Jun 28th, 1:30 PM

Assessment of Equilibrium Scour by a Submerged Circular Turbulent Impinging Jet in Cohesive Soils

Mahmud Rashedul Amin
University of Saskatchewan, mahmud.amin@usask.ca

Kerry Mazurek
University of Saskatchewan, kerry.mazurek@usask.ca

Recommended Citation

Amin, M.R., Mazurek, K. (2016). Assessment of Equilibrium Scour by a Submerged Circular Turbulent Impinging Jet in Cohesive Soils. In B. Crookston & B. Tullis (Eds.), Hydraulic Structures and Water System Management. 6th IAHR International Symposium on Hydraulic Structures, Portland, OR, 27-30 June (pp. 467-476). doi:10.15142/T3350628160853 (ISBN 978-1-884575-75-4).

6th International Symposium on Hydraulic Structures Portland, Oregon, USA, 27-30 June 2016
Hydraulic Structures and Water System Management
ISBN 978-1-884575-75-4 DOI: 10.15142/T3350628160853

Assessment of Equilibrium Scour by a Submerged Circular Turbulent Impinging Jet in Cohesive Soils

M.R. Amin[1] and K.A. Mazurek[1]
[1]Dept. of Civil and Geological Engineering
University of Saskatchewan
Saskatoon, SK S7N 5A9
Canada
E-mail: Kerry.Mazurek@usask.ca

ABSTRACT

In this paper, results from a study where detailed measurements of the time development of the scour holes produced by a submerged circular vertical impinging jet in cohesive soils from long-term scour tests are presented. This is the type of jet used in the ASTM standard Jet Erodiblity Test, which relies on measurements of the time development of scour for prediction of soil erodibility parameters. In the experiments, measurements of the entire scour hole were taken after scouring times of 5 min, 10 min, 15 min, 20 min, 30 min, 40 min, 50 min, 1 h, 1.5 h, 2 h, 4 h, 8 h, 16 h, 24 h, and then at an interval of 24 h thereafter until the scour hole was considered to have reached equilibrium. The measurements were taken on a 2 mm grid using a computer-controlled laser displacement meter. For the tests, two types of manufactured pottery clays were used. The growth of the maximum depth of scour, average scour hole radii, centerline depth of scour, and scour hole volume were evaluated. It was seen that the characteristic dimensions of the scour hole that have been typically been used to assess equilibrium state, namely, the maximum and centerline scour holes, come to equilibrium more quickly than other locations in the scour hole. Results also showed the Sumer et al. (1993) model for predicting the time development of scour worked well for the present tests.

Keywords: *cohesive soils, clays, impinging jets, scour, erosion, time development.*

1. INTRODUCTION

Understanding the time development of scour of soils below hydraulic structures is important due to the potential losses associated with the undermining of the foundations of these structures. Most often the flows issuing over, through, or below hydraulic structures are in the form of turbulent jets. As such, scour by jets has been a topic of active research over the last 80 years. Further, results from tests assessing the scour produced by vertical impinging jets are also used to assess the erodibility of soils. The jet erodibility test developed by Greg Hanson and his colleagues of the Agriculture Research Service of the US Department of Agriculture (Hanson 1990, Hanson 1991, Hanson and Cook 1997, Hanson and Cook 2004) is an ASTM standard test for erodibility (ASTM D5852, 2007).

Often experiments of scour by jets are run until the scour hole has reached its final or largest size, called the equilibrium, ultimate, or asymptotic state. The equilibrium state is used to help determine the largest size a scour hole might get under particular hydraulic conditions of flow for a given soil. It is thought by some that a scour hole never actually reaches a final size due to the potential for large turbulent fluctuations, and, therefore, some treat this state as a "practical" largest size. Additionally, there has been uncertainty in deciding how to assess when a scour hole has reached equilibrium.

Equilibrium scour has been defined differently in different studies. According to Chabert and Engeldinger (1956), the depth of scour does not change "appreciably" with time at equilibrium condition. Ettema (1980) distinguished three phases of scour and indicated that the scour depth remains "practically" unchanged with time in the last phase, known as the equilibrium phase. Coleman *et al.* (2003) inferred that at equilibrium condition, the scour depth might continue to increase at a "relatively slow rate." The interpretation of equilibrium scour is different by the selection of the words "appreciably," "practically," and "relatively slow rate" in these studies (Simarro *et al.* 2011), and a quantifiable definition of the equilibrium scour is required. Lauchlan (1999) adopted a uniform period of only 24 hours for bridge pier scour experiments. Coleman *et al.* (2003) considered that the equilibrium condition is achieved when the rate of scour had reduced to 5% of the minimum dimension of the structure (e.g., pier diameter, abutment length, etc.) in a 24-hour period. Sheppard *et al.* (2004) followed a similar approach for local scour experiments with circular piles in cohesionless sediments. Ahmed and Rajaratnam (1998) adopted a relatively conservative approach and ran experiments with cylindrical pipers in cohesionless sediments for 2-3 weeks until the incremental increase in scour depths were less than 1 mm in 24 hours. Grimaldi (2005) identified the equilibrium condition when the scour rate is reduced to 5% of one-third of the pier diameter in 24 hours. Fael *et al.* (2006) proposed to consider the reduction of scour rate in 24 hours to two times of the mean diameter of the cohesionless sediment after they conducted local scour experiments at vertical-wall abutments. However, Simarro *et al.* (2011) and Chreties *et al.* (2008) criticized such quantifications of equilibrium scour because these values are arbitrary, and any change in these arbitrary values may produce significant change in measured equilibrium dimensions and time.

