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Perspectives on the Jet Erosion Test (JET): Lessons Learned, Challenges, and Opportunities in Quantifying Cohesive Soil Erodibility

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Highlights

- *The JET is a key instrument for in-situ and laboratory measurement of soil erodibility.*
- *Operation and reporting guidelines are needed to ensure consistency across JETs and applications.*
- *JET design improvements and hydrodynamic studies are needed to inform proper analyses and limit operator effects.*
- *Erodibility databases should be developed that report JET, soil, and fluid properties.*

Keywords. Critical Shear Stress, Cohesive Soils, Erosion, Erodibility, Jet Erosion Test, Scour.

Introduction

The Jet Erosion Test (JET) is a device used to evaluate erodibility of cohesive soils in field or laboratory conditions by measuring the scour versus time response to a submerged water jet impinging normally against the soil surface. The JET was originally developed and tested by Hanson (1990, 1991) and has become one of the most used instruments for quantifying cohesive soil erodibility (NASEM, 2019; Wahl, 2021). The JET has been used for quantifying the erodibility of streambanks, levees, earthen embankments, gullies, and hillslopes (Allen et al., 1999; Simon et al., 2000; Wynn et al., 2008; Hanson, 2019; Wahl, 2019; Fox, 2019a).

Some specific examples of JET application include stream restoration, bridge scour, and dam failure analyses. For example, the stream restoration industry is now a multi-billion-dollar industry each year. As engineering and architectural firms continue to adopt process-based approaches (Shields et al., 2003; Simon et al., 2007; Bigham, 2020), the JET will be front and center as a key instrument for quantifying the erodibility of in situ stream channel materials. Scour protection methods are needed around bridge piers and evaluations of their effectiveness rely on JET-based techniques to quantify changes in soil erodibility. The National Inventory of Dams includes 90,000 earthen dams on America’s waterways, many of which are classified as high hazard. The ability to predict the long-term viability of those dams is dependent on process-based information provided by JETs and other tools capable of quantifying cohesive sediment erodibility (Hanson, 2019).

Significant research has been performed on the design, operation, and analysis of JET data, and devices on several scales have been used through the years (Figure 1). An ASTM standard (D5852) was developed for the first JET (ASTM, 2007), having a 13-mm nozzle and requiring an exposed soil surface. Subsequently, devices described in recent literature as “original” JET used a 6-mm nozzle to erode soil within a 0.3-m submergence tank with arrangements that allowed testing on both horizontal and sloped surfaces (e.g., streambanks approaching vertical). Due to the size and water requirements of the original JET, two smaller and lighter versions of the JET, called the modified JET (Hanson and Simon, 2001, 2002) and then the “mini” JET (Figure 1) with a 3-mm nozzle, were developed. The “mini” JET was evaluated against the original JET by Al-Madhhachi et al. (2013) for two soil textures. Detailed plans for constructing a JET can be obtained from the USDA ARS Hydraulic Engineering Research Unit in Stillwater, OK; also, several universities provide contract services to construct JETs, such as the NC State University Biological and Agricultural Engineering Research Shop.

Figure 1. Original JET (left) and “mini” JET (right) being used in the laboratory. Pictures by Abdul-Sahib Al-Madhhachi.

Recent research has also reconsidered how JET data are analyzed for deriving erodibility parameters, incorporating these solution techniques into new automated spreadsheet tools, and even considered the validity of linear versus nonlinear detachment models for cohesive sediments. Also, the impact of various factors on JET-derived soil erodibility parameters have also been investigated by researchers worldwide (e.g., Al-Madhhachi et al., 2014, 2019; Hashim et al., 2020).

The JET device evaluates soil erodibility using a small-scale, controlled environment in which scour is caused by a submerged water jet impinging normally against a soil surface. The test can be performed in situ on a horizontal or inclined surface, or in the laboratory with remolded soil specimens in compaction molds or samples recovered from the field. The JET is initially positioned about seven or more nozzle diameters away from the soil surface and erodes a scour hole whose depth is measured along the jet axis at periodic time intervals using a physical probe. The hydrodynamics of the JET have been studied so that the shear stress applied to the soil surface can be estimated as the scour hole deepens (Hanson and Cook, 2004). Measurements of the evolution of scour depth can be used to determine soil erodibility parameters that relate applied shear stress to observed scour through a selected soil erosion equation. Linear (equation 1 from Partheniades, 1965) and nonlinear (as an example, see equation 2 from Wilson, 1993) detachment models have been used for predicting volumetric erosion rates ((See PDF for eq.), m/s), defined as the volume of detachment per unit area per time or change in the scour hole depth over time:

$$\varepsilon_r = k_d\,(\tau - \tau_c)^a \qquad (1)$$

$$\varepsilon_r = \frac{b_o\sqrt{\tau}}{\rho_b}\left(1 - exp\left\{-exp\left(3 - \frac{b_1}{\tau}\right)\right\}\right) \qquad (2)$$

where τ is the applied shear stress (Pa), τ_c is the critical shear stress (Pa) and k_d is the erodibility coefficient, $m^3/(N\text{-}s)$, of the linear detachment model (Partheniades, 1965), a is a dimensionless exponent commonly assumed to be one, b_o ($g/(m\text{-}s\text{-}N^{0.5})$ and b_1 (Pa) are two semi-mechanistically defined parameters of the Wilson (1993) nonlinear detachment model, and ρ_b is the bulk density (g/m^3). Some have proposed modifications to equation (1) to assign an exponent other than one on the excess shear term, $(\tau - \tau_c)$ (Knapen et al., 2007), with a range of values reported for this exponent: 0.5 (Van Damme and Riteco, 2018), 1.5 (Foster et al., 1977), 1.75 (Walder, 2016), and 2.0 (Partheniades, 1965).

Since the early 2000s, there is a rapidly growing database of scientific and engineering literature focused on technical modifications and improvements to the JET device, the testing procedure, the theory of JET hydrodynamics, and appropriate detachment models to utilize with JET data (Figure 2). With support from the American Society of Agricultural and Biological Engineers (ASABE), a targeted workshop was held in October 2019 that summarized the historical advances made on this instrument and attracted a new audience to participate in a dialogue and collaboration on the JET and its use across a wide range of soil erosion applications. Twenty-three individuals with diverse backgrounds in academia, government, and consulting participated. The objective of this perspectives paper is to convey lessons learned regarding the use of the JET and future research needs identified during this workshop, helping the scientific and engineering community set a path for not only the use of the JET but also other techniques for quantifying cohesive sediment detachment and erosion rates.

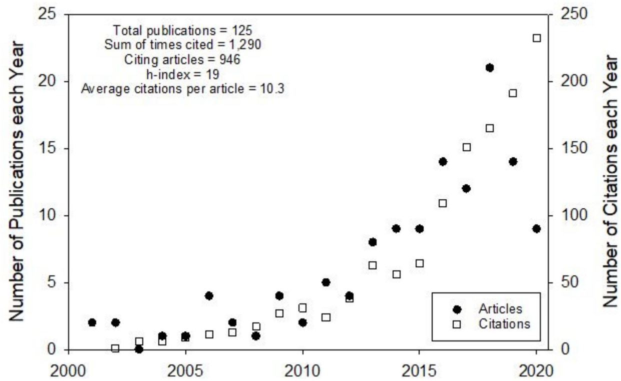

Figure 2. The number of peer-reviewed publications and citations to those articles on the Jet Erosion Test (JET). Data is from Web of Science on the topic "Jet Erosion Test" prior to 2020.

Lessons Learned

Laboratory & Field Implementation: Additional research is needed comparing the performance of the original and "mini" JET. Research by Al-Madhhachi et al. (2013) evaluating the "mini" JET device documented a consistent under-prediction of (See PDF for eq.) as compared to (See PDF for eq.) measured using the original JET. They suggested a multiplicative adjustment coefficient (0.1-0.5) to the equilibrium scour depths produced by the "mini" JET, which would lead to an increase of the calculated (See PDF for eq.) value, but further research is needed to validate this coefficient across a wide range of soil textures. Al-Madhhachi et al. (2013) evaluated the "mini" versus original JET devices based on only two soil types. At the time of the workshop, the participants indicated that such additional research had not been performed.

Another key aspect that should be considered when performing a JET is the calibration of the discharge coefficient (C), as the discharge coefficient for the JET nozzle must be known to compute the applied shear stress at the soil surface (Hanson and Cook, 2004). In many cases, C is assumed to be a constant for a JET device, but it is important to note that in field installations where the pressure head applied to the jet tube must be measured at a significant distance from the jet tube itself, the C coefficient is affected by head losses in the intervening water supply tubing. Changes to the field setup may require recalibration of the coefficient. Research has also shown that C can vary significantly with water temperature and only slightly with water salinity (Quiah, 2021). Users should calibrate their C relative to the conditions under which the JET will be operated. For significant field campaigns, this may also require users to track the temperature of inflow water sources and adjust C during analyses (Akinola et al., 2018).

