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Time Development of Scour in a Cohesive Material due to a Submerged Circular Turbulent Impinging Jet

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This paper presents some results of experiments performed to examine the time development of scour in cohesive soil caused by a submerged circular turbulent impinging jet. The growth of the maximum depth of scour, the scour depth at the jet centerline, and the volume of scour was observed in one cohesive soil consisting of 40 % clay, 53 % silt, and 7 % fine sand. The jet diameter used was 4 or 8 mm, the height of the jet above the sample was 40–116 mm, and the jet velocity was in the range of 4.97–25.9 m/s. It was seen the material eroded primarily by removal of small to large chunks of material, called mass erosion. Although erosion occurred by mass erosion, the scour holes grew in an approximately linear relation with the logarithm of time and reached an asymptotic state. Two models for predicting the time development of scour are compared. It is seen that it may be difficult to predict the early part of the scour process well. Mass erosion appears to be a difficult scour process to model due to the discrete nature of the process.

I. Introduction

The prediction of scour by flows in the form of turbulent water jets is of considerable importance for the design of stable hydraulic structures such as dams, culverts, weirs, and drops. Many investigations have been performed to study scour by jets in a variety of configurations. These studies have been primarily carried out in clean, coarse grained or "cohesionless" materials. Much less studied has been scour in fine-grained or "cohesive" soils. The case of scour by submerged circular turbulent impinging jets in fine-grained materials has particularly received some attention [1,12,14,15]. There has been interest in using this form of jet to assess the erodibility of soils [4,5,6,7,9] and to evaluate the erosion of channel banks produced by ship propellers and thrusters [8]. Nonetheless, scour by these jets in fine-grained materials is still not well understood.

This lack of progress for cohesive materials is partly because there are more than one form of erosion and the type of erosion that will be observed for a particular soil under given flow conditions cannot yet be predicted. Erosion can occur by the removal of individual particles or aggregates from the surface of the soil, called "surface erosion" [13]. Erosion can also occur by the removal of large lumps or chunks of soil of various size [12,14, 15], called "mass erosion". For the time development of scour in mass erosion, if the maximum depth of scour is plotted against the logarithm of time there will be in sudden jumps or discontinuities that correspond to the removal of large chunks [15]. It is the most common form of erosion for lower void ratio materials, where the void ratio $e=V_v/V_s$, and V_v and V_s are respectively the volume of voids and solids in the soil. With respect to erosion, a low void ratio soil has a void ratio less than about 1 [16].

This paper discusses the results of an experimental study of the time development of scour of a low void ratio (e=0.73), fine-grained soil composed of 40 % clay, 53 % silt, and 7 % fine sand. The model for assessing the time development of scour by vertical impinging jets developed by Rajaratnam and Beltaos [17] for cohesionless soil, is compared to the models for predicting scour by these jets used by Ansari et al. [1] for cohesive materials. Potential difficulties in developing these type of models for cohesive soils are also discussed.

II. Experimental Setup and Experiments

For each experiment, a soil sample of 224 m length, 175 mm width, and 85 mm depth was submerged within a octagonal tank of 610 mm height and 570 mm diameter made of 19 mm thick clear acrylic. The experimental setup is shown in Fig. 1. A vertical circular turbulent jet impinged on the sample from a height of 40–116 mm. The jet of velocity U_o of 4.97–25.9 m/s was created by flow through a 830 mm long, 120 mm diameter plenum and then a well-designed nozzle of diameter d of 4 or 8 mm. This gave jet Reynolds numbers R of 26000–98500, where $R = \rho U_o d/\mu$, and ρ and μ are the density and dynamic viscosity of the eroding fluid. The relative impingement height H/d, where H is the height of the jet above the sample, thus ranged from 8.1–29.0, so that for all experiments the jet was set at a large impingement height [3]. The flow was provided by a 1/2 hP jet pump and fed from a 880 L fiberglass tank containing City of Edmonton tap water, which itself was fed from a city water supply line. A magnetic flow meter was used to measure the flow rate. Water was not recirculated in the apparatus to avoid an increasing sediment concentration, and temperature through an experiment. The details of the experiments are given in Table 1. Note that the experiments presented here are part of a more comprehensive data set given in Mazurek [10].

Only one type of soil was used for testing. This soil was a pottery clay obtained from Plainsman Clays Ltd of Medicine Hat, Alberta, Canada. This was done so that a

Figure 1. Experimental setup

large number of samples of similar characteristics could be tested under varied flow conditions. The samples were periodically tested for homogeneity for their vane shear strength, water content, grain size distribution, Atterberg Limits, and activity and contained about 40 % clay sized particles (less than 2 μm), 53 % silt (2 to 60 μm) and 7 % sand (60 μm to 2 mm). They consistently had a vane shear strength, S_v, of about 20 kPa, a liquid limit of 36 %, a plastic limit of 18 %, a dry density of 1540 kg/m^3, and an activity of 0.4. The water content of samples prior to submergence of the sample, w_c, averaged 26.0 % with a 97 % saturation. After testing, the water content, w_f, increased to a depth-averaged value over the top 30 mm of the sample of 27.7%. Electron micrographs, as seen in Fig. 2, showed the clay had an aggregated fabric with random particle orientations. An X-Ray diffraction test showed that the clay component of the soil consisted of kaolinite and illite.

The samples were prepared for testing by first pushing a 0.5 mm thick rectangular band of galvanized sheet metal into the sample. This was done to help prevent the block from splitting apart during testing and to ease placement of the samples within the apparatus. The surface of the soil was then cut with a very thin metal wire using a guide to ensure that all of the samples were the same height. After this preparation, the sample was submerged in tap water and jet flow was initiated.