A graphical approach has been used in many studies in scour experiments with turbulent wall jets and circular impinging jets to reduce arbitrariness in assessing equilibrium scour (e.g., Rajaratnam and Berry 1977, Rajaratnam and Beltaos 1977, Rajaratnam 1982, Rajaratnam 1981). In this method, the scour depth is plotted against the logarithm of time to observe the change of gradient in the resulting curve. When the gradient approaches zero, the system is considered to be in equilibrium. Cardoso and Bettess (1999) utilized the graphical approach in experiments of local scour at bridge abutments in a sand bed.

In these previous studies, the equilibrium condition was assessed using the time development of the maximum or centerline depth of scour. In cohesionless soils, these two depths generally coincide in scour by vertically impinging circular jets. However, in clayey soils, this is often not the case (Mazurek *et al.* 2001). Because of mass erosion in clayey soils, the scour hole may not be at equilibrium although the maximum and centerline scour depths may have appeared to reach this state. In this paper, results for the time development of scour from two long-duration tests of scour by submerged, vertical turbulent impinging jets in cohesive soils are reported. The entire scour hole was measured at different intervals during testing to assess whether equilibrium was in fact reached. Additionally, time development of scour results are compared to predictions from four models.

2. EXPERIMENTAL SETUP AND EXPERIMENTS

The scour testing was performed inside an octagonal Plexiglas tank of 1.2 m depth and 1.1 m height. Figure 1 shows the experimental setup. A 0.95 m long plenum was centered above the tank and hung vertically to an iron frame with hinges so that the plenum could be moved sideways along a vertical plane. A circular nozzle with a diameter d of 8 mm was attached at the bottom of this plenum. The nozzle was designed following the standards laid out in ASME (1990) so that the flow contraction occurred smoothly without any significant head loss, and the velocity across the nozzle would be uniform. City of Saskatoon tap water was pumped to the jet plenum from a constant head tank. Flow rates were measured using both an ultrasonic flow meter and a mercury U-tube manometer. A device was constructed to ensure that the jet impinged vertically on the soil sample set below the jet. The jet was set at a height H of 85 mm of the sample so that the relative impingement height H/d = 10.6. For the first test (clay sample P300), the jet velocity U_o was 8.99 m/s so that the jet Reynolds number at the nozzle, $R=U_o d/\nu$, was 71625, where ν is the kinematic viscosity of water at test temperature. For the second test (clay sample M370), the jet velocity was 10.69 m/s with a jet Reynolds number of 85152.

For each measurement of the shape of the scour hole, the flow was diverted back to the constant head tank and the jet plenum was moved away from the sample. The scour hole was then measured using a laser optical profiler mounted on a two-dimensional (in the horizontal plane), computer-controlled traverse system set above the jet tank. The traverse system was operated using National Instruments LabVIEW 5.5. The profiler moved on a 2 mm fine grid over the sample. The sample was kept under water during profiling so that the sample would not crack due to shrinkage as it dried. Therefore, the depth recorded was less than the actual depth due to refraction. The depths were corrected later to take this into account. The measurements were taken at 5 min, 10 min, 15 min, 20 min, 30 min, 40 min, 50 min, 1 h, 1.5 h, 2 h, 4 h, 8 h, 16 h, 24 h and then after every 24 h until the equilibrium condition was achieved. During the test, the eroded volume was plotted against the logarithm of time to see whether the resulting curve had started to become parallel to the x-axis, which was an indication that the scour hole was in equilibrium. The test duration for Test 1 (P300 clay) was 168 h, while the Test 2 (M370 clay) ended after 312 h of testing.

