A METHOD FOR ESTIMATING EROSION PARAMETERS FROM JET EROSION TEST

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Abtract: *The erosion law of soil cohesive is modeled using the excess shear stress equation, which includes two erosion parameters: the erosion coefficient (k_D) and the critical shear stress (τ_c). Between the exist devices, a Jet Erosion Test (JET) is a standardized device available for deriving the erosion parameters of soil cohesive. The JET data are typically analyzed using a Blaisdell solution approach. A second solution approach based on direct parameter optimization to the measured erosion depth data has recently been proposed but with limited evaluation. The aims of this work were to develop a new solution (or method) to predict erosion parameters, and to compare with three approaches. A series of JET conducted in laboratory on Silty soil were used to evaluate the performance of this new solution approach.*

Keywords: Jet Erosion Test (JET), erosion parameter, erosion coefficient, critical shear stress.

1. INTRODUCTION

The soil erosion phenomenon is an important subject to study in civil engineering and especially in hydraulic engineering. Erosion phenomenon caused by water occurs when the effective shear stress (τ_e) exceeds the critical shear stress (τ_c) at the boundary of the soil. We can assess the erosion rate of cohesive soils with an assumption that the erosion rate is proportional to the effective shear stress and is expressed by the following equation [8].

$$\dot{\varepsilon} = k_D.(\tau_e - \tau_c)^a \qquad (1)$$

where, $\dot{\varepsilon}$ is the erosion rate (cm/s), k_D is the erosion coefficient (cm^3/N-s), τ_e is the effective shear stress (Pa), τ_c is the critical shear stress (Pa) at which erosion does not or quasi not occur, and, a is an empirical exponent commonly assumed to be unity [1], [10].

Numerous studies have derived k_D and τ_c for cohesive soil using different techniques: large flumes [8], small flumes [4], laboratory Hole Erosion Test [14], and a submerged Jet Erosion Test [1], [8]. The submerged Jet Erosion Test (JET) was developed for measuring these parameters in situ as well as in the laboratory [7], [8]. The JET device consists of an impinging jet connected to a constant water source, a "can" that serves to both hold the JET in position and to submerge the test soil in water, and a point gauge to measure the depth of scour produced by the JET. A detailed description of the JET and the testing methodology has been presented by numerous studies [1], [7], [8].

Hanson and Simon [7] suggested an inverse relationship between k_D et τ_c, $k_D = 0.2\tau_c^{-0.5}$ to estimate k_D as a function of τ_c for cohesive soils. This relationship was recently updated by Simon et al., [11] based on hundreds of JET on streambanks across the U.S, $k_D = 1.62\tau_c^{-0.838}$. In many cases, it has been reported that the equilibrium erosion depth of Blaisdell solution approach [3] that forms the basis for deriving erosion parameters does not always converge to a reasonable solution [11]. A second solution approach based on direct parameter optimization to the measured erosion depth data has recently been proposed by Robert Thomas (Department of Geography, University of Hull, U.K.) but with limited evaluation [1], [5], [11]. In fact, such an iterative solution was originally proposed by Hanson and Cook [8] as "method 1," but the solver routine never converged to a stable solution and was therefore not investigated

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further in that paper. Simon et al. (2010) found that a solution methodology based on "method 1" provided a reduction in the scatter of the k_D-τ_c relationship, but the values obtained led to an over-prediction of erosion when used in model simulations, while the original Blaisdell solution under-predicted erosion. Recently, by using the erosion depth solutions for limited data set, Daly et al., [1] found an inverse relationship between the two erosion parameters $k_D = 157\tau_c^{-1.62}$ with $R^2 = 0.56$.

2. AN IMPROVEMENT – A NEW METHOD FOR ESTIMATING EROSION PARAMETERS

Analytical methods for JET proposed by Hanson and Cook [8], assuming that the erosion rate can be determined by the rate of variation in the erosion depth (dJ/dt)

$$dJ/dt = k_D.(\tau_e - \tau_c) \qquad (2)$$

where, J is the erosion depth at the center of the sample (cm), dJ/dt is the erosion rate (cm/s), τ_e is derived from the diameter of the jet nozzle and the distance from the jet orifice to the surface of the sample (Figure 1).

