GUIDANCE ON APPLIED PRESSURE HEADS FOR QUANTIFYING COHESIVE SOIL ERODIBILITY WITH A JET EROSION TEST (JET)

Collection
Research Brief

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HIGHLIGHTS

- Jet erosion test (JET) is a commonly used instrument for quantifying soil erodibility.
- Uncertainty remains on an appropriate applied pressure head to ensure high-quality JET data.
- Numerical analysis was used to derive minimum and maximum heads for four soil classifications.
- Ideal applied pressure heads depend on soil erodibility parameters and user-selected JET characteristics.

ABSTRACT. *The Jet Erosion Test (JET) is one of the few instruments available for measuring cohesive soil erodibility in situ, but uncertainty remains regarding an appropriate initial applied pressure head for the test. Users typically iterate on an initial applied pressure head setting when testing soil. This iteration is necessary to ensure a reasonable erosion rate and the total amount of scour while imposing applied shear stresses that match the expected application range when using JET-derived erodibility parameters. This research used a numerical analysis of simulated JETs to determine both minimum and maximum applied pressure heads, ensuring a logistically appropriate estimation of soil erodibility parameters. First, the minimum head was set to generate at least 25 mm of scour, established based on data from previous in situ JETs. Second, the maximum applied pressure head was set to ensure that no excessively large initial applied shear stress impacted the estimation of erodibility parameters from a linear regression on erosion rates. Analyses were conducted for four selected soil erodibility classes: highly erodible, more erodible, erodible, and moderately resistant soils. Curves showing the ideal applied pressure ranges were generated for initial time intervals of scour depth measurements of 60, 90, 120, 180, 240, and 360 s and dimensionless initial nozzle heights of 1.00, 1.25, and 1.50. The appropriate range in the applied pressure head depended not only on the soil erodibility classes but also on the initial time interval for scour depth measurements, total test duration, and dimensionless initial nozzle height above the soil surface. Users should ensure that a minimum applied pressure head is exceeded for resistant soils. Maximum applied pressure heads should be considered for erodible, more erodible, and highly erodible soils, dependent on the initial time interval for scour depth measurements and dimensionless initial nozzle heights. Wider ranges of acceptable applied pressure heads were observed with smaller initial time intervals. The procedure presented in this research can be readily adapted by JET users to reflect specific testing conditions (e.g., different data collection intervals and test durations) for ensuring the a priori use of effective pressure head settings.*

Keywords. *Cohesive soils, Erodibility, Jet erosion test, Pressure head, Soil erodibility.*

Originally developed by Hanson (1990), the jet erosion test (JET) remains one of the most commonly used instruments for quantifying cohesive soil erodibility (Hanson and Simon, 2001; Wynn et al., 2008; Khanal et al., 2016a; Lisenbee et al., 2017; Akinola et al., 2018; Ali et al., 2021). An ASTM standard was developed for the operation of the JET and the analysis of JET data (ASTM, 2007). Since its development, continued advancements have been made regarding the design of the instrument and the analysis of JET data. According to Wahl (2021), "ASTM Standard D5852 for the submerged jet erosion test was last renewed in 2007 but has since been withdrawn without replacement. New standards are under consideration, but substantial development of both new devices and new data analysis methods has taken place since the original standard was issued." For example, a smaller and lighter version of the JET, called the "mini"-JET (fig. 1), was evaluated against the original JET by Al-Madhhachi et al. (2013a). Recent research has also reconsidered the way that JET data are analyzed for deriving erodibility parameters, incorporating these solution techniques into new automated spreadsheet tools (Fox et al., 2022).

The operation of the JET has generally remained consistent since its original development. Typically, the JET is operated by applying a constant pressure head (h) on the

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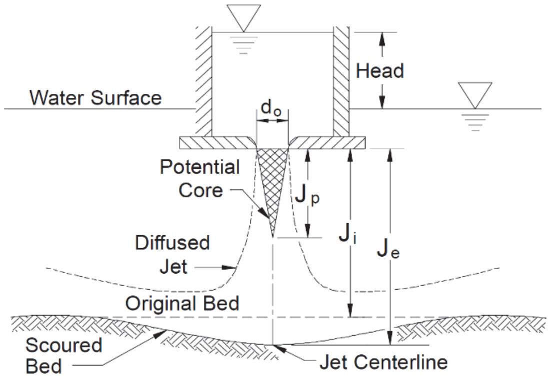

Figure 1. Depiction of parameters for circular submerged jet. Source: Hanson and Cook (2004).