Limited guidance currently exists regarding the setting of operational parameters of the JET, such as the jet pressure, initial nozzle distance, time intervals for data collection, and total test time. Flexibility is called for and exercised in practice because soil erodibility can vary by many orders of magnitude (e.g., Hanson and Simon, 2001). However, this makes standardization and interpretation difficult. In response, Karamigolbaghi et al. (2017), in examining the three-dimensional hydraulics in the mini-JET tank and identifying the influence of its smaller size on erodibility estimates, called for more specific and consistent test conditions. Soil moisture greatly affects resultant erodibility parameters as the jet test tank fills. Delayed time prior to running the test is needed for the local soil water content to equilibrate. A more standard practice is needed to determine this local equilibration time. Overall, variability in erodibility parameters created by different soil, water, and test conditions calls for the creation of a standard test to which all other tests can be compared.

Of course, many JET variables are test specific. For example, Hanson and Cook (2004) noted that before running a JET the tractive stress range for the intended application should be determined so that the test is conducted at a similar range of shear stresses. However, this is not always possible; for example, JETs on highly erodible soils will likely erode too quickly in cases where the pressure head is set high to mimic anticipated ranges of the applied shear stress. In many cases, utilizing test shear stresses in the same range as the application shear stresses can result in cases where one obtains too few measurements to accurately fit an erosion model and/or the scour hole depth exceeds the measurement range of the point gauge. Therefore, users of the JET are commonly required to treat the applied pressure head, h, as an iterative setting when conducting JETs in the field. Questions are consistently raised regarding an appropriate h relative to the properties of the cohesive soils being tested with JETs to generate meaningful test data. Selection of h may affect the estimated erodibility parameters (see Figure 3 as an example), but there can also be significant variability between different sites and test specimens, making it difficult to isolate the effects of h. There is often tension between an h that permits jet tests of the soil and the necessary h to generate the expected range of shear stress for application of the detachment model. Of course, this assumes JET operation using constant head conditions where the shear stress is maximum at the start of the test and then decreases throughout the test. Mahalder et al. (2018a) recommended a new testing procedure applying incrementally increasing pressure heads in a multiple pressure setting (MPS) approach. Further comparison of constant head versus the MPS approach are needed.

The workshop also emphasized that the JET remains a labor-intensive instrument. The current version of the "mini" JET device uses a rotatable plate to block the water jet at various time increments to allow manual measurement of the scour depth. Automating the JET to remove the requirement for manual operation would result in significant savings of labor and time. Automated measurement should be aimed at achieving a higher sampling frequency. New designs should be considered that make the instrument more user-friendly. Nguyen et al. (2017) proposed a modified version of Hanson's (1990, 1991) original JET where the scour depth sensor can be rotated along an arc to measure the erosion profile rather just the scour at the center of the sample. This modification allows the determination of the volume of soil eroded by the jet. A deflector plate at the base of the device is used to stop the jet but remains manually activated. The workshop identified further device improvements as a key research opportunity.

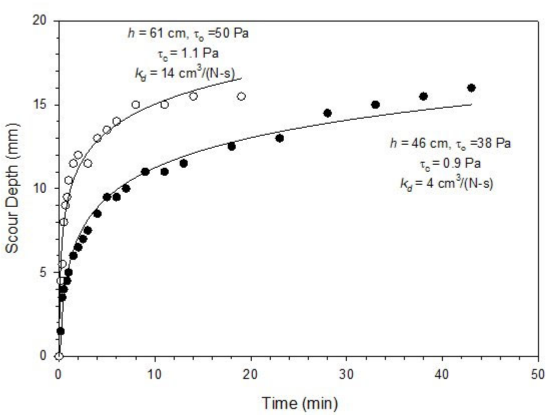

Figure 3. Comparison of scour depth versus time and derived erodibility parameters using the Blaisdell technique for side-by-side JETs (approximately 30 cm apart) conducted with different heads (46 cm and 61 cm) at a streambank site on the Barren Fork Creek by Daly et al. (2015a). Note that the experimental times of the test are different.

