# Improving the Reliability of Soil Erosion Estimates

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## Abstract

Measured soil erosion-resistance parameters exhibit large variability (up to several orders of magnitude) not only between different soil types, but also for same or similar soil types. This variability is not only caused by the inherent, spatial variability in soil properties (e.g., texture, density, moisture, and organic content), but also by the different instrumentation and post-processing techniques employed to quantify soil erosion-resistance. We conducted JET and EFA tests on silt and silty sand Unified Soil Classification System soil types obtained from the banks along the Lower American and Sacramento Rivers, CA. We showed that using modified post-processing techniques of JET and EFA tests, which use applied shear stress at the grain/aggregate scale, mass surface erosion regime, and uncertainty in estimated shear stress and measured erosion rate, results in similar distributions of soil erosion-resistance parameters. Calibration of model erosion-resistance values against observed bank erosion showed the distribution of calibrated values for the silt soil type was similar as that measured. However, for the silty sand soil type the distribution of calibrated erodibility values differed slightly from that measured. We recommend that erosion calculations of fine-grained, cohesive soils should be based on measured data that are carefully analyzed to account for variability introduced by instrumentation and soil heterogeneity and match the expected, erosion regime. Erosion estimation reliability can further be improved by employing a thorough calibration process.

## Introduction

Measured soil erosion-resistance parameters exhibit large variability (up to several orders of magnitude) not only between different soil types, but also for same or similar soil types (Simon et al., 2010). This variability is not only caused by the inherent, spatial variability in soil properties (e.g., texture, density, moisture, and organic content), but also by the different instrumentation and post-processing techniques employed to quantify soil erosion-resistance. Two widely used measurement methods are the Jet Erosion Test (JET; Hanson and Cook, 2004) and Erosion Function Apparatus (EFA; Briaud et al., 2001). Both JET and EFA measurements have shown that the erosion function (that is, relationship between soil erosion rate and shear stress exerted by flow on the soil surface) is often non-linear, which generally indicates differing erosion mechanics along the erosion function (e.g., Papanicolaou et al., 2017). For example, at higher applied shear stresses, aggregates or chunks of soils are detached (mass erosion regime), which are much larger than the detached particles at small excess shear stresses (particle-by-particle erosion regime), resulting in magnitude differences in the volumetric rate of detachment. The rate of soil erosion is most commonly calculated using a linear excess shear stress equation (Ariathurai and Arulanandan, 1978), in which the portion of the hydraulic shear stress exerted on the soil that exceeds a soil critical shear stress, is multiplied by an erosion rate coefficient (also called detachment or erodibility coefficient). Post-processing techniques that fit a linear excess shear stress equation to the measured non-linear erosion function can introduce significant variability in the measured critical shear stress and erodibility coefficient values. In addition to the systematic post-processing discrepancies, the JET and EFA use different hydraulics to erode soil samples and different techniques to determine the applied shear stresses. The inherent differences between devices and methods typically leads to dissimilarities in their respective erosion functions.

We conducted JET and EFA tests on silt and silty sand Unified Soil Classification System (USCS) soil-type samples obtained from the banks and near-bank floodplain along the Lower American River, CA. Soil erosion resistance was quantified using (1) the standard post-processing techniques of JET and EFA methodologies, and (2) improved post-processing techniques that account for sources of variability. Further, we used these soil erosion-resistance distributions to conduct an analysis with the Bank Stability and Toe Erosion Model (BSTEM) of bank erosion along the Lower American River to examine the reliability of erosion estimates by comparing the results to observed erosion.

## Methods

Erosion-resistance in this study is represented by two parameters: critical shear stress ($\tau_c$) and erodibility coefficient ($k_d$). The critical shear stress of a soil is the threshold shear stress flowing water has to exceed to commence erosion of the soil. The erodibility coefficient represents the rate at which the soil erodes once the critical shear stress has been exceeded. Critical shear stress and erodibility coefficient can be calculated from the erosion function, which is the relation between soil erosion rate ($E$, dependent variable) and applied shear stress ($\tau$, independent variable). The critical shear stress is the shear stress where the erosion function first exceeds zero erosion-rate (i.e., $E = 0$ if $\tau \leq \tau_c$ and $E > 0$ if $\tau > \tau_c$). The erodibility coefficient is the slope of the erosion function. In this study the erosion function is approximated by a linear excess shear stress equation: $E = k_d(\tau - \tau_c)$.