nozzle of the JET device to create a submerged water jet that impinges on the soil surface. It should be noted that Mahalder et al. (2018) used a multi-pressure approach to address how pressure head selection affects the estimated erodibility parameters. Follow-up research by Mahalder et al. (2022) compared the multi-pressure operation of a "mini"-JET to measurements from a laboratory pressurized conduit flume and reported similar estimates in critical shear stress but differences in the erodibility coefficient. Additionally, the standard practice remains the selection and use of a single, constant *h* (table 1). Next, the test should ideally be performed until a quasi-equilibrium scour depth is obtained, but this is not always practical; therefore, a total test duration of approximately 1 to 2 hr is typically used for in situ tests (Al-Madhhachi, 2013a; Daly et al., 2015; Daly et al., 2016; McNichol et al., 2017; Khanal et al., 2020; Swanson and Castro-Bolinaga, 2022), although shorter times are also common under more controlled conditions. Collected data can be analyzed to estimate erodibility parameters for cohesive soils in either linear or nonlinear detachment models for predicting erosion rates across a range of applied shear stress (Fox, 2019; Khanal et al., 2020; Wahl, 2021; Fox et al., 2022).

Questions are consistently raised, especially with respect to developing an updated standard, about an appropriate *h* to use during a JET, which is frequently thought to be dependent on the properties of the cohesive soils being tested. Hanson and Cook (2004) noted that before running a JET, the applied stress (τ) range should be determined to match that of interest when applying the erodibility parameters. However, this is not always possible. For example, JETs on highly erodible soils will likely erode too quickly to an equilibrium scour depth (i.e., before a series of early-time, high-shear stress scour depth measurements could have been obtained without very high-frequency time intervals) when the *h* is large based on anticipated ranges of τ. In many cases, this can cause the scour depth to exceed the range of the point gauge (typically 100 mm for the in situ "mini"-JET). It should also be noted that soil moisture content can significantly influence erodibility parameters for cohesive soils. Khanal et al. (2020) suggested that higher soil moisture increased initial resistance to erosion but also increased the erosion rate. Therefore, even resistant soils can become more erodible once the applied shear stress exceeds the critical shear stress due to changes in soil moisture content.

Table 1. Example JET studies that also report soil properties. Not all quantified soil properties are shown in the table.

Reference	Identifying Soil Type or Location	Disturbed (D) or Undisturbed (UD) Sample	Sand (%)	Silt (%)	Clay (%)	Bulk Density (g cm^{-3})	Soil Moisture Content (%)	Average Applied JET Pressure Head, *h* (cm)
Wilson et al. (2020)	Providence	D	15	69	16	1.27	---	32.4
	Calloway	D	2	88	10	1.24	---	32.4
	Ost-Clark	D	48	24	27	1.24	---	32.4
	Arkabutla	D	23	66	12	1.18	---	32.4
Wardinski et al. (2018)	Sandy loam	D	72	16	12	1.42	21	185.0
	Sandy clay loam	D	56	21	23	1.32	26	202.0
	Clay loam	D	40	26	34	1.22	33	262.0
Nguyen et al. (2017)	Silty clay loam	D	0	63	37	1.65	17	130.0
Lisenbee et al. (2017)	Sandy clay loam	UD	65	17	18	1.32	21	71.0
Liu et al. (2017)	Sandy loam	D	70	16	14	1.60	---	32.4
	Silt loam	D	3	72	24	1.40	---	32.4
	Silty clay	D	5	55	39	1.20	---	32.4
Enlow et al. (2017)	Fivemile Creek sand layer	UD	72	19	9	1.50	---	38.5
	Willow Creek sand layer	UD	77	16	7	1.30	---	38.5
	Barren Fork Creek	UD	35	50	15	1.20	---	57.0
	Illinois River	UD	20	62	18	1.20	---	57.0
Khanal et al. (2016b)	Sandy loam	D	54	38	8	1.78	15	79.0
	Clay loam	D	30	33	36	1.61	20	79.0
Daly et al. (2015)	Barren Fork Creek	UD	47	39	14	1.30	24	46.0
	Cow Creek	UD	42	42	16	1.31	13	60.0
	Fivemile Creek clay layer	UD	56	25	19	1.44	29	220.0
Al-Madhhachi et al. (2013a)	Clayey sand	D	57	18	25	1.90	---	109.0
	Silty sand	D	72	13	15	1.74	---	109.0
Al-Madhhachi et al. (2013b)	Clayey sand	D	57	18	25	1.60	---	64.0
	Cow Creek silty sand	D	72	13	15	1.60	---	64.0
Wahl (2010)	SM – silty sand	D	76	19	5	1.69	11	69.0
	s(CL) - sandy lean clay	D	31	50	19	1.75	12	71.0
	Lean clay with sand (CL)s	D	20	50	30	1.83	14	134.0
Hanson and Hunt (2007)	Silty sand	D	63	31	6	1.80	12	77.5
	Lean clay	D	25	49	26	1.75	16	77.5

Therefore, there is an inherent need for a balance between selecting a logistically reasonable *h* versus the necessary *h* to generate τ in the expected range when the detachment model is applied. Such a balance is not uniformly implemented in practice. Some studies have used a consistent *h* across all soil types (e.g., Wilson et al., 2020), while others have varied *h* relative to the soil properties (e.g., Wahl, 2010). Examples of these studies are shown in table 1.