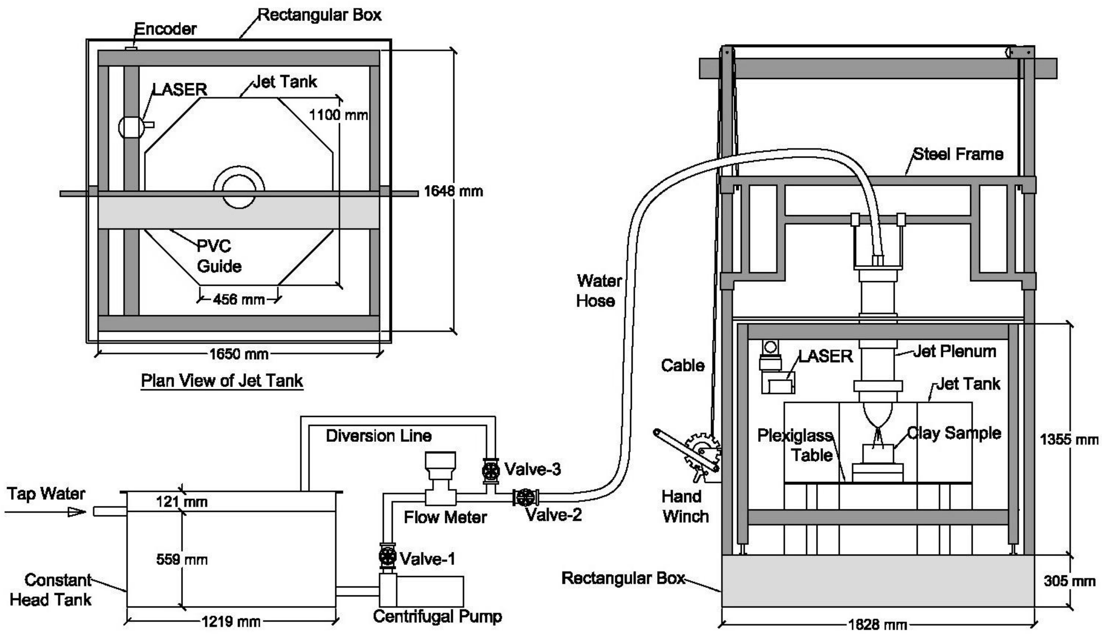

Figure 1. Experimental setup

The P300 and M370 soil samples were manufactured pottery clays from Plainsman Clays of Medicine Hat, Alberta, Canada. These were used instead of the natural soil samples since disturbances due to sampling in natural samples can have a strong influence on the development of scour in clayey soils. The P300 soil sample contained 50% clay, 47% silt, and 2% fine sand, while the M370 soil sample contained 55% clay, 43% silt, and 2% fine sand. Table 1 gives the soil properties of each sample, which were determined following the ASTM standards D854-14 (2014), D2216-10 (2010), D4318-10 (2010), and D7263-09 (2009).

Table 1. Properties of the clay samples used in scour testing experiments.

Clay Sample	Specific Gravity, G_s	Average Water Content, w_c (%)	Liquid Limit, *LL* (%)	Plastic Limit, *PL* (%)	Bulk Density, ρ_b (kg/m^3)	Dry Density, ρ_d (kg/m^3)	Degree of Saturation, S_w (%)
P300	2.70	31.3	34.0	18.5	1916	1686	98
M370	2.69	28.9	43.3	15.1	1951	1788	100

3. OBSERVATIONS OF THE TIME DEVELOPMENT OF SCOUR

The time developments of the characteristic dimensions of the scour hole are plotted in Figure 2. The dimensions used for assessing equilibrium were scour hole volume (V), cubic root of scour hole volume or the average scour hole depth (ε_{avg}), depth of scour hole along the jet centerline (ε_{cl}), maximum depth of scour hole (ε_m), the maximum depth found along a section (ε_{ms}), average radius of scour hole (r_{avg}), average half-width of scour hole for scour depth on the jet centerline (b_{cl}), and average half-width of the scour hole for the maximum depth (b_m). The half-width of the scour hole is the radial distance from jet centerline to the location where b_{cl} = ½ ε_{cl} for the centerline depth, or b_m = ½ ε_{ms} for the maximum depth. The average values of scour hole radii and half-widths were determined by averaging these dimensions from four different sections of the scour hole for a particular measurement. The maximum scour depth of the section that took the longest time to reach equilibrium was used as ε_{ms}. For assessing the time to reach equilibrium, the graphical approach was used. First, the aforesaid dimensions of the scour hole were plotted against the logarithm of time in individual graphs. A "plateau" or potion of the curve parallel to the time axis was identified near the final stage of scouring, and a tangent was drawn to that plateau. The co-ordinates of the point of tangency gave the equilibrium scour dimension and time to reach equilibrium.

From Figure 2, it can be seen that for a significant portion of scouring before the equilibrium condition, the scour hole volume and depths increased linearly with the logarithm of time (Fig 2a to 2e) in scour testing in clayey soils with vertical impinging jets in cohesive soils, which is consistent with the observations of Mazurek (2001), Mazurek *et al*. (2001), and Moore and Masch (1962). However, this relationship was not seen clearly in the case of scour hole radii (Fig. 2f to 2h). Particularly in Fig. 2g, b_{cl} for Test 2 first decreased before coming into equilibrium. One of the reasons for such a behavior is the removal of large soil chunks, which resulted in skewed scour hole shape during the initial phase of the scouring process. As the scouring went on, the scour hole took a more symmetrical shape.

The removal of large soil chunks also resulted in some parallel plateaus in the development of the scour hole radius, which can be best seen in Test 1 in Fig. 2f. This happened because when a large chunk was removed, the radius did not change for few subsequent measurements. The temporal development of the average radii of the scour hole was affected most by the large chunk removal.