Solution Techniques & Interpretation of Results: The objective when analyzing and interpreting results is to find parameters of an equation relating applied stress, observed erosion, and parameters of the soil that define the threshold condition and change in rate of erosion versus increased stress. The first decision that must be made is to select the erosion equation, and the linear excess shear stress equation (equation 1) has been the most common choice. Once an erosion model is selected, JET data are used to find the model parameters that fit the observed data to the chosen model. There are currently three solution techniques that have been widely used to interpret JET results using a linear excess shear stress equation (Figure 4): the Blaisdell solution (Hanson and Cook, 2004), the iterative solution (Simon et al., 2010), and the scour-depth solution (Daly et al., 2013). The curve-fitting objectives and methods vary somewhat, but all these solutions were originally considered during JET development (Hanson and Cook, 2004); data analysis limitations at the time moved the analysis towards the Blaisdell technique, which first estimates the (See PDF for eq.) by fitting a hyperbolic function to extrapolate the equilibrium scour depth (limit of scour at infinite time). The stress corresponding to this jet distance is taken to be the (See PDF for eq.). In the second stage of the analysis, the (See PDF for eq.) is adjusted to fit a function that predicts the times at which observed scour depths occurred during the test.

Recent research has suggested the use of the iterative solution or scour-depth solution (Daly et al., 2013). The motivation for considering these other methods came first from the anecdotal observations of JET users that the equilibrium scour depth predicted by the Blaisdell method was sometimes very large, with an associated small value of the (See PDF for eq.) Controlled comparisons of these solution techniques has confirmed that the Blaisdell solution tends to estimate lower (See PDF for eq.) than the iterative and scour depth solutions (Khanal et al., 2016a; Wahl, 2019, 2021). This lower (See PDF for eq.) also leads to a lower estimated (See PDF for eq.) because an optimal linear fit must pass through the middle of the observed shear stress versus erosion rate data. The scour-depth and iterative solutions both optimize (See PDF for eq.) and (See PDF for eq.) simultaneously, which generally produces better-fitted results with higher estimated (See PDF for eq.) and higher (See PDF for eq.). However, the iterative and scour-depth solutions may not yield a true (See PDF for eq.) as the solutions are both sensitive to how often and for how long scour depth measurements are taken.

And while these higher values of the (See PDF for eq.) and the (See PDF for eq.) may appropriately fit the data within the range of shear stress evaluated during a JET, many times these coefficients are applied to shear stress ranges that are much less than or far exceeded those experienced during the test itself. This is especially an issue when one is trying to conduct a JET on less cohesive soils, which cannot sustain high stresses and erode quickly. Even if attempting to measure scour depths at very short time intervals, there are practical limits that inhibit a significant number of points to capture the scour hole progression. This implies that there is nonlinear behavior in applications (slower erosion at high stresses than would be extrapolated from tests performed at low stresses), but there is still a lack of data collected in controlled conditions that clearly demonstrate this. In totality, these issues confound efforts to further evaluate how the performance of each solution technique is impacted by the quality and quantity of the data collected during a JET. These issues also make it difficult to develop a JET standard that recommends a single testing procedure and solution methodology for users of the JET device.

Nonlinear Cohesive Soil Erosion: The perception that soil erosion is nonlinear in practice has led some researchers to suggest that JETs and other erosion tests should be analyzed using fundamentally nonlinear relations between the applied shear stress and erosion rate (Mehta and Partheniades, 1982; Wilson, 1993; Walder, 2016). Mehta and Partheniades (1982) suggested an exponential function with accelerating erosion rates at higher excess shear stresses, where(See PDF for eq.) and (See PDF for eq.) are constants greater than 1:

$$\varepsilon_r = a' exp\left(b' \frac{\tau-\tau_c}{\tau_c}\right) \qquad (3)$$

Al-Madhhachi et al. (2014) demonstrated analysis of JET data with a nonlinear cohesive sediment detachment model originally developed by Wilson (1993) where the erosion rate accelerates gradually at low stresses, is approximately linear for moderate stresses, and asymptotically approaches a square root function at large value of excess shear stress.

Recent research supports both linear and nonlinear approaches (Figure 4). For example, Wardinski et al. (2018) reported that for most of their JET experiments, statistical analysis rejected the assumption of linearity between the erosion rate and applied shear stress. However, Wahl (2021) suggested that simpler linear regressions between erosion rate and excess shear provided the most consistent fits to JET data. Based on scour hour development and soil properties, a general consensus has developed that a linear model appears to be best applied on highly cohesive soils (more narrow scour hole development) whereas a nonlinear model appears to be best studied in less cohesive soils (wider scour hole development). If nonlinear relationships are confirmed moving forward, one issue is that mainstream models that simulate cohesive sediment detachment are largely constructed around the concept of a linear excess shear stress relationship.