As an example of the impact of the applied *h* on JET-derived erodibility parameters, Khanal et al. (2016b) suggested that a greater *h* resulted in similar critical shear stress (τ_c) but greater erodibility coefficients (k_d) for the same soil. An example of the variability observed in side-by-side JETs conducted on the same streambank at the same time is shown in figure 2. The two different applied *h* generated initial stresses of approximately 40 and 50 Pa at *h* of 46 and 61 cm, respectively. A key question that remains is whether these differences in the erodibility characterization were due to fine-scale variations between the side-by-side JETs in terms of soil properties, wetting-drying cycles, and other characteristics, or if this difference in characterization was due to differences in the applied *h*.

The objective of this research was to provide guidance and a documented procedure that can be used by JET users to determine an appropriate *h* for ensuring quality data for estimating erodibility parameters. Because of the variability in how JETs are performed by various investigators and the limited number of reported soil and JET-operational parameters, we utilized a numerical approach for this research rather than a meta-analysis of previous JETs (table 1). Furthermore, several solution approaches for JET data have been proposed in the literature, including the commonly used Blaisdell solution, an iterative solution, and the scour depth approach (Daly et al., 2013). The use of a specific solution technique can impact the derived erodibility parameters (Wahl, 2021). The goal of this research was to focus on a straightforward fit of the erosion rate versus the applied stress data rather than investigating variability due to the solution technique. Therefore, the analysis consisted of generating simulated JET data for a given set of soil erodibility parameters, *h,* and JET settings. The generated JET data were used to estimate both a minimum *h* at which significant scour would be created for reasonable data analysis and the maximum *h* at which the test would provide a reasonable fit to the data to estimate the erosion rate versus shear stress with reasonable confidence.

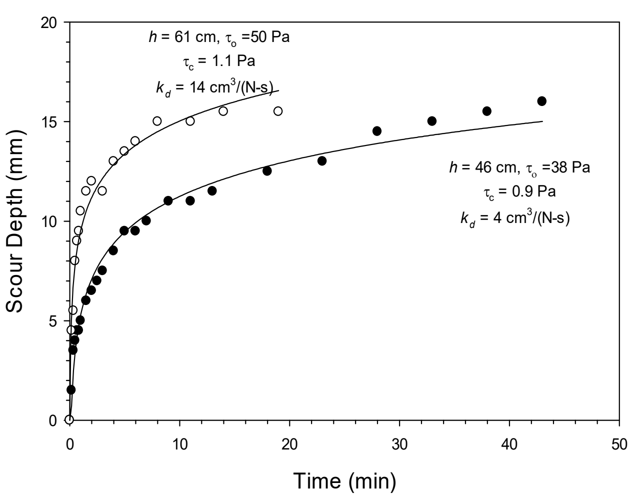

Figure 2. Comparison of scour depth versus time and derived erodibility parameters using Blaisdell technique for side-by-side JETs (approximately 30 cm apart) conducted with different heads (46 cm and 61 cm) at streambank site on Barren Fork Creek by Daly et al. (2015).

Methodology

A numerical procedure was developed to simulate JETs and generate a set of simulated applied shear stress (τ) and corresponding erosion rate (ε_r) data points. The methodology was applied to four idealized soils with predetermined erodibility coefficients based partially on the classification system suggested by Hanson and Simon (2001), as shown in table 2. We used average values of the erodibility parameters based on the approximate center of three of the categories proposed by Hanson and Simon (2001) and added a category between erodible and highly erodible to expand the analysis.

Assumptions made in the numerical analysis are listed hereafter. The applied constant pressure head, *h*, was held constant during the total test duration. Typical conditions for a JET based on the characteristics of the "mini"-JET frequently used for in situ testing (fig. 1) were assumed. The JET parameters were taken as follows: coefficient of friction, C_f = 0.00416; diffusion constant, C_d = 6.3; and a jet nozzle diameter, d_o = 0.32 cm (Hanson and Cook, 2004). This produced a potential core length of $J_p = C_d d_o$ = 2.0 cm. The initial jet orifice height, J_i, was set to 20 mm (or 2 cm); therefore, J_i/J_p = 1.0. Using these values, the velocity at the jet nozzle, U_o, maximum stress due to the jet velocity at the nozzle, τ_o, and the initial stress, τ_i, were calculated using the following equations (Hanson and Cook, 2004):

$$U_o = \sqrt{2gh} \tag{1}$$

$$\tau_o = C_f \rho U_o^2 \tag{2}$$

$$\tau_i = \tau_o \left(\frac{J_p}{J_i} \right)^2 \tag{3}$$

where *g* is the gravitational acceleration and ρ is the fluid density. The calculations were verified using the example given in Hanson and Cook (2004) for which a J_i/J_p = 1.0 with an applied *h* of 1.0 m resulted in initial stress of 82 Pa. Typically, C_f is assumed independent of the applied *h*; however, if relationships are known ahead of time, then the procedure can easily be adapted to incorporate those relationships.