The JET and EFA methods use different hydraulic principles to: erode the soil surface, measure soil erosion rate, and estimate shear stress applied by the flow on the soil surface. As a result, erosion functions and erosion-resistance parameters will not only vary by soil but could also vary by method for similar soils. The following procedure was used to progressively improve compatibility between soil erosion-resistance parameters derived by the JET and EFA methods:

1. Using linear regression fit a linear trendline representing the linear excess shear stress equation through the ‘as-is’ erosion function measured (or output) by the EFA and JET methods. Calculate the erosion-resistance parameters critical shear stress and erodibility coefficient from the trendline.
2. Same as Step 1 but limit the erosion function to the portion representing the mass soil erosion regime.

3. Same as Step 2 but base the erosion function on the shear stress acting at grain or (small) soil particle roughness length scales.
4. Same as Step 3 but account for uncertainty in measured erosion rate and estimated applied shear stress.

Step 1 includes all measured data (i.e., entire erosion function) produced by a test. However, the measured erosion function by EFA and JET methods typically includes two erosion regimes: (1) particle-by-particle erosion regime at small excess shear stresses ($\tau - \tau_c$) and (2) mass erosion regime during which aggregates and clods are detached from the soil surface at larger excess shear stresses. A measured erosion function may cover both erosion regimes or only regime (1) or (2). Erosion-resistance parameters from erosion regime (2) are typically used by computer models, simulating bank erosion processes, as the magnitude of erosion can be orders of magnitude greater for this erosion regime. Therefore, Step 2 ensures that the derived erosion-resistance parameters represent an identical erosion regime. The erosion function output by the JET is based on applied shear stresses acting at the grain roughness scale. These shear stresses are commonly associated with erosion and sediment transport. The erosion functions of the EFA method is based on total shear stress that includes both skin friction (grain-scale roughness) and form drag (topographic features much greater than sediment grains or soil particles) components. Erosion-resistance parameters derived in Step 3 are therefore based on erosion functions that are associated with similarly scaled applied shear stresses. The uncertainty in measured erosion rate and estimated applied shear stress can be significant and varies by test method. Accounting for this uncertainty as part of the linear regression allows for both an improved estimate of erosion-resistance parameters themselves and quantification of their uncertainty (Step 4).

Soils were either collected for laboratory testing (EFA and JET) or tested in situ (JET) at 18 combined sites on the Lower American River and Sacramento River (Table 1). Erosion testing results were grouped by USCS soil type. Here, we only present results for silt (ML) and silty sand (SM) USCS soil types.

**Table 1.** Summary of data sets and test method used to characterize the erosion resistance of bank soils on the Lower American and Sacramento Rivers, CA. The collecting agencies are: ARS, U.S. Department of Agriculture, Agricultural Research Service; TAMU, Texas A&M University; and USACE, U.S. Army Corps of Engineers.

| Collecting agency | Date | Test | Number of tests | Description | Reference |
|---|---|---|---|---|---|
| ARS | Fall 2018 | Mini-JET | 27 | In-situ test on bank surfaces | Langendoen & Ursic (2020) |
| TAMU | Fall 2019 – Winter 2020 | EFA | 36 | Laboratory test on collected field samples | Briaud et al. (2020) |
| USACE | Fall 2011 | JET | 6 | Laboratory test on collected field samples | Wibowo & Robbins (2012) |
| USACE | Fall 2011 | JET | 3 | Laboratory test on collected field samples | Wibowo & Robbins (2017) |
| USACE | Fall 2011 | EFA | 12 | Laboratory test on collected field samples | AuBuchon (2019; personal communication) |

To provide recommendations on the use and application of the derived erosion-resistance parameters pertinent to the evaluation of bank erosion on the Lower American River, USACE-Sacramento District conducted a number of simulations with BSTEM to calibrate erosion-resistance parameters at eight bank erosion sites on the Lower American River (Rivas et al., 2021). The calibrated erosion-resistance parameters are for the following USCS soil types: CL, ML, SM, and SP.