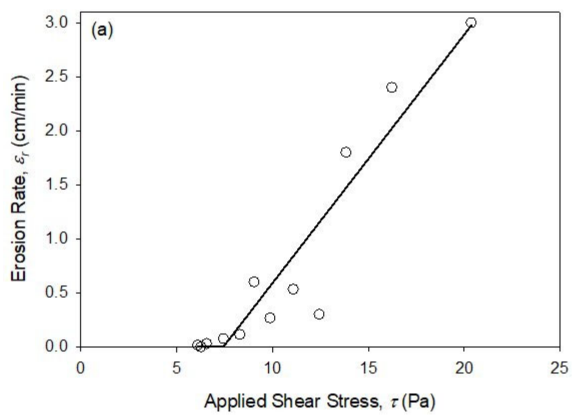

Figure 4. Example of (a) linear and (b) nonlinear relationships between shear stress and erosion rate collected during JETs from Wardinski et al. (2018).

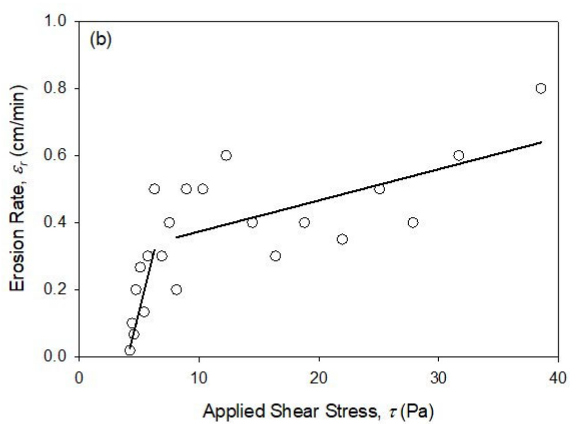

Figure 4. Example of (a) linear and (b) nonlinear relationships between shear stress and erosion rate collected during JETs from Wardinski et al. (2018).

Of course, cohesive sediment detachment and the fundamental mechanism of the removal process remain uncertain and there exists considerable variability in the data even when collected under well-controlled laboratory conditions with a JET or even a flume. At higher (See PDF for eq.), does the detachment process become fundamentally different (moving from particle to aggregate detachment) than at lower applied (See PDF for eq.)? Research conducted on cohesive sediment beds has highlighted the existence of distinct erosion modes: surface or particle erosion and mass erosion (Winterwerp et al., 2012; Papanicolaou et al., 2017). If a nonlinear relationship truly does exist, then this may be a reason why the iterative and scour depth solutions result in significant overestimations of erosion rates when applied to JET data collected over low shear stress ranges. Among important research needs, the workshop targeted better understanding of the fundamental detachment mechanisms, the conditions under which they occur, and appropriate mathematical models for these mechanisms (Bonelli, 2019; Fox, 2019b).

Additional Research Opportunities

JET Hydrodynamics & Physics of Scour Hole Formation: The current operation of the JET and "mini" JET focuses on measuring the depth of the scour hole along the axis of the jet, which is typically the location of maximum scour depth. However, the shape of the scour hole may also provide valuable information regarding the erodibility characteristics of the soil being tested. Two types of scour holes are typically observed: wide and shallow (weakly deflected jet regime) versus narrow and deep (strongly deflected jet regime). Scour hole dimensions can also be impacted by mechanisms other than shear-flow-induced erosion, such as settling of larger soil particles or collapse of the scour hole sidewalls. Can new versions of the JET be developed that allow not only the measurement of the scour depth directly below the nozzle but also the entire shape of the scour hole at various times during the test? Using hydro-morphodynamic numerical modeling, we need to be able to answer how jet diffusion varies with the shape of the scour hole, building upon the research by Amin and Mazurek (2016).

JET Hydro-Morphodynamic Numerical Modeling: Simulating the complex processes that govern cohesive soil erosion by an impinging submerged turbulent jet of water remains a major challenge, specifically regarding how to accurately model coupled changes in shear stress distribution and scour hole geometry as erosion progresses. To date, efforts can largely be grouped into two categories: fixed-bed and mobile-bed.

Fixed-bed efforts have focused on developing a better quantitative understanding of the JET hydrodynamics via computational fluid dynamics (CFD). These efforts have implemented fixed scour hole geometries to characterize variables such as shear stress distribution, velocity field, and static pressure. Weidner et al. (2012) created a range of geometries by adjusting the ratio of scour hole's depth to the radius, allowing the simulation of the hydrodynamics inside narrow and wide scour holes. Their findings indicated that scour hole geometry affects the magnitude and location of the maximum shear stress with wider scour holes resulting in lower magnitudes and locations farther away from the water jet centerline.