The procedure was developed based on specified time intervals for measured scour depths and to generate JET-simulated scour depth (*J*) data for specified time intervals and

Table 2. Characteristics of the soils used to generate simulated erosion rate versus applied shear stress curves.

Soil Classification	Critical Shear Stress, τ_c (Pa)	Erodibility Coefficient, k_d (cm^3/N-s)
Highly Erodible	0.01	10.0
More Erodible	0.05	1.00
Erodible	0.10	0.50
Moderately Resistant	5.00	0.10

throughout a specified total test duration. For given h, JET device characteristics, soil classification with associated k_d and τ_c values (table 2), initial time intervals for scouring and total test duration, the procedure for generating simulated JET data is summarized in table 3. First, a continuous erosion curve was created to simulate the hypothetical erosion process at a short time resolution of 1 s using the excess shear stress equation:

$$\varepsilon_r = \frac{dJ}{dt} = k_d \left(\tau - \tau_c\right) \tag{4}$$

where

$$\tau = \tau_o \left(\frac{J_p}{J}\right)^2 \tag{5}$$

Then, a simulated sampled JET erosion rate curve was derived from the continuous erosion curve based on user-specified initial time intervals and total test durations. In this analysis, initial time intervals of 60, 90, 120, 180, 240, and 360 s and test durations of 60 or 90 minutes were investigated; however, users of the procedure can select different values based on their typical JET setup and operation. Initially, the erosion curve was sampled at a time interval equal to the initial time interval. When the calculated change in scour depth was less than 0.1 cm (1.0 mm since this is the resolution of the point gauge on a "mini"-JET), the time intervals used to sample the continuous erosion curve were doubled. For each sampling interval, the averages of the applied τ and observed ε_r were calculated. These steps were repeated until the total test duration was approximately equivalent to the specified total test duration (table 3).

Simulated JET-data points for ε_r versus τ were derived using this procedure. A linear regression model was fit to these data points to calculate the erodibility parameters using the approach suggested by Wahl (2021) using the average ε_r versus the average applied τ. As mentioned earlier, several solution approaches for JET data have been proposed in the literature (Daly et al., 2013), and the use of a specific solution technique will impact the magnitude of JET-derived erodibility parameters (e.g., Wahl, 2021). Herein, fitting the ε_r versus τ more closely mimicked the scour depth approach, except that erosion rates instead of scour depths were used. It is worth noting that this analysis represented an "ideal-case" for a JET in that variability due to differences in physical properties and environmental conditions was not considered.

Using the JET-simulated data and associated erodibility parameters, the minimum and maximum h values appropriate for a JET under the assumed conditions were then determined. To calculate the minimum applied h, the total scour depths were analyzed from 187 previous "mini"-JET experiments. Those studies included raw data from JETs performed by Al-Madhhachi (2013a), Daly et al. (2015), Daly et al. (2016), McNichol et al. (2017), Khanal et al. (2020), and Swanson and Castro-Bolinaga (2022). We used the 25th percentile from these previous JETs (fig. 3) to set a criterion to generate at least 25 mm (approximately 1.0 inch) of scour to reasonably characterize the erodibility. Therefore, for a combination of initial time intervals for measured scour depths and total test duration, we adjusted h until the total simulated scour was approximately 25 mm. It should be noted that this criterion can be adjusted by the user of the procedure if they typically operate JETs with less or greater scour depths.

To estimate the maximum allowable h, we aimed to limit the test condition in which an exceptionally large τ was applied at the beginning of the test that acted as an outlier and deteriorated the fit of k_d and/or τ_c. This situation is commonly observed when using the JET in the field, especially on more erodible soils; it inhibits the fit of ε_r versus τ to derive the erodibility parameters as the majority of the total

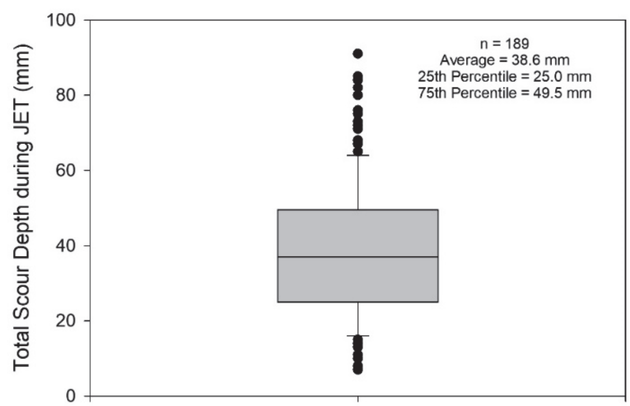

Figure 3. Total scour depth from 189 "mini"-jet erosion tests (JETs) conducted on range of soils.