## Results

Figures 1 and 2 compare the erosion-resistance parameters derived under Steps 1 and 4 for EFA and JET methods. The EFA- and JET-derived erosion-resistance parameters are more similar for Step 4 than Step 1. Table 2 lists the results of two-sample Kolmogorov-Smirnov (KS) tests conducted to compare the critical shear stress and erodibility coefficient distributions for silts and silty sands derived using the EFA and JET methods. When the KS statistic $\alpha$ is small or the $p$-value of the test is large the tested distributions are the same (i.e., we cannot reject the null hypothesis that the two distributions are the same). Generally, the $\alpha$ values are fairly large but improved (i.e., became smaller) for Step 4 compared to Step 1. Also, the $p$ values improved for Step 4 relative to Step 1. Therefore, the distributions of erosion-resistance parameters compare better for Step 4 than they do for Step 1, which is shown in Figures 1 and 2. The KS tests indicate that the EFA- and JET-derived critical shear stress distributions for silty sand soils are different for Step 1 (small $p$ values) but compare reasonably well for Step 4 ($p_{SM} > 0.11$ and $p_{ML} > 0.201$). The erodibility coefficients determined by EFA and JET methods are different for Step 1, but compare reasonably well for silts and quite well for silty sand soils.

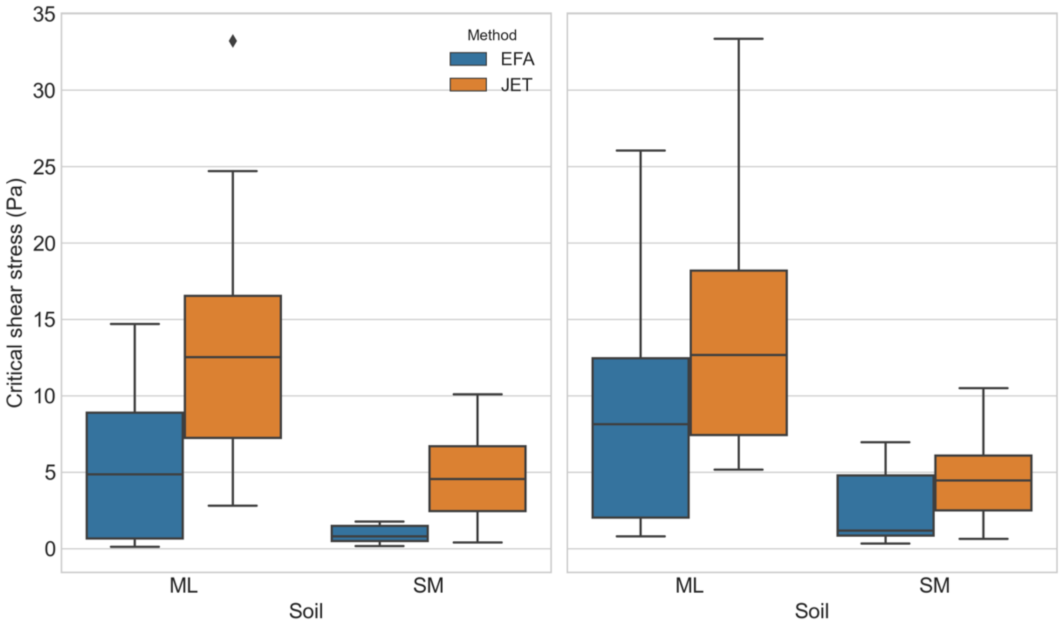

**Figure 1.** Comparison of (a) critical shear stress derived using standard EFA and JET post-processing techniques (Step 1 of followed procedure) and (b) critical shear stress associated with erosion functions based on grain shear stress, mass surface erosion regime, and include uncertainty in estimated shear stress and measured erosion rate (Step 4 of followed procedure) for silt (ML) and silty sand (SM) soil types.