A comparison of time to reach equilibrium, determined from the graphical approach among different dimensions of the scour hole for Tests 1 and 2, is given in Table 2. In Test 1, the volume, average depth, and maximum depth reached equilibrium condition at the same time. The centerline took the shortest amount of time, and section-wise maximum depths took the longest to reach equilibrium state. Also, the half-widths took a considerable amount of time to reach equilibrium. This indicates in this particular test, while the maximum and centerline scour depths were not changing and the average radius of the scour hole was also constant, the side slope of the scour hole was still eroding. In Test 2, the average radius of the scour hole came to equilibrium condition considerably earlier than the section-wise maximum depth, similar to Test 1. This contrasts with the development of scour hole radius in cohesionless soils, where the radius continues to grow even after the depth reaches equilibrium state (Rajaratnam and Beltaos 1977).

Table 2. Equilibrium size and time to reach equilibrium for different characteristic dimensions of the scour hole.

Dimensions considered to test equilibrium condition	Test 1		Test 2	
	Time to Equilibrium (h)	Equilibrium Size (mm^3 for V, mm for others)	Time to Equilibrium (h)	Equilibrium Size (mm^3 for V, mm for others)
Volume, V	48	260241	16	351977
Average depth ((volume)$^{1/3}$), ε_{avg}	48	63.85	16	70.61
Centerline depth, ε_{cl}	48	31.68	240	37.82
Maximum depth, ε_m	48	36.88	16	40.52
Sectional maximum depth, ε_{ms}	48	36.85	312	38.68
Average radius, r_{avg}	16	72.00	48	74.00
Average half-width for centerline depth, b_{cl}	72	45.67	144	45.00
Average half-width for maximum depth, b_{max}	72	43.73	96	44.40

For Test 2, there was a large difference in equilibrium time considering the scoured volume and section-wise maximum depths. The volume came to equilibrium quickly, as little changes in volume could not be identified using the graphical approach. This is also true for the average scour depth, which was derived directly from the scour hole volume.

Though the observations of the time development of scour hole dimensions can vary from test to test, assessing the equilibrium using the section-wise or sectional maximum scour depth seems appropriate. The equilibrium time assessed using the sectional maximum scour depths was long enough for other dimensions of the scour hole to reach equilibrium as well.