Table 3. Summary of steps used to calculate the simulated scour depth from specified soil and JET parameters.

Step #	Description of Calculation
0	Decide on JET applied pressure head, JET device characteristics, soil classification with associated k_d and τ_c values (table 2), initial time intervals for measured scour depths, and JET test duration
Part 1: Calculate the continuous erosion curve using a time interval, Δt = 1 s	
1a	Calculate the erosion rate (dJ/dt) using equation 4
1b	Calculate scour during simulation time interval using $\Delta J = dJ/dt \times \Delta t$
1c	Calculate total scour depth, $J = J_i + \Delta J$
1d	Estimate applied shear stress at end of interval using equation 3
Repeat steps 1a-1d until the erosion rate becomes less than 1 mm of scour during an interval of 60 s	
Part 2: Create the simulated JET erosion rate curve	
2a	Start at $t = 0$ with J_i = initial depth, τ_i = initial applied shear stress, Δt = initial time interval
2b	Using the continuous erosion curve from Part 1, find the scour depth, J_{i+1}, and corresponding shear stress, τ_{i+1}, at $t = t + \Delta t$
2c	Calculate the change in scour, $\Delta J = J_{i+1} - J_i$
	i. If $\Delta J < 1$ mm, do not record data, double Δt, and redo step 2b with new Δt
	ii. If $\Delta J \geq 1$ mm, calculate the erosion rate as $\Delta J/\Delta t$ and the average stress as $(\tau_{i+1} + \tau_i)/2$ and record these values. Keep the same time interval, Δt, and move on to the next iteration in step 2b
2d	Repeat steps 2b-2c until the total time equals the total duration of the test

scour is observed immediately at the start of the test. We first used the following criteria to demonstrate the procedure in this research: the applied h was too large if the applied τ representing the initial stress was more than 100% greater than other applied τ on the JET-sampled erosion curve. We then repeated the analysis for a more restrictive criterion (50%) to evaluate the impact of this criterion on the maximum applied h. This criterion can be adjusted by the user, where a higher percentage means a less restrictive criterion regarding the applied h. We then iterated on h, starting with the previously defined minimum applied h and then increasing h until the criterion on the τ was exceeded.

In recognizing that the appropriate applied h for JETs depended not only on soil erodibility but also on the JET settings, we also varied the ratio of J_i/J_p as part of the analysis. Holding J_p constant at 2 cm (i.e., assuming a constant nozzle diameter), we increased J_i, the initial jet orifice height, to 25 mm (J_i/J_p = 1.25), and then to 30 mm (J_i/J_p = 1.50) and repeated the analyses.

RESULTS AND DISCUSSION

For a 60-minute test duration with J_i/J_p = 1, the minimum applied h values required to generate 25 mm of scour were approximately 2.0, 20, 45, and 250 cm for the highly erodible, more erodible, erodible, and moderately resistant soils, respectively. The selected total test duration influenced the minimum applied h. The minimum applied h to generate 25 mm of scour decreased slightly for longer test durations. The corresponding values for a 90-minute test duration compared to those reported earlier were approximately 1.5, 15, 30, and 175 cm, respectively. Note that JET users can select any value of the total maximum scour at the end of the test as part of this procedure. Users that are comfortable with very small total scour depths (e.g., for soils that are uniformly packed under laboratory conditions) at the end of the test likely do not need to consider a minimum applied h, but we recommend at least 25 mm of total scour for the in situ testing of cohesive materials (based on fig. 3).

The applied maximum h values were greater for the moderately resistant soils as compared to the more erodible soils, and the range of appropriate h values increased as soil resistance increased. An example showing the derivation of the maximum applied h is shown in figure 4 for the case of highly erodible soil with J_i/J_p = 1, three different applied h, and an initial time interval of 60 s. Note that as the applied h increased, the initial JET sampled τ extended further from the other applied τ. For this case, an applied h of approximately 40 cm resulted in an initial τ for the JET that exceeded the τ of the other data points by more than 100%. Again, the user has the ability to select the criterion regarding the magnitude of the initial τ relative to the other applied τ values.