Mobile-bed efforts have focused on developing a better quantitative understanding of the coupled water-soil phenomena. Initial efforts combined CFD simulations for solving the JET hydrodynamics with erosion laws and adaptive remeshing for simulating the evolution of the water-soil interface. Mercier et al. (2014a, 2014b) implemented a combined Euler-Lagrange method that tracked the displacement of the soil-water interface as erosion progressed. Their findings showed that such a method can effectively model coupled changes in shear stress distribution and scour hole geometry. Nonetheless, they also showed that predictions were highly sensitive to input parameters for the erosion law (i.e., (See PDF for eq.)and (See PDF for eq.)) and the selected turbulence model closure, highlighting the need for benchmark validation tests.

More recent mobile-bed efforts have combined CFD simulations for solving the JET hydrodynamics with the discrete element method (DEM) for describing the solid phase. The DEM approach allows one to model a collection of discrete granular particles, providing an enhanced understanding of the fluid-solid interaction forces and removing the need to apply semi-empirical erosion laws. Zhang et al. (2019) implemented the DEM approach together with CFD simulations based on the Reynolds-averaged Navier-Stokes equations to characterize features of the impinging water jet as a function of the ratio of jet height to nozzle diameter. However, their results were limited by the lack of calibration of the DEM parameters used to represent the soil physics. Following the work of Cuellar et al. (2015, 2017), Benseghier et al. (2020) coupled the DEM approach with CFD simulations based on the Lattice Boltzmann Method (LBM) to examine the onset of jet erosion for cohesionless granular particles. Although the satisfactory agreement with experimental data highlighted the advantages provided by the LBM-DEM approach, remaining challenges include accounting for highly turbulent flows and cohesive granular samples with a range of grain sizes.

Numerical simulations are expected to be at the forefront of advancing our quantitative and predictive understanding of JET hydro-morphodynamics. The workshop encouraged further development in numerical simulations to provide insight into parameters that are very difficult to measure in-situ and in the laboratory, and ultimately, allowing the development of more accurate methods to estimate soil erodibility parameters.

Reporting, Standards & Benchmark Testing: In asking whether the JET was repeatable, Hanson and Hunt (2007) and Thompson (2019) both reported that testing cohesive soils with the JET in both the laboratory and field was highly sensitive to changes in bulk density and moisture content. Because erosion parameters can vary over orders of magnitude at a single site, Thompson (2019) recommended a minimum of 10 JETs should be conducted for each site. Such recommendations were in line with those suggested by Daly et al. (2015b).

With the large number of influential parameters on cohesive soil erodibility, measurements should be reported with much more critical data than currently reported in the literature, especially when JETs are performed. Studies infrequently report many of the key drivers that influence erodibility parameters. These should include JET-operation parameters (calibrated JET nozzle discharge coefficient, applied pressure head during the test, time between sample wetting and testing, intervals of scour hole depth measurement, and solution methodology); soil properties (moisture content, soil temperature, bulk density, texture, and structure) (Mahalder et al., 2018b); and characteristics of the JET fluid (temperature, salinity, and pH; Hoomehr et al., 2018). The workshop specifically called for the creation of a widely shared database of soil erodibility measurements (both (See PDF for eq.) and (See PDF for eq.) or equivalent parameters) obtained from the JET like the recent report by the NASEM (2019) focused on geotechnical property correlation to erodibility, but such a database will only be effective if much more information is provided when JET results are presented.

For laboratory testing, it was concluded from the workshop that standardized, reproducible sample preparation and testing procedures were needed for cohesive soils potentially with a benchmark soil. When using remolded samples, documenting soil sample preparation methods is critical. Factors such as the moisture content at compaction, the compaction effort, and the resistance (Grissinger, 1966; Kamhuis and Hall, 1983; Akinola et al., 2018). Similar, erosion testing methods impact test results. For example, Khanal et al. (2016a) noted that using higher applied pressure heads with JETs results in higher variability in JET-derived parameters when conducting tests on the same soil. Also, the selected time intervals and total test duration affected erodibility parameters, especially at larger head settings. The nonlinearity and sampling rate of the erosion function could affect the linear regression analysis outcome such that for largerpressure heads, users may need to collect scour depth data more frequently. The workshop identified the need to ascertain optimally jet pressure settings for various soil types and conditions. Research by Akinola et al. (2019) documented that temperature differences between the eroding fluid and the soil significantly affected soil erosion rate; therefore, the soil and eroding fluid temperature should be equilibrated prior to testing. Also, a benchmark soil, like the documented procedures for calibrating the fluid discharge coefficient (*C*), would allow new users of the JET to validate their instrument and testing procedures before use in less controlled environments.