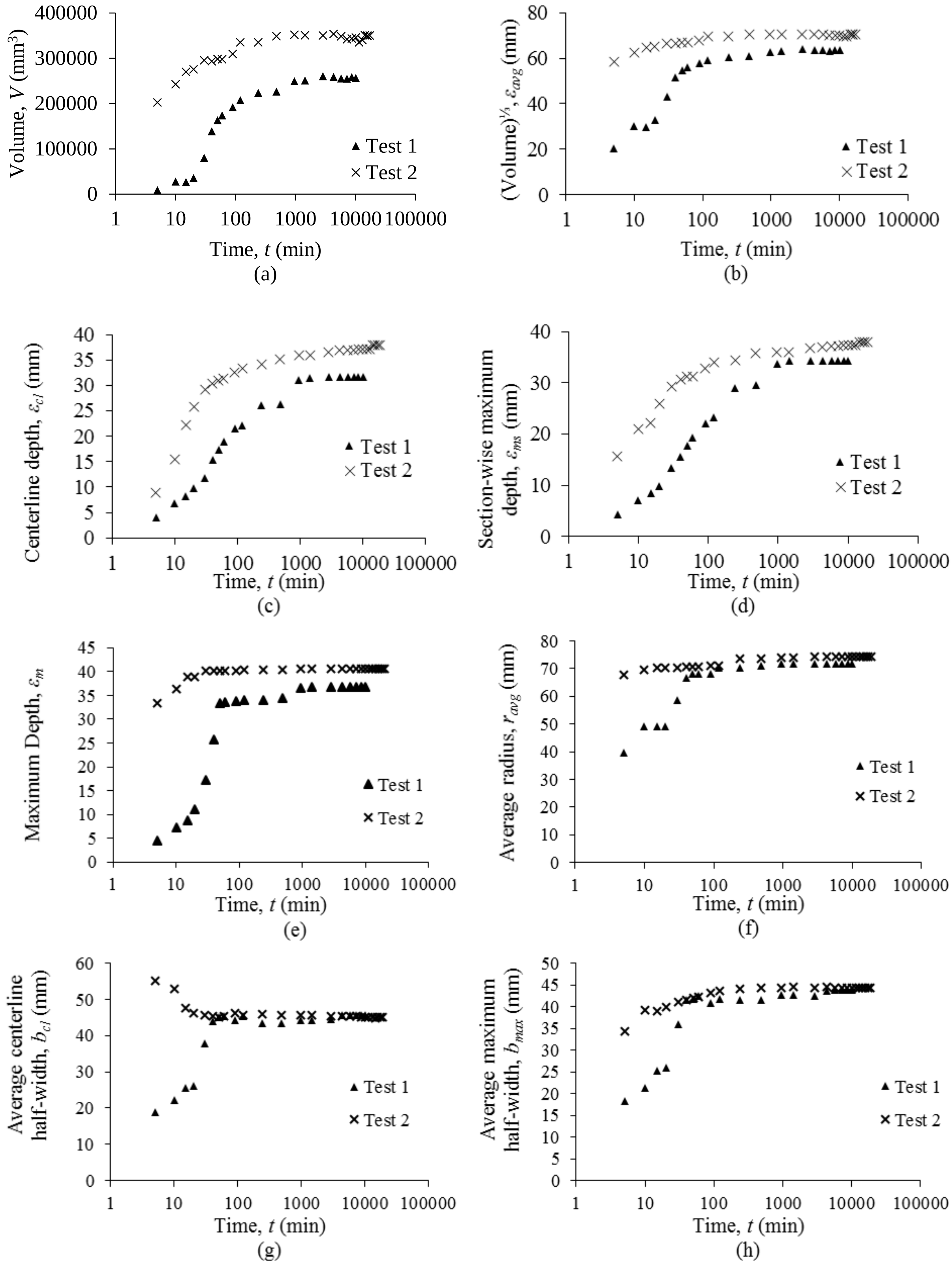

Figure 2. Time development of (a) volume, (b) average depth, (c) centreline depth, (d) sectional maximum depth, (e) maximum scour depth, (f) average radius (g) average centreline half-width, and (h) average maximum half-width of scour hole in Test 1 and Test 2.

The measurement of the maximum scour depths and other dimensions were subjected to measurement errors. These errors could produce a wrong outcome using the graphical approach, as this approach considers no visible change of time development plot at equilibrium condition. In reality, the dimension might still be in equilibrium if the changes in that dimension with time were within the margin of error. Therefore, the sectional maximum scour depths for Test 1 and Test 2 were again assessed for equilibrium time using the instrumental error of the laser optical profiler with traverse system. From analysis, it was found that the measurement system had an instrument error of ±0.25 mm for each measurement. Hence, the equilibrium time was defined when two successive depth measurements did not change by 0.25 mm in 24 h. The equilibrium time assessed by this definition using the section-wise maximum scour depths were found to be 48 h and 288 h for Test 1 and Test 2, respectively, whereas from a graphical approach, these values were 48 h and 312 h, respectively.

4. METHODS FOR DETERMINING THE EQUILIBRIUM SCOUR DEPTH

The determination of equilibrium scour depth requires the knowledge of time development of scour. Among several models for time development of scour, four of them are described briefly in this section.

Blaisdell et al. (1981) produced a hyperbolic function for the temporal development of scour hole for local scour downstream of a cantilevered pipe or culvert outlet. Hanson and Cook (1997 and 2004) later used this model for scouring by normal impingement of submerged circular jet. The hyperbolic function can be shown as follows:

$$\left(f - f_0\right)^2 - x^2 = A^2 \tag{1}$$

where f=ln(H/d)-ln($U_o t/d$), f_o=ln(H_e/d), and x=ln($U_o t/d$); in which A is the semi-transverse axis of the hyperbola, H is the height of the jet origin from the soil surface, H_e is the vertical distance of the scour hole from the jet nozzle at equilibrium, d is the jet diameter at its origin, and U_o is the jet velocity at its origin. The observed scour data is fitted with the hyperbolic function using A and f_o as parameters.

Sumer *et al.* (1993) performed a series of scour experiments with circular and square piers in cohesionless sediments and developed a general equation for time development of scour hole:

$$\varepsilon_{cl} = \varepsilon_e\left(1 - e^{-t/T_1}\right) \tag{2}$$

where ε_{cl} is the centerline scour depth at time t, ε_e is the scour depth at equilibrium condition, and T_1 is the time scale of scour process. T_1 represents the time at which "significant" amount of scour occurs. Quantitatively, T_1 is the intercept from the asymptote of the scour depth versus time curve by the gradient of the curve at the initiation of scour. Using T_1 and ε_e as parameters, Eq. (2) is fitted to the observed scour data.

Mazurek (2001) showed that the plot of the dimensionless centerline scour depths against dimensionless time collapses into one single curve for the same soil under different hydraulic conditions. The following equation was developed for the time development of scour hole in the tested clayey soils:

$$\frac{\varepsilon_{cl}}{\varepsilon_{cl\infty}} = 0.10 ln\left(\frac{t}{t_{80}}\right) + 0.79 \tag{3}$$

where $\varepsilon_{cl\infty}$ is the centerline scour depth at equilibrium condition and t_{80} is the time to reach 80% of the equilibrium scour depth. This model assumes the time development of the centerline scour hole depth is logarithmic. However, this relationship was not tested for other scour hole dimensions, such as the cubic root of the scour volume, the maximum scour depth, and radius of the scour hole.