The maximum h depended on the initial time interval for data collection (fig. 5). Larger ranges in the applied h can be used if using shorter initial time intervals for measured scour depths, as shown in figure 5. This was because data could be obtained to appropriately capture the rapid change in the scour depth at the beginning of the test when τ was the highest. These early-time, high-stress scour depth data were critically important for estimating k_d for more erodible and highly erodible soils. When using large initial time intervals

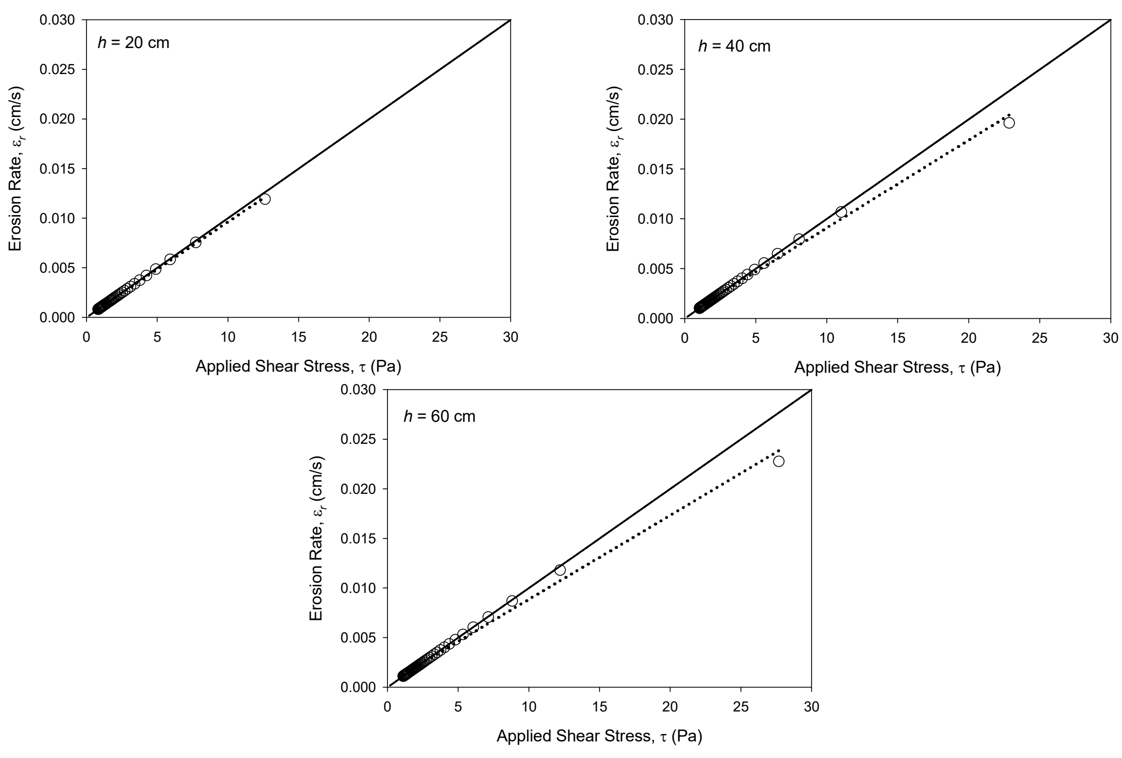

Figure 4. Example of linear regression between applied shear stress and erosion rate for three different applied pressure heads (top left = 20 cm, top right = 40 cm, and bottom = 60 cm) for highly erodible soil (τ_c = 0.01 Pa, k_d = 10.0 cm^3/N-s) with J_i/J_p = 1, 60 s initial time intervals for measured scour depths and 60-minute total test duration. Solid line is simulated erosion curve. Circles are hypothetical JET data points and dashed line is linear regression for JET points.