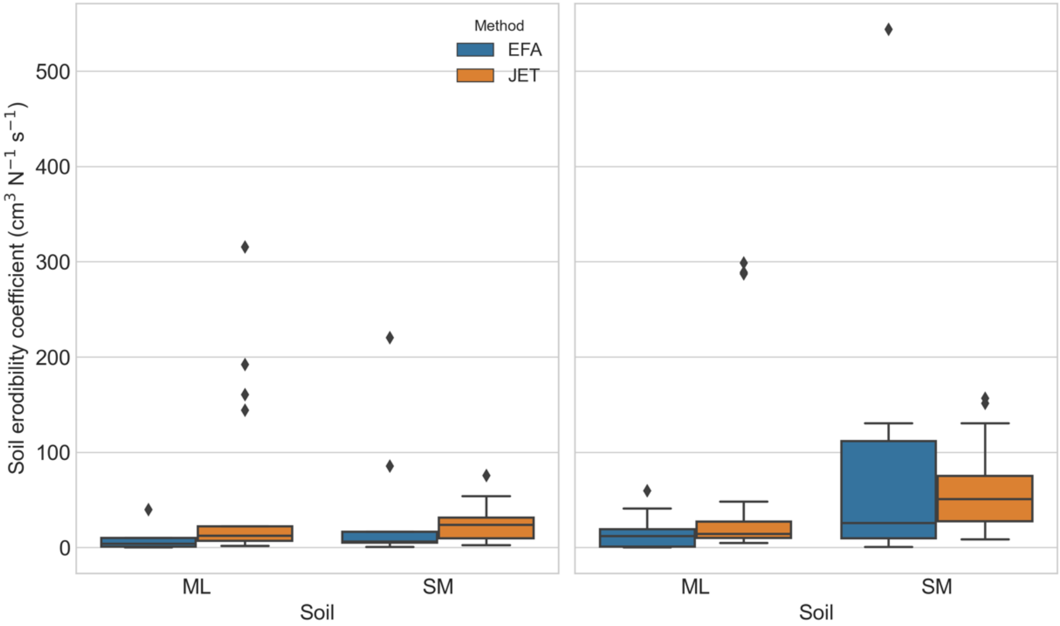

**Figure 2.** Comparison of (a) erodibility coefficient derived using standard EFA and JET post-processing techniques (Step 1 of followed procedure) and (b) erodibility coefficient associated with erosion functions based on grain shear stress, mass surface erosion regime, and include unertainty in estimated shear stress and measured erosion rate (Step 4 of followed procedure) for silt (ML) and silty sand (SM) soil types.

**Table 2.** Output parameters $\alpha$ and $p$ from Kolmogorov-Smirnov (KS) tests indicating if distributions of critical shear stresses and erodibility coefficients derived by EFA and JET methods for silt (ML) and silty sand (SM) soil types are the same. Tests were conducted for erosion-resistance parameters determined for Steps 1 and 4 of the presented analysis procedure. The parameter $\alpha$ is the KS statistic and $p$ is the two-tailed $p$ value.

| | **Silt (ML)** | | | | **Silty sand (SM)** | | | |
|---|---|---|---|---|---|---|---|---|
| | **Step 1** | | **Step 4** | | **Step 1** | | **Step 4** | |
| **Parameter** | $\alpha$ | $p$ | $\alpha$ | $p$ | $\alpha$ | $p$ | $\alpha$ | $p$ |
| **Critical shear stress** | 0.500 | 0.088 | 0.400 | 0.201 | 0.833 | $4.4\ 10^{-4}$ | 0.500 | 0.114 |
| **Erodibility coefficient** | 0.556 | 0.041 | 0.400 | 0.201 | 0.500 | 0.114 | 0.306 | 0.638 |

Figure 3 compares the calibrated erosion-resistance parameters to those measured using EFA and JET methods. The calibrated erosion-resistance parameters for silts compare well with those measured. For silty sands the calibrated erosion-resistance parameters plot towards the larger measured critical shear stresses and smaller measured erodibility coefficients.