Using Erodibility Parameters: Erodibility parameters can be used to classify soils into descriptive erodibility categories like those presented by Hanson and Simon (2001). They characterized the erodibility of cohesive soils as very erodible, erodible, moderately resistant, resistant, and very resistant based on the linear excess shear stress parameters ((See PDF for eq.) and (See PDF for eq.)). A similar classification approach is also used in geotechnical engineering applications to characterize soils from very high erodibility to non-erosive (Shafii, 2018).

Additional research has attempted to correlate basic soil physical properties with erodibility parameters obtained from JETs analyzed using the excess shear stress model (Julian and Torres, 2006; Wynn and Mostaghimi, 2006; Daly et al., 2016; Mahalder et al., 2018b; NASEM, 2019). The objective of this work is to make it possible estimate erodibility parameters when basic soil characteristics are known, without the need for conducting a JET. While several relationships have been developed to estimate (See PDF for eq.) based on soil properties, fewer widely tested and verified relationships are available to relate(See PDF for eq.) to soil physical properties. Also, numerous relationships have been reported and used in modeling to relate(See PDF for eq.) and(See PDF for eq.) (Figure 5). Hanson and Simon (2001) proposed equation (4a) based on 83 in situ JETs; Simon et al. (2011) suggested a modified form shown in equation (4b) from JETs on erodible and nonerodible streambanks across the United States; Criswell et al. (2016) conducted flume experiments on gravels and reported the relationship shown in equation (4c):

$$k_d = 0.2\tau_c^{-0.5} \qquad (4a)$$

$$k_d = 1.62\tau_c^{-0.84} \qquad (4b)$$

$$k_d = 2.2\tau_c^{-0.5} \qquad (4c)$$

For soils used in engineering construction, Hanson et al. (2011) offers relations between both(See PDF for eq.) and (See PDF for eq.) and soil clay content, compaction energy, and water content at the time of compaction. The National Academies of Sciences, Engineering, and Medicine (NASEM, 2019) study specifically noted: "…geotechnical properties were found to have a mixed and complex relationship with erosion resistance in general."

Linear and nonlinear soil erodibility parameters can also be used as input to numerical models for hillslope, streambank, and earthen embankment and levee erosion prediction models (Clark and Wynn, 2007; Langendoen and Simon, 2008; Khanal et al., 2016b; Mittelstet et al., 2017; Enlow et al., 2018; Kassa et al., 2019). In such applications, in situ testing offers the potential to incorporate conditions that may be difficult to replicate in lab settings. However, as noted earlier, when JETs are conducted in situ, significant variability is commonly reported in the measurements due to the multitude of factors that influence soil erodibility. For example, higher soil moisture within a specific soil type increased initial resistance to erosion but also increased the overall erosion rate (Khanal et al., 2020). For this reason, the workshop team encouraged the use of probabilistic modeling approaches as opposed to direct modeling applications that use a single-averaged value of erodibility parameters to generate a single model prediction. Several JETs should be conducted on the soils of interest, and then the variability observed in these measurements should be incorporated into the models to generate a distribution of predictions.

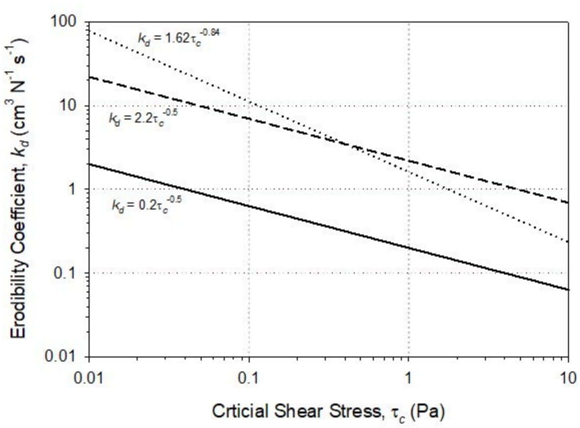

Figure 5. Comparison of proposed relationships between soil erodibility coefficient ((See PDF for eq.)) and the critical shear stress ((See PDF for eq.)) for a linear detachment model.

