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Critical assessment of jet erosion test methodologies for cohesive soil and sediment

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ABSTRACT

The submerged Jet Erosion Test (JET) is a commonly used technique to assess the erodibility of cohesive soil. Employing a linear excess shear stress equation and impinging jet theory, simple numerical methods have been developed to analyze data collected using a JET to determine the critical shear stress and erodibility coefficient of soil. These include the Blaisdell, Iterative, and Scour Depth Methods, and all have been organized into easy to use spreadsheet routines. The analytical framework of the JET and its associated methods, however, are based on many assumptions that may not be satisfied in field and laboratory settings. The main objective of this study is to critically assess this analytical framework and these methodologies. Part of this assessment is to include the effect of flow confinement on the JET. The possible relationship between the derived erodibility coefficient and critical shear stress, a practical tool in soil erosion assessment, is examined, and a review of the deficiencies in the JET methodology also is presented. Using a large database of JET results from the United States and data from literature, it is shown that each method can generate an acceptable curve fit through the scour depth measurements as a function of time. The analysis shows, however, that the Scour Depth and Iterative Methods may result in physically unrealistic values for the erosion parameters. The effect of flow confinement of the impinging jet increases the derived critical shear stress and decreases the erodibility coefficient by a factor of 2.4 relative to unconfined flow assumption. For a given critical shear stress, the length of time over which scour depth data are collected also affects the calculation of erosion parameters. In general, there is a lack of consensus relating the derived soil erodibility coefficient to the derived critical shear stress. Although empirical relationships are statistically significant, the calculated erodibility coefficient for a given critical shear stress has an uncertainty of several orders of magnitude. This study shows that JET results should be used with caution and the magnitude of the uncertainty in the derived erodibility parameters should be carefully considered.

1. Introduction

Cohesive sediment is an important component in riverine systems, and cohesive soil erosion is known to be a major source of sediment in impaired streams (Wilson et al., 2008). Soil erosion and degradation have led to increased pollution, causing ecological damage such as fish habitat loss (Kondolf et al., 2006; USEPA, 2007), as well as scour around bridge piers, which is the primary cause of bridge failure (Briaud and Oh, 2010). Assessing and mitigating the impacts of cohesive soil erosion on the environment remain the focus of much research (e.g., Wan and Fell, 2004; Wilson et al., 2008). Contrary to non-cohesive sediment, the assessment of cohesive sediment erosion is challenging because of the complex interactions between parameters that affect entrainment processes and their variation in time (Grissinger, 1982; Black et al., 2002; Aberle et al., 2004; Grabowski et al., 2010).

Numerous studies have examined the erosion of cohesive soil (e.g., Winterwerp and van Kesteren, 2004; Owens and Collins, 2006; USBR, 2006; Partheniades, 2009). The primary focus of these studies has been to improve methods to predict the entrainment of cohesive sediment in a wide range of geomorphic environments (Knapen et al., 2007; Grabowski et al., 2011). While models have used unit stream power, rainfall intensity, or boundary shear stress (Rose et al., 1983; Nearing et al., 1989; Hanson, 1990), many soil erosion models assume the

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erosion rate E_r (L/T) is proportional to the soil's erodibility coefficient k_d and a flow variable X raised to a power a:

$$E_r = k_d (X)^a \tag{1}$$

The most common version of Eq. (1) uses excess shear stress as the flow variable and a equal to unity (Hanson and Cook, 2004), i.e.,

$$E_r = k_d (\tau - \tau_c) \tag{2}$$

where τ and τ_c are the applied shear stress on the soil surface and the critical shear stress for erosion, respectively. A non-linear equation, however, may improve erosion prediction (Houwing and Van Rijn, 1998; Walder, 2015), and this point is further discussed below. To date, there is no universally accepted methodology to estimate τ_c and k_d from soil properties (Knapen et al., 2007), and the best approach thus far has been to determine these indices directly from laboratory or field measurements. While many factors are known to affect the erodibility of cohesive sediment, a detailed theory that includes all of these effects remains elusive (Walder, 2015).

The submerged Jet Erosion Test (JET; Hanson and Cook, 2004) was developed to test materials in laboratory and field settings in an attempt to treat the factors controlling the erosion process as lumped parameters, effectively captured in time and space by derived values of τ_c and k_d. The JET apparatus (Hanson and Cook, 2004) consists of a jet tube with a nozzle of diameter $d_0 = 6.4$ mm that is mounted inside an enclosed cylinder. Water flows from a constant head level h_0 to the nozzle and produces a turbulent, circular jet, which impinges onto the soil from an initial height above the surface H_i. As long as the applied shear stress caused by the impinging jet is greater than the soil's critical shear stress, the jet will erode soil particles at and near the point of impingement and a scour hole will form. The depth of scour along the jet centerline is measured at time intervals after starting the test. Ideally, the test would continue until the scour hole reaches an equilibrium depth, at which point the applied and critical shear stresses would be equal. Since the test is likely to be shorter in duration, methods of extrapolation have been developed to project the observed data to the depth at equilibrium H_e, and the sediment's critical shear stress and the erodibility coefficient can be determined by fitting the data using Eq. (2). The accuracy of this methodology, however, depends heavily on jet hydrodynamics, a precise estimation of the applied shear stress, and the method of extrapolation.