Daly et al. (2013) suggested a method of solving the excess shear stress equation (Eq. (7)) to analyze the experimental results of scour testing of cohesive sediments by jets:

$$\dot{E} = k_d \left(\tau_o - \tau_c \right)^m \tag{4}$$

where $\acute{E}$ is the erosion rate of the sediment during scour testing, k_d is the erodibility parameter, τ_o is the applied maximum shear stress on the soil surface by the jet, τ_c is the critical shear stress, and m is an empirical exponent. τ_c represents the threshold shear stress of the soil, below which no erosion can occur. The applied shear stress is computed using the following equation:

$$\tau_o = C_f \rho \left(C_d U_o \frac{d}{H} \right)^2 \tag{5}$$

where C_f is the skin friction coefficient, ρ is the density of water at test temperature, and C_d is the jet diffusion constant. From experiments with circular impinging jets on smooth and flat surfaces, Hanson *et al.* (1990) obtained $C_f = 0.00416$. Rajaratnam (1976) gives $C_d = 6.3$. Following Hanson (1990) and Hanson and Cook (1997 and 2004), Daly adopted $m = 1$ for cohesive sediments. The proposed method for the solution of Eq. (4) is straightforward. k_d and τ_c are considered as solution parameters. Using an equation solver, the values of these parameters are adjusted to optimize the solution for each data point. For equilibrium condition, the applied shear stress on the soil reduces to the threshold value, critical shear stress and corresponding jet height is the equilibrium jet impinging height, H_e. Then the equilibrium depth can be simply derived by deducting the initial jet impinging height, H_i from the equilibrium jet impinging height.

5. ANALYSIS AND DISCUSSION

The time development of the maximum scour depth along a section of the scour hole (ε_{ms}) was computed using the aforesaid four different models for the entire test durations of Test 1 and Test 2 to see how well these models fit the experimental data and how correctly they can predict the maximum equilibrium scour depths (ε_{me}). Table 3 shows the estimated equilibrium scour depths using different approaches.

The equilibrium scour depths predicted by the Blaisdell et al. (1981) curve fitting procedure were significantly larger than the observed equilibrium scour depth. This indicates that either the curve fitting approach overestimated the equilibrium scour depths or the experiments were not conducted up to the equilibrium condition. However, previous studies (Laursen 1952, Rajaratnam and Beltaos 1977, Rajaratnam and Berry 1977) suggested that the depth of scour increases linearly with logarithm of time and suddenly starts to become parallel with the time axis when equilibrium phase initiates. From experimental results, it can be inferred that the performed scour tests actually reached equilibrium phase, and, hence, that the curve fitting approach overestimated the equilibrium scour depths.

The general equation developed by Sumer *et al.* (1993) was solved for the observed data points. The solutions fit well for the observed data points with correlation coefficients $r^2=0.98$ for Test 1 and $r^2= 0.99$ for Test 2. Figure 3 shows the accuracy of the Summer *et al.* (1993) approach. Though for both tests the curve fits were good, the predicted equilibrium scour depths were slightly underestimated.

The Mazurek (2001) model for time development of scour reasonably fit the data for both the tests. However, this model assumes the time development of scour depth is linear with the logarithm of time for the whole scouring process, which is not the case in reality. Therefore, instead of fitting the observed scour data near the equilibrium state, the predicted curve was increasing logarithmically. As a result, maximum scour depths were overestimated.

Table 3: Estimation of equilibrium depths of scour using different methods.

Analysis Methods	Equilibrium Depth, ε_{ms} (mm) for Test 1	Goodness of fit		Equilibrium Depth, ε_{ms} (mm) for Test 2	Goodness of fit	
		Correlation coefficient, r^2	Root Mean Square Error, RMSE (mm)		Correlation coefficient, r^2	Root Mean Square Error, RMSE (mm)
Graphical Approach	36.85	-	-	38.68	-	-
Blaisdell *et al.* (1981)	134.31	0.83	10.61	50.18	0.58	10.62
Sumer *et al.* (1993)	35.86	0.98	2.01	37.60	0.99	1.01
Mazurek (2001)	40.32	0.77	7.90	42.90	0.52	3.69
Daly *et al.* (2013), *m*=1	36.79	0.76	9.07	37.92	0.16	23.07
Daly *et al.* (2003), *m*=2.5	37.16	0.84	6.79	38.33	0.73	5.87