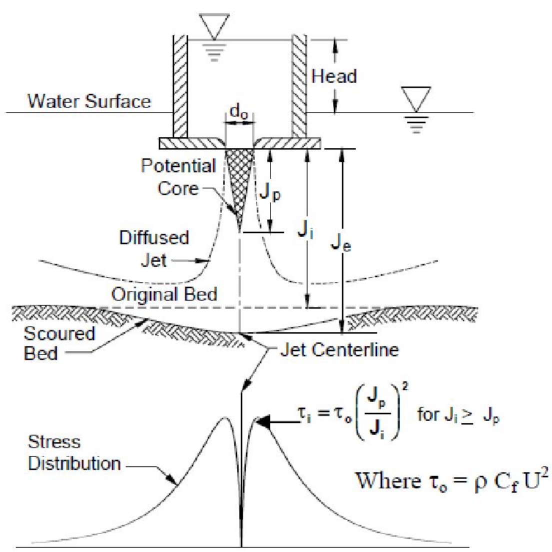

Figure 1: Principle of JET and stress distribution around the jet axis [8]

Following the theory of jet, in a potential core close to the jet, the jet velocity is uniform, and the shear stress is maximal. Beyond the potential core, the jet no longer retains a potential core, the peak jet velocity decreases linearly, and the effective shear stress decreases linearly versus the square of the distance from the nozzle of the jet. In theory, the shear stress at the center of the jet is zero but in practice maximum scour usually occurs directly beneath the jet, so it is assumed that the theoretical peak shear stress applies to the centerline of the jet [10].

Numerous researches have used this equation to calculate erosion [1], [6], [13]. The assessment of soil erosion parameters is based on diffusion principles developed by Stein et al., [12]. Equation (1) is written as:

$$dJ/dt = k_D\left(\frac{\tau_o.J_P^2}{J^2} - \tau_c\right), \; J > J_P \qquad (3)$$

Stein and Nett, Hanson and Cook developed similar analytical procedures to determine soil erosion parameters. They assumed that the critical shear stress corresponded to the stress at the depth (J_e) at which the scour did not vary and the erosion rate was equal to zero [8], [9], [13]:

$$\tau_c = \tau_o\left(\frac{J_P}{J_e}\right)^2 \qquad (4)$$

where, J_P is the length of the jet potential core, with $J_P = C_d.d_0$; C_d is the diffusion coefficient (C_d = 6.2 – 6.3 [2]); J_i is the initial distance between the jet orifice and the surface of the soil; J_e is the final distance between the jet orifice and the surface where erosion does not occur; d_0 is the nozzle diameter (cm); τ_0 is maximum shear stress due to the jet velocity at the nozzle (Pa) and $\tau_0 = C_f.\rho.U_0^2$; C_f is the coefficient of friction equal to 0.00416 [10]; ρ is the water density (g/cm^3); U_0 is the initial velocity at jet orifice, U_0 is derived from Bernoulli expression, $U_0 = C\sqrt{2.g.h_1}$ with the discharge coefficient C = 1 and the real hydraulic head h_1 (cm).

Unfortunately, the depth J_e is very long to obtain. The method used is therefore a method of fitting between an incomplete experimental curve and a theoretical curve of erosion depth versus time. The asymptote is the value of J_e from which the critical shear stress is derived. The parameter k_D is another fitting parameter and represents the rate at which the asymptote is reached. The equation of the theoretical curve is obtained from the integration of equation (3) which gives the following equation [8], [9], [10]:

$$t_m = \frac{J_e}{k_D \tau_c}\left[0.5\ln\frac{J_e + J}{J_e - J} - \frac{J}{J_e} - 0.5\ln\frac{J_e + J_i}{J_e - J_i} + \frac{J_i}{J_e}\right] \quad (5)$$