## Conclusions

We conducted JET and EFA tests on silt and silty sand Unified Soil Classification System soil types obtained from the banks along the Lower American River, CA. Using their standard post-processing techniques, distributions of JET and EFA soil erosion-resistance values for each soil type differed significantly. However, accounting for sources of variability during the post-processing stage resulted in distributions of JET- and EFA-derived soil erosion-resistance values that were similar. Further, we used these soil erosion-resistance distributions to conduct a stochastic analysis with the Bank Stability and Toe Erosion Model (BSTEM) of bank erosion along the Lower American River. Calibration of model erosion-resistance values against observed bank erosion showed the distribution of calibrated values for the silt soil type was similar as that measured. However, for the silty sand soil type the distribution of calibrated erodibility values significantly differed from that measured. We recommend that erosion calculations of fine-grained, cohesive soils should be based on measured data that are carefully analyzed to account for variability introduced by instrumentation and soil heterogeneity and match the expected, study erosion regime. Erosion estimation reliability can further be improved by employing a thorough calibration process.

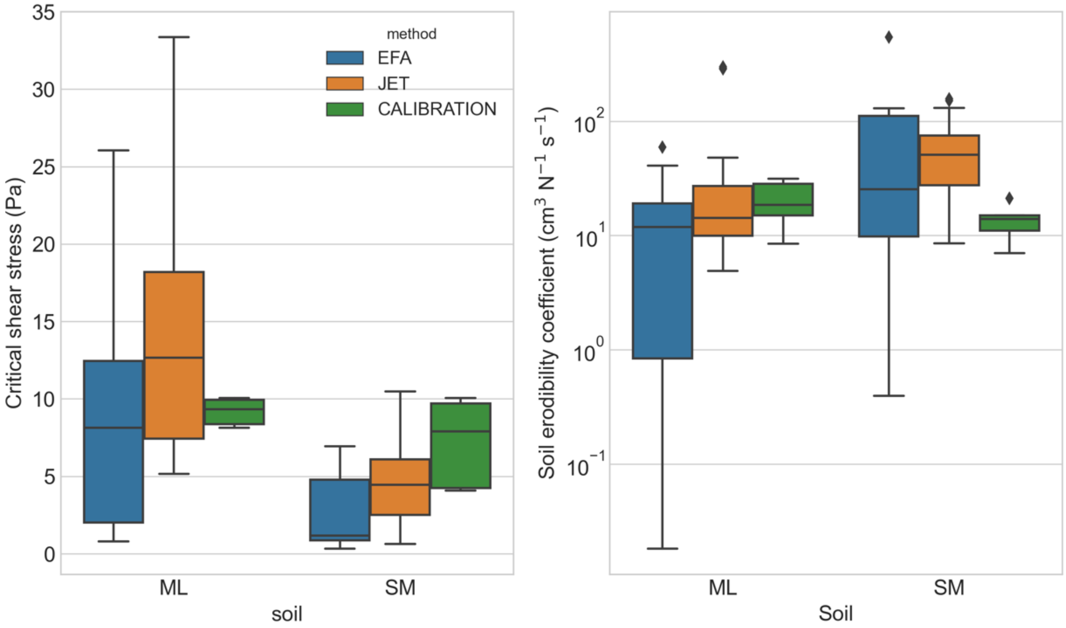

**Figure 3.** Comparison of soil erosion-resistance derived using EFA and JET methods and those calibrated using BSTEM models for silt (ML) and silty sand (SM) soil types: (a) critical shear stress and (b) erodibility coefficient. Measured critical shear stresses are associated with erosion functions based on grain shear stress, mass surface erosion regime, and include uncertainty in estimated shear stress and measured erosion rate.

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