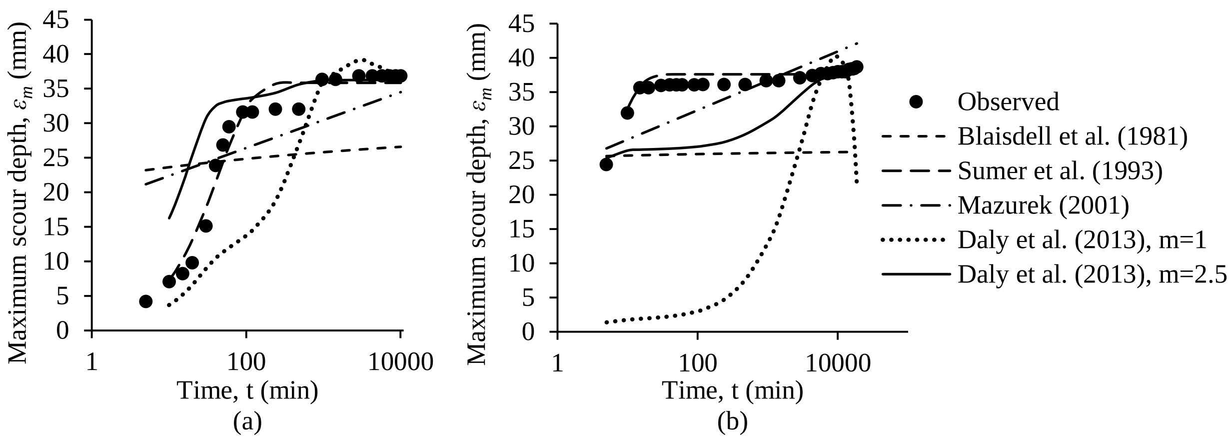

Figure 3: The performance of different time development models for fitting experimental data of (a) Test 1, and (b) Test 2.

Using the Daly *et al.* (2013) approach, the excess shear stress equation was fitted with the observed data for *m*=1. Like the Blaisdell curve fitting approach, multiple solutions were possible. Therefore, the solutions were again optimized to minimize the curve fitting errors. For P300 soil sample, estimated values of k_d and τ_c were 1.4×10^{-7} m^3/N-s and 49.3 N/m^2, respectively. For the M370 sample, these values were 1.0×10^{-7} m^3/N-s and 68.2 N/m^2, respectively. For both samples, the estimated equilibrium scour depths were very close to those obtained by the graphical approach. However, the curve fitting was poor. This implies that if experimental data with less data points were used instead of full scouring data till equilibrium, the predicted scour depth would be much different than the observed one. The same analysis was performed again for erosion exponent *m*=2.5, as suggested by Walder (2015). This time, k_d and τ_c for the P300 sample were 2.1×10^{-9} m^3/N-s and 49.0 N/m^2, respectively, and 5.6×10^{-9} m^3/N-s and 67.4 N/m^2 for the M370 sample, respectively. The model fit the experimental data well, and the predicted scour depths were close to the scour depths obtained using graphical approach.

Apart from the above four time development model of scour, another model developed by Ansari (2003) was also considered for scour depth prediction and fitting of experimental results. However, the Ansari (2003) scour model requires three unknowns to solve for the curve fitting, i.e., the equilibrium scour depth, the time to reach equilibrium, and an exponent. Therefore, it was not possible to use that model to predict equilibrium scour depth. Rather, using observed equilibrium depth and equilibrium time, Ansari's (2003) time development equation was solved for the exponent, and then the equation was used to find the goodness of fit. This model showed reasonable fit with r^2=0.71 for Test 1 and r^2=0.51 for Test 2. The obtained exponent values were 0.12 and 0.02 for Test 1 and Test 2, respectively.

6. CONCLUSIONS

Time development of entire scour hole shape was observed from scour testing of two clayey soils by circular impinging jets. Using the graphical approach, the time to reach equilibrium for each dimension was obtained. The results showed that the radius of the scour hole in clayey soils reached equilibrium soonest, and this observation is different from previous studies of cohesionless soils scouring, where the radius continued to grow after the depth reached equilibrium. In this work, since the entire scour hole was measured with time, it also was seen that although the centerline scour depth and overall maximum scour depth reached equilibrium, the scour hole was still growing. Four different analytical models were evaluated for their ability in equilibrium scour prediction by fitting experimental data. Among the models, the Sumer *et al.* (1993) model predicted the equilibrium scour depth quite accurately and offered best fit with the observed data.

7. REFERENCES

Ahmed, F., and Rajaratnam, N. (1998). "Flow around bridge piers". *Journal of Hydraulic Engineering*, 124(3), 288-300.

Anderson, C.L. (1975). Chapter II. Sediment Transportation Mechanics; Section C, Erosion of Sediment- Local Scour. Sedimentation Engineering, Manual No. 54. Vanoni, Vito A. (Ed.), ASCE, USA.

Ansari, S.A., Kothyari, U.C., and Raju, K.G.R. (2003). "Influence of cohesion on scour under submerged circular vertical jets*"*. *Journal of Hydraulic Engineering*, 129(12), 1014–1019.

ASME (American Society of Mechanical Engineers). (1990). Measurement of Fluid Flow in Pipes Using Orifice, Nozzle, and Venturi. ASME, New York. (ASME MFC-3M-1990).

ASTM (American Society of Testing and Materials) D2216-10(2010), Standard Test Methods for Laboratory Determination of Water Content of Soil and Rock by Mass, ASTM International, West Conshohocken, PA.

ASTM D422-63(2007)e2, Standard Test Method for Particle-Size Analysis of Soils, ASTM International, West Conshohocken, PA.

ASTM D4318-10(2010)e1, Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils, ASTM International, West Conshohocken, PA.

ASTM D5852-00(2007)e1, Standard Test Method for Erodibility Determination of Soil in the Field or in the Laboratory by the Jet Index Method, ASTM International, West Conshohocken, PA

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

Cardoso, A.H., and Bettess, R. (1999). "Effects of time and channel geometry on scour at bridge abutments". *Journal of Hydraulic Engineering*, 125(4), 388–399.