The parameters k_D and τ_c, corresponding to the rate of erosion and the critical shear stress of the soil are the best values for the correlation between the two curves. The parameter of τ_c from (4) and J_e can be estimated by first fitting using the erosion depth data versus time and a hyperbolic function for determining the equilibrium erosion depth [2] which is assumed to reach at an indefinite time:

$$x = \sqrt{(f - f_0)^2 - A^2} \quad (6)$$

where $x = \log\left(\frac{U_0 t}{d_0}\right)$; $f = \log\left(\frac{J}{d_0}\right) - x$; $f_0 = \log\frac{J_e}{d_0}$; A is the value for the semi-transfer and semi-conjugate of the hyperbola. The two values A and f_0 are the parameters fitted by the least square error method. The least square error is expressed by the following equation:

$$\sum_i^n \left(x_{th,i} - x_{epx,i}\right)^2 \quad (7)$$

When we used Blaisdell solution approach, the results were not always convergent. Therefore, we found the value of A, and f_0, and the predicted scour data (predicted evolution erosion depth) which is simultaneous satisfying two conditions: 1. the deviation between predicted scour data and observed scour data is minimal; 2. equation (7) in which predicted scour data were used instead of observed scour data reaches a minimal value.

This value of τ_c is then be inserted into Equation 5 and undergoes a second fitting to find k_D. The values k_D was the parameters fitted by the least square error method using equation 7. The spreadsheet routine was established using Solver Excel module to solve two above condition and estimate the erosion parameter (k_D and τ_c).

3. RESULTS AND DISCUSSION

Based on the results of these tests, we have established a relationship between the erosion parameters (from Figure 2 to Figure 4). There is an inverse relationship between the erosion coefficient and the critical shear stress (Figure 2), an inverse relationship between the critical shear stress and the equilibrium erosion depth (Figure 4), and a directly proportional relationship between the erosion coefficient and the equilibrium erosion depth (Figure 3). Fitting these relationships with an exponential function yields good correlation coefficients R^2, of 0.894, 0.99 and 0.915, respectively.

Figure 2 shows that a loose soil which has a high erosion coefficient has a small critical shear stress and, on the other hand, a dense soil which has a small erosion coefficient has a high critical shear stress. We can note mainly in Figure 4 that the critical shear stress strongly influences the erosion of soils.

To validate relationship between k_D and τ_c, we have realized 194 tests on a silt soil by varying the real hydraulic head, h_1, depth of immersion in water of the specimen, h_2, and distance between the nozzle of jet and the specimen and also pre-wet time of sample before testing.

We have compared (Figure 5) correlation between k_D and τ_c estimated by us method with previous proposed relationships by Hanson and Simon [7], and Simon et al., [11], and Daly et al., [6]. The relationship proposed by Hanson and Simon [7], and Simon et al., [11] resulted in lower τ_c, the relationship proposed by authors is close to relationship proposed by Daly et al., [6], so the estimation method proposed by author can use to estimate the erosion parameters.