As noted earlier, modelers must also be aware of the range of shear stress applied during a JET versus that which will occur in the event(s) being modeled. In many cases, models that use JET-derived erodibility parameters may be applied for a shear stress range that are very different from the range over which the erodibility parameters were estimated. This is especially true for more erodible soils where a smaller applied pressure head may be needed for the JET to avoid scour holes that progress too quickly. Across a limited shear stress range the erodibility may appear to be linear, but not when across much broader ranges of shear stresses as part of model applications.

In the complicated domain of cohesive soil erodibility, users should be aware that JET measurements can be time- and hydrologic-dependent (Wynn et al., 2008). Changes in soil moisture content and temperature can significantly influence erosion rates, as previously discussed. Subaerial processes and number of wetting/drying and freeze-thaw cycles greatly influence the erodibility of soils (Fox et al., 2007; Wynn et al., 2008). Therefore, related field work assessing and classifying the complexity of bank material both longitudinally as well as vertically, noting capillary fringe height, root depth, and weathering intensity related to interflood periods are needed to properly characterize erodibility with JETs (Wynn et al., 2008; Enlow et al., 2017; Akinola et al., 2018).

Vegetation introduces additional complexity to characterizing the erodibility of soils. For example, Termini (2016) conducted flume experiments with vegetated beds noting the influence of full vegetation on the shear stress distribution and that turbulent structures developed within and between vegetated elements. Roots bind soil particles together while above-ground vegetation can impact the applied shear stress reaching the cohesive soil surface (Wynn and Mostaghimi, 2006; Smith et al., 2021). Researchers testing vegetated soils have typically removed the above-ground vegetation prior to jet-testing so that just the soil erodibility parameters are measured; however, roots exposed during testing can also deflect the jet, affecting jet diffusion and the applied shear stress. Studies using jet test devices to evaluate the effects of roots on soil erodibility parameters have shown a decrease in k_d and an increase in t_c with increasing root density (Wynn and Mostaghimi, 2006; Zhu and Zhang, 2017; Khanal and Fox, 2017; Smith et al., 2021), demonstrating the erosion resistance provided by vegetation.

At this point, no consensus exists on how to mechanistically modify erodibility parameters or the applied shear stress that may be acting on the soil to account for the effects of roots, above-ground vegetation, moisture content, and soil and water temperatures. Alternative approaches are used to empirically adjust erodibility parameters in numerical models, such as using a multiplier (a) in the linear excess shear stress equation to modify the applied shear stress (Daly et al., 2015b; Enlow et al., 2018):

$$\varepsilon_r = k_d(\alpha\tau - \tau_c) = \alpha k_d\left(\tau - \frac{\tau_c}{\alpha}\right) \quad (5)$$

Erodibility parameters can change not only temporarily but also spatially with depth into a soil profile (Mehta and Partheniades, 1982). Mahalder et al. (2018a) suggested that the MPS approach accounted for the increased bulk density from a streambank surface inward into the streambank face where the streambank surface was subjected to subaerial processes, but additional research is needed on this approach and ability for JETs to account for spatial variability in erodibility. The workshop group suggested that improved methodologies are needed to remove the empiricism in accounting for erodibility changes and develop more mechanistic approaches to eventually be able to dynamically model temporal and spatial changes in soil erodibility (Fox, 2019a).

Conclusions

The JET is one of the most commonly used instruments for quantifying cohesive soil erodibility in situ. Over the past two decades, there has been a growing body of research published on the design and use of the JET, analysis techniques for estimating erodibility parameters, JET hydrodynamics, and utilization of JET-derived soil properties in hydraulic and sediment transport models. The workshop sponsored by ASABE in October 2019 highlighted the following additional research needs and focus areas for further development:

- Additional comparisons of the original JET to the “mini” JET for a wide range of soil textures.
- The influence of confinement (submergence tank) on jet hydrodynamics.
- Further investigations on how jet diffusion varies with the progression of scour hole and relative to scour hole shape.
- Development of operating guidelines to ensure more consistent test conditions, sample preparation, variable reporting, and analysis procedures for the JET.
- Selection and use of a benchmark soil to validate JET operation.
- Development of a JET erodibility database across soil types.
- JET design improvements to reduce labor requirements and to make the instrument less influenced by operator effects.
- Further quantification of detachment and entrainment mechanisms for cohesive soils across a wide range of applied shear stress.
- Continued advancements in numerical simulation tools for verifying JET operation and analysis procedures.
- Improved methodologies for incorporating JET-derived parameters into less empirical, more physically-based hydraulic and sediment transport models.

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