Jet impingement theory proposed by Beltaos and Rajaratnam (1977) is the foundation for the JET analysis. Three methods of extrapolation and data analysis have been used for the JET: (1) Blaisdell Method (Blaisdell et al., 1981), (2) Iterative Method (Simon et al., 2010), and (3) Scour Depth Method (Daly et al., 2013). Common among these methods are the use of the linear excess shear stress equation and the assumption of an unconfined jet impinging a smooth, flat bed. The underlying assumptions of the JET methodology have been previously criticized (Table 1), and the issues identified likely increase the predictive uncertainty of the derived erodibility coefficients. In most cases, there is no clear recommendation as to how to revise the methodology in light of this criticism, or such revisions have not been implemented into the test standard.

The main objective of this study is to critically evaluate the jet impingement theory used in the JET and to assess the extrapolation techniques used to derive erodibility indices with the JET. This analysis will use a relatively large dataset obtained from a wide range of locations in the USA. The possible relationship between the erodibility indices τ_c and k_d in cohesive soils, which has strong practical use and broad implications for modeling, also is critically examined. Finally, a review of deficiencies in the JET methodology is presented as a guide for future work.

2. Governing equations and numerical methods

As the jet impinges the soil surface, soil is eroded and the scour depth is measured as a function of time. Using equations developed originally for analyzing the JET results (Hanson and Cook, 2004), the shear stress τ in the jet impingement zone is quantified using:

$$\tau = \tau_0 \left(\frac{H_p}{H}\right)^2 \tag{3}$$

where H is the nozzle height from the soil surface, H_p is the potential core length where the mean centerline velocity of the jet remains the same as that exiting from the nozzle, and τ_0 is the maximum shear stress of the jet. These parameters are evaluated from:

$$H_p = C_d d_0 \tag{4}$$

$$\tau_0 = C_f \rho U_0^2 \tag{5}$$

where ρ is the fluid density, U_0 is the nozzle velocity, and C_d and C_f are friction coefficients. If the test is performed for a sufficiently long time, the scour hole may reach the equilibrium depth, defined as the point where $E_r \rightarrow 0$ and $\tau = \tau_c$. One complication in determining the equilibrium scour depth is that the time needed to reach equilibrium can be very long (Blaisdell et al., 1981; Mazurek, 2001), hours to days, and a test typically is not run long enough to reach this condition in field deployments (typically lasting about 60 min). To address this issue, three methods have been developed to derive the soil's erodibility indices from the JET results.

2.1. Blaisdell method

Blaisdell et al. (1981) proposed a hyperbolic function to estimate the equilibrium scour depth in association with bridge piers. Hanson and Cook (2004) used this methodology for the JET results. Using Eq. (3), the equilibrium scour depth H_e is determined, and the critical shear stress is estimated by:

$$\tau_c = \tau_0 \left(\frac{H_p}{H_e}\right)^2 \tag{6}$$

Eq. (3) for any time after starting the test can be rewritten using the above relationships as:

$$\tau = C_s \frac{\rho U_0^2}{(H/d_0)^2} \tag{7}$$

where $C_s = C_f C_d{}^2$ is the maximum shear stress coefficient. Hanson and Cook (2004) assumed $C_s = 0.16$. Substituting this into Eq. (2), the

Table 1
Summary of JET methodology inconsistencies reported in literature.

Inconsistencies	Effect on the test results	Reference
Unconfined environment	Under-estimating the maximum applied shear stress by a factor of 2.4	Ghaneeizad (2016); Ghaneeizad et al. (2015a, 2015b)
Flat bed	Flow regime alteration; changing the shear stress magnitude and distribution	Ghaneeizad (2016); Ghaneeizad et al. (2016); Mercier et al. (2012); Weidner (2012)
Smooth bed	Under-estimating the maximum applied shear stress by a factor of 5	Rajaratnam and Mazurek (2005)
Linear erosion law	Erosion rates are better represented by non-linear equations	Houwing and van Rijn (1998); Khanal et al. (2016); Walder (2015)
Extrapolation techniques	Different techniques result in different erosion parameters, sometimes with a large difference	Cossette et al. (2012)