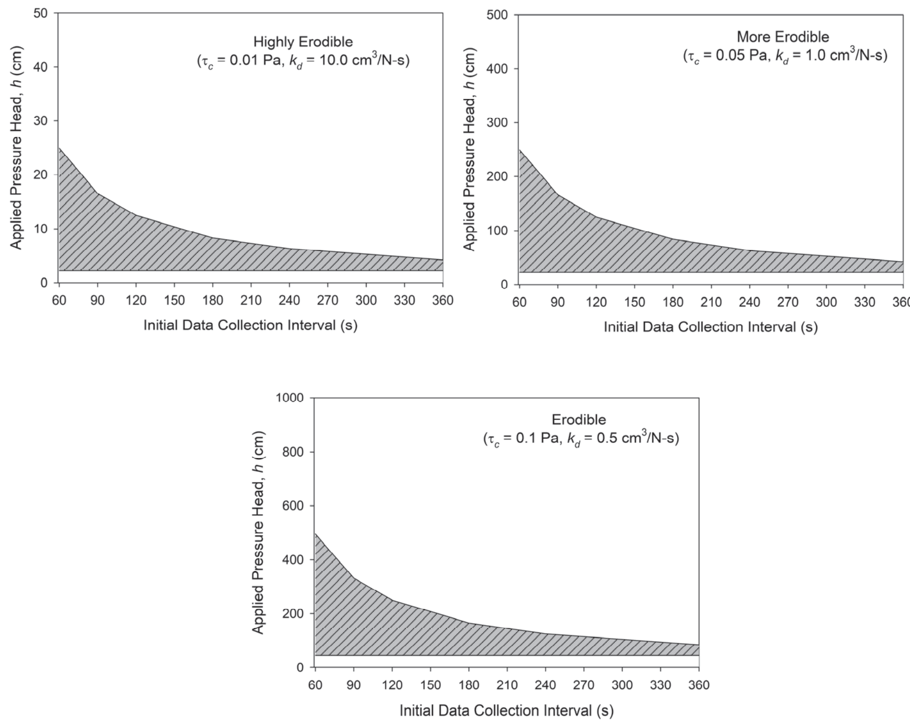

Figure 5. Relationship between initial time intervals for measured scour depths and appropriate applied pressure head for highly erodible (left top), more erodible (right top), and erodible (bottom) soils for J_i/J_p = 1 and total test duration of 60 minutes. Shaded region is range between minimum and maximum applied pressure heads. Graph used criterion that initial applied stress was no more than 100% greater than all other applied shear stress on JET sampled erosion curve.

for measured scour depths, it was imperative to be within a specific applied *h* range. A longer total test duration did not impact the maximum applied *h* based on the criteria related to the initially applied τ. However, longer test durations do allow the collection of additional data points at lower τ that can control the statistical fit of the ε_r versus τ relationship, somewhat reducing the overall weight of the early-time, high τ data. Longer test durations also lead to improved estimations of τ_c by ensuring that the test more closely reaches quasi-equilibrium conditions (Hanson and Cook, 2004). The criterion related to the initially applied τ does impact the maximum estimated *h* (fig. 6). A more restrictive criterion (initially applied τ no more than 50% more than other applied τ) resulted in a lower maximum applied *h*. JET users would need to decide on an appropriate limit for this initial τ.

The shaded region in figure 5 is the range between the minimum and maximum applied pressure heads derived using this procedure. JET users would simply need to ensure that a selected initial applied *h* was within this range to feel comfortable that additional uncertainty in their derived erodibility parameters is not associated with an inappropriate *h* selection. Considering the inherently large variability of soil erodibility parameters when doing in situ JETs, we should minimize any additional variability created by the instrument setup. The procedure explicitly demonstrates that for those running JETs under highly controlled conditions, such as when data collection intervals are small, a large range of applied *h* can be used and users do not need to extensively consider their maximum applied *h*. Figures 5 and 6 do not show the appropriate applied *h* ranges for moderately and even more resistant soils, as the maximum allowed *h* was generally several meters, except for large (greater than 360 s) initial time intervals. If a reasonable initial time interval is used, users only need to ensure that the minimum applied *h* is achieved relative to the anticipated test duration for moderately resistant soils.

An additional variable that should also be considered when performing JETs and ensuring an appropriate *h* range is the ratio of J_i/J_p. Note that all the above results were for the case where J_i/J_p = 1.0. The minimum applied *h* to reach 25 mm of scour was slightly greater as the ratio of J_i/J_p increased (fig. 7). For example, for the 60-minute test duration on a more erodible soil, the minimum *h* values were 22, 30, and 38 cm for J_i/J_p = 1.00, 1.25, and 1.50, respectively. The impact of the ratio of J_i/J_p was even greater for the maximum applied *h*, where corresponding values to those above were 250, 485, and 840 cm (fig. 7). These results were consistent with the initial jet orifice height being placed further from the eroding surface. Therefore, a greater *h* was required to generate the necessary scour with a significant initial applied τ. This additional complexity in that the minimum and maximum applied *h* depended on not only the soil erodibility classification but also the JET setup and characteristics further supports the use of the procedure proposed in this research.

CONCLUSIONS

A key question regarding the operation of a JET remains the selection of an appropriate applied pressure head. In many cases, JET users are forced to not only iterate to identify the ideal pressure head setting for the soil being tested but also to ensure that the applied stress matches the stress range of interest when applying the JET-derived erodibility

