cdot s)$
1 $cm^3/(N \cdot s)$=3.6 (mm/hr)/Pa=0.5655 (ft/hr)/psf