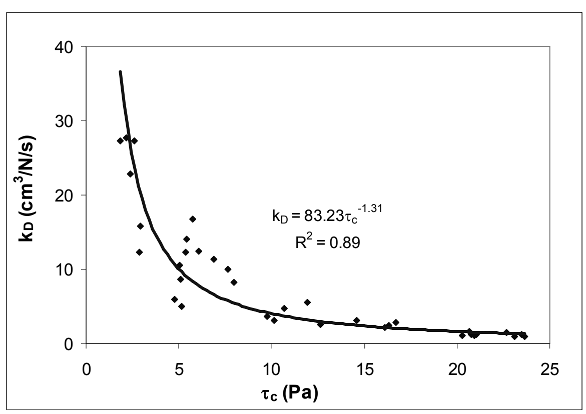

Figure 2: Relationship between erosion coefficient and critical shear stress

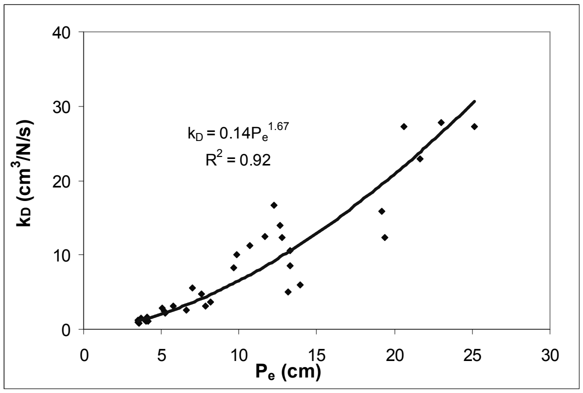

Figure 3: Relationship between erosion coefficient with equilibrium erosion depth

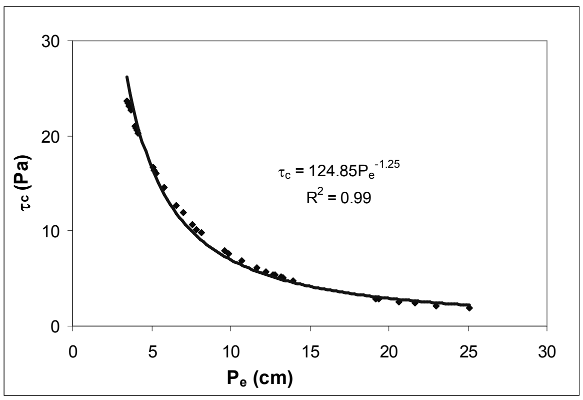

Figure 4: Relationship between critical shear stress with equilibrium erosion depth

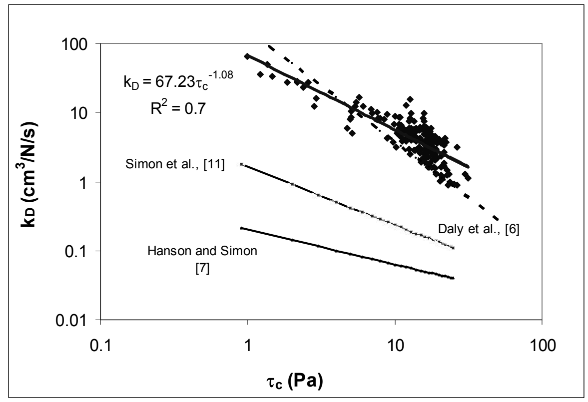

Figure 5: Correlation between k_D and τ_c and comparison to previously proposed relationship by Hanson and Simon [7], and Simon et al., [11], and Daly et al., [6]

4. CONCLUSION

This work presents a new method to evaluate the erosion parameters of soil cohesive using the JET. An inverse relationship is observed between the erosion coefficient (k_D) and the critical shear stress (τ_c), and between the equilibrium erosion depth (P_e) and the critical shear stress. And a directly relationship is obtained between the erosion coefficient and the equilibrium erosion depth.

REFERENCES

[1]. Al-Madhhachi, A. T., Hanson G. J., Fox G. A., Tyagi A. K., and Bulut, R. (2013). "Measuring soil erodibility using a laboratory "mini" JET". *Transactions of the ASABE,* 56(3), 901-910.

[2]. Beltaos, S., and Rajaratnam, N. (1977). "Impingement of axisymmetric developing jets". *Journal of Hydraulic Research*, 15(4), 311-326.

[3]. Blaisdell, F.W., Anderson, C.L., and Hebaus, G.G. (1981). "Ultimate dimensions of local scour". *Journal of the Hydraulics Division*, ASCE 107(HY3), 327-337.

[4]. Briaud, J.L., Fellow., Ting, F.C.K., Chen, H.C., Cao, Y., Han, S.W., Kwak, K.W. (2001). "Erosion function apparatus for scour rate predictions". *Journal of geotechnical and geoenvironmental engineering,* 127(2), 105-113.