Chabert, J., and Engeldinger, P. (1956). Etude des affouillements autour des piles de ponts. Serie A. Laboratoire National d'Hydraulique, 6, Qui Watier, Chtou, France (in French).

Chreties, C., Simarro, G., and Teixeira, L. (2008). "New experimental method to find equilibrium scour at bridge piers". *Journal of Hydraulic Engineering*, 134(10), 1491–1495.

Coleman, S.E., Lauchlan, C.S., and Melville, B.W. (2003). "Clear-water scour development at bridge abutments". *Journal of Hydraulic Research*, 41(5), 521–531.

Daly, E.R., Fox, G.A., and Miller, R.B. (2013). "A scour depth approach for deriving erodibility parameters from jet erosion tests". *Transactions of the ASABE*, 56(6), 1343–1351.

Ettema, R. (1980). Scour at bridge piers. Report No. 216, School of Engineering, University of Auckland, Auckland, New Zealand.

Fael, C.M.S., Simarro-Grande, G., Martín-Vide, J.P., and Cardoso, A.H. (2006). "Local scour at vertical-wall abutments under clear-water flow conditions". *Water Resources Research*, 42(10), 1–12.

Grimaldi, C. (2005). Non-conventional countermeasures against local scouring at bridge piers. Ph.D. Thesis. Hydraulic Engineering for Environment and Territory. University of Calabria, Cosenza, Italy.

Hanson, G.J. (1990). "Surface erodibility of earthen channels at high stresses. Part II-developing an in situ testing device". *Transactions of the ASAE*, 33(1), 132–137.

Hanson, G.J. (1991). “Development of a jet index to characterize erosion resistance of soils in earthen spillways”. *Transactions of the ASABE*, 34(5), 2015–2020.

Hanson, G.J., and Cook, K.R. (1997). “Development of excess shear stress parameters for circular jet testing”. *ASAE* Paper No. 972227, 21p.

Hanson, G.J., and Cook, K.R. (2004). “Apparatus, test procedures, and analytical methods to measure soil erodibility in situ”. *Applied Engineering in Agriculture*, 20(4), 455–462.

Hanson, G.J., Robinson, K.M., and Temple, D.M. (1990). “Pressure and stress distributions due to a submerged impinging jet”. *Proc., National Conference on Hydraulic Engineering*, ASCE, Stillwater, United States, 525-530.

Hanson, G.J., Robinson, K.M., and Temple, D.M. (1990). “Pressure and stress distributions due to a submerged impinging jet”. *Proc. ASCE National Conference on Hydraulic Engineering*, USDA ARS, Hydraulic Engineering Research Unit, Stillwater, United States, 525-530.

Lauchlan, C.S. (1999). Countermeasures for pier scour. Ph.D. Thesis. University of Auckland, Auckland, New Zealand.

Mazurek, K.A. (2001). Scour of Clay by Jets. Ph.D. Thesis, Department of Civil Engineering, University of Alberta, Edmonton, Alberta.

Mazurek, K.A., Rajaratnam, N., and Sego, D.C. (2001). “Scour of cohesive soil by submerged circular turbulent impinging jets”. *Journal of Hydraulic Engineering,* 127(7), 598–606.

Moore, W.L., and Masch, F.D. (1962). “Experiments on the Scour Resistance of Cohesive Sediments”. *Journal of Geophysical Research*, 67(4), 1437–1446.

Rajaratnam, N. (1976). Turbulent Jets. Elsevier, New York, 304p.

Rajaratnam, N. (1981). “Erosion by plane turbulent jets”. *Journal of Hydraulic Research*, 19(4), 339–358.

Rajaratnam, N. (1982). “Erosion by submerged circular jets”. *Journal of the Hydraulics Division*, 108(2), 262–267.

Rajaratnam, N., and Beltaos, S. (1977). “Erosion by impinging circular turbulent jets”. *Journal of the Hydraulics Division*, 103(10), 1313–1328.

Rajaratnam, N., and Berry, B. (1977). “Erosion by circular turbulent wall jets. *Journal of Hydraulic Research*, 15(3), 277–289.

Sheppard, D.M., Odeh, M., and Glasser, T. (2004). “Large scale clear-water local pier scour experiments”. *Journal of Hydraulic Engineering*, 130(10), 957–963.

Simarro, G., Fael, C.M.S., and Cardoso, A.H. (2011). “Estimating equilibrium scour depth at cylindrical piers in experimental studies. *Journal of Hydraulic Engineering*, 137(9), 1089–1093.

Sumer, B.M., Christiansen, N., and Fredsoe, J. (1993). “Influence of cross-section on wave scour around piles”. *Journal of Waterway Port Coastal and Ocean Engineering*, 119(5), 477–495.

Walder, J.S. (2015). “Dimensionless erosion laws for cohesive sediment”. *Journal of Hydraulic Engineering*, 10.1061/(ASCE)HY.1943-7900.0001068 , 04015047.