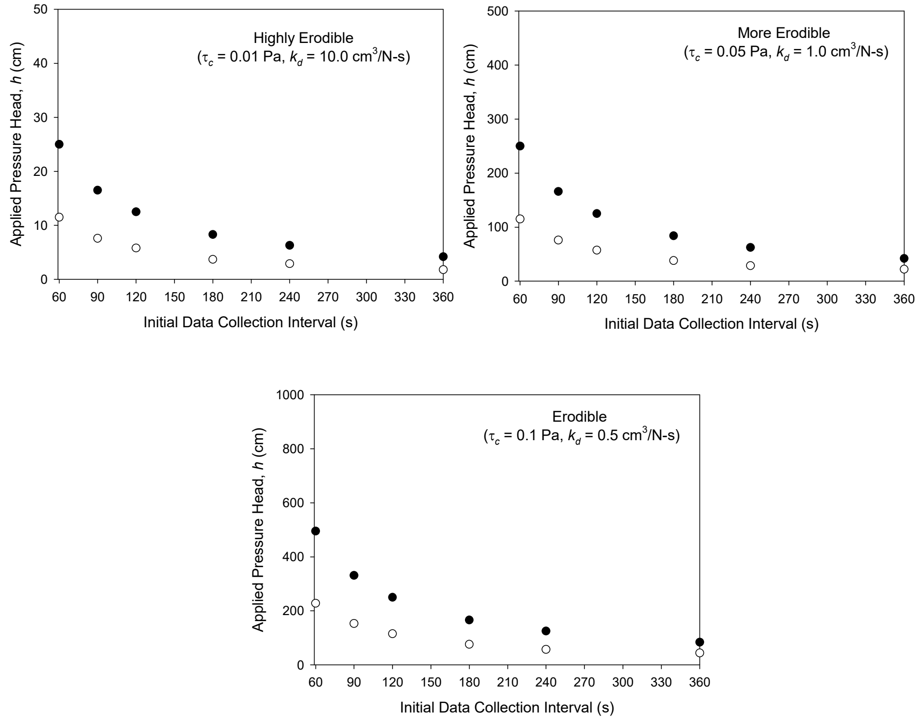

Figure 6. Relationship between initial time intervals for measured scour depths and maximum applied pressure head for highly erodible (left top), more erodible (right top), and erodible (bottom) soils for J_i/J_p = 1 and total test duration of 60 minutes. Solid black circles = initial applied stress was no more than 100% greater than all other applied shear stress on the JET sampled erosion curve. Open circles = initial applied stress was no more than 50% greater than all other applied shear stress on JET sampled erosion curve.

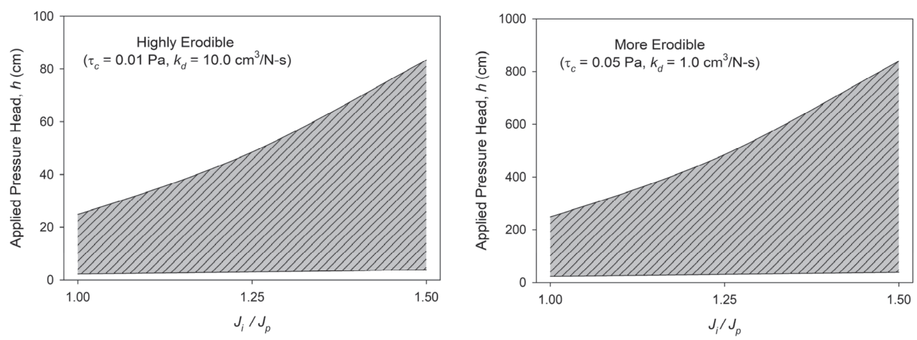

Figure 7. Relationship between the ratio of initial jet orifice height, J_i, and potential core length, J_p, to appropriate applied pressure head (h). Note that figures assume initial time interval for measuring scour depths of 60 s with total test duration of 60 s. Shaded region is range between minimum and maximum applied pressure heads.

parameters. This research demonstrated a procedure that can establish an appropriate range of pressure heads to ensure high-quality JET data; the procedure depended on several variables, not only the soil properties but also user-selected settings for the JET operation. Therefore, guidance cannot be derived based on just a meta-analysis of previous JETs relative to soil properties. The appropriate applied pressure head range depended on the erodibility classification of the soil, the total test duration for the minimum applied pressure head, the initial time intervals for measured scour depths for the maximum applied pressure head, and the ratio of the initial jet orifice height to the potential core length. The procedure developed in this research can be used to identify an ideal range for JET-applied pressure head settings for predetermined erodibility parameters for highly erodible, more erodible, erodible, and moderately resistant soils, and the procedure can easily be adapted for additional soil and test conditions. JET users must be more aware of an appropriate JET-applied pressure head range when using larger initial time intervals for measured scour depths and for tests with shorter total durations. Note that users must still be able to assess the erodibility category a priori. This is where a database of previous JETs would be incredibly beneficial. Of course, the procedure in this manuscript was limited by assuming best-case conditions for JET analyses relative to soil homogeneity and other sources of variability. Because we know that this variability and heterogeneity exist in situ, it is likely best to use applied pressure heads near the middle of the range of appropriate pressure heads reported in this research or derived using the procedures proposed in this research. While adjustments may still be needed in the field due to this ideal analysis, this research provides a procedure that can be followed to determine an appropriate initial applied head, whether using a constant head or multi-pressure approach, that builds on the previous literature on the JET and can move us toward an operational standard.

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