[5]. Cossette, D., K. A. Mazurek, and C. D. Rennie. 2012. Critical shear stress from varied methods of analysis of a submerged circular turbulent impinging jet test for determining erosion resistance of cohesive soils. In *Proc. 6th Intl. Conf. on Scour and Erosion (ICSE6)*, 11-18. Paris, France: Société Hydrotechnique de France (SHF).

[6]. Daly, E.R., Fox G.A., Al-Madhhachi A. T., and Miller, R.B. (2013). "A erosion depth approach for deriving erodibility parameters from Jet Erosion Tests". *Transactions of the ASABE* 56(6): 1343-1351.

[7]. Hanson, G.J., and Simon, A. (2001). "Erodibility of cohesive streambeds in the loess area of the midwestern USA". *Hydrological processes*, l 15(1), 23-38.
[8]. Hanson, G.J., and Cook, K.R. (1997). "Development of excess shear stress parameters for circular jet testing". *ASAE paper,* No.972227.
[9]. Hanson, G.J., Robinson, K.M., and Cook, K.R. (2002). "Scour below an overfall: Part II. Prediction". *Transaction of ASAE*, 45(4), 957-964.
[10]. Hanson, G.J., and Cook, K.R. (2004). "Apparatus, test procedures, and analytical methods to measure soil erodibility in situ". *American Society of Agricultural Engineers ISSN 0883-8542,* 20(4), 455-462.
[11]. Simon, A., Pollen-Bankhead, N., and Thomas, R.E. (2011). "Development and application of a deterministic bank stability and toe erosion model for stream restoration". In *Stream Restoration in Dynamic Fluvial Systems: Scientific Approaches, Analysis, and Tools,* 453-474. Geophysical Monograph Series, vol.194. Washington, D.C.: American Geophysical Union.
[12]. Stein, O.R., Alonso, C.V., and Julien, P.Y. (1993). "Mechanics of jet scour downstream of a headcut". *Journal of Hydraulic Research,* 31(6), 723-738.
[13]. Stein, O.R., and Nett, D.D. (1997). "Impinging jet calibration of excess shear sediment detachment parameters". *Transactions of the ASAE,* 40(6), 1573-1580.
[14]. Wan, C.F., and Fell, R. (2004). "Investigation of rate of erosion of soils in embankment dams", *Journal of Geotechnical and Geoenvironmental Engineering ASCE,* 130, 373-380

Tóm tắt:

PHƯƠNG PHÁP ƯỚC LƯỢNG CÁC THÔNG SỐ TỪ THIẾT BỊ JET EROSION TEST

Định luật xói của đất dính được mô hình hóa sử dụng phương trình ứng suất chống cắt dư, phương trình bao gồm hai thông số xói: hệ số xói (k_D) và ứng suất chống cắt giới hạn của đất (τ_c). Trong số những thiết bị hiện có, Jet Erosion Test (JET) là một thiết bị được tiêu chuẩn hóa để xác định các thông số xói của đất dính. Số liệu từ thí nghiệm JET được phân tích sử dụng cách tiếp cận của Blaisdell. Cách tiếp cận thứ hai là tối ưu hóa trực tiếp các thông số để đo thông số độ sâu hố xói được phát triển gần đây, tuy nhiên còn nhiều hạn chế. Mục đích của bài báo này là phát triển một cách tiếp cận mới (hoặc phương pháp) để dự đoán các thông số xói, và so sánh kết quả với ba cách tiếp cận hiện có. Một loạt các thí nghiệm JET thực hiện ở phòng thí nghiệm trên đất dính Silty được sử dụng để đánh giá hiệu quả của cách tiếp cận mới này.

Từ khóa: Jet Erosion Test (JET), thông số xói, hệ số xói, ứng suất chống cắt giới hạn.

BBT nhận bài: 15/3/2015

Phản biện xong: 11/5/2015