For each test, the maximum scour depth ε_m, centerline scour depth ε_{cl}, and volume of scour ξ, were measured at times of approximately 2 min, 5 min, 15 min, 1 h, 2 h, 4 h, 8 h, 24 h, 48 h, 72 h, and 96 h, and then at 24 h intervals until asymptotic state was reached. This was when there was no significant change in the scour hole volume over 24 h (less than 0.5 mL). For each measurement, the flow was stopped, the tank drained, and the water was carefully vacuumed from the scour hole. The maximum and centreline depths of scour were measured using a thin wooden rod that was adapted for use as a point gauge. This rod had a blunt end, as it was observed in preliminary experiments that mass erosion might be initiated at a location where there were even small marks on the sample. To find the scour hole volume, a small graduated cylinder was used to refill the scour hole with water. During each test, measurements were taken of the eroding water conductivity, pH, and temperature. At the end of each test, the sample was removed from the tank and detailed measurements of the scour hole profile were taken along two perpendicular sections through the jet centerline using a point gauge. These measurements were relative to the unscoured soil surface.

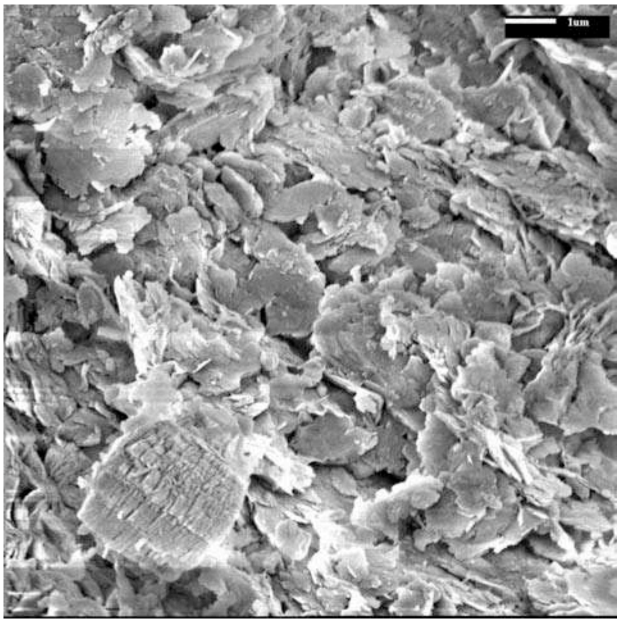

Figure 2. Electron micrograph of the soil at 7500X magnification

III. OBSERVATIONS

A. Forms of Erosion

During some initial trials to investigate the characteristics of erosion of the soil used for the experiments, three forms of erosion were observed. At lower shear stresses (less than a maximum shear stress on the sample surface of about 15 Pa), erosion occurred only on the surface of the sample by the removal of circular flakes of 1 to 3 mm diameter and thickness of less than 0.5 mm. This "flake erosion" did not produce a significant amount of scour in the sample.

At higher shear stresses (greater than about 48 Pa), the erosion of chunks or lumps of soil occurred intermittently by mass erosion. A small chunk tended to be cubical in shape and was about 3 mm long, 2 mm thick, and 2 mm wide. The large chunks tended to be more angular in shape and could be up to 130 mm by 40 mm by 20 mm in size. Fig. 3 shows some typical larger eroded chunks. Mass erosion appears as if the particles are being ripped by the flow from the sample surface. This process was intermittent and there was no obvious pattern to timing of the removal of chunks or their size. In general, however, larger chunks tended to be eroded near the start of a test

TABLE 1. Details of Experiments

Expt.	H (mm)	d (mm)	U_o (m/s)	w_c (%)	w_f (%)	S_v (kPa)	χ (Pa)	$(\chi-\chi_c)/\chi_c$	R 10^4	Temp (°C)	t_e (h)	t_{80} (h)	t_{50} (h)	t_{35} (h)
8/8.1/6.1/1	65	8	6.17	26.50	28.09	20.5	576	0.92	4.3	14.9	84.43	35.39	12.91	6.47
8/8.1/7.0/1	65	8	6.96	26.18	27.41	20.8	734	1.45	5.4	18.9	117.95	37.14	2.30	0.82
8/8.1/7.4/1	65	8	7.44	26.20	27.55	18.9	839	1.80	5.6	18.3	117.43	31.21	1.69	0.40
8/8.1/8.4/1	65	8	8.36	24.43	-	19.6	1058	2.53	5.9	15.6	93.75	8.69	0.22	0.09
8/8.1/9.0/3	65	8	8.95	25.52	27.41	20.2	1214	3.05	7.0	19.9	92.00	28.46	1.74	0.37
8/8.1/9.0/4	65	8	8.95	26.50	27.26	16.1	1214	3.05	6.3	11.8	104.89	27.84	0.48	0.27
8/8.1/9.0/5	65	8	8.95	25.50	27.54	21.7	1214	3.05	4.7	4.8	95.35	30.57	4.78	3.36
8/8.1/9.0/6	65	8	8.95	25.81	27.56	22.6	1214	3.05	4.7	4.8	154.43	101.54	23.54	16.48
8/8.1/9.9/1	65	8	9.93	26.85	28.59	18.4	1493	3.98	7.3	16.9	93.42	15.09	0.03	0.02
8/14.5/9.0/1	116	8	8.95	26.06	27.83	17.5	381	0.27	7.0	20.1	97.47	7.64	4.37	0.95
8/14.5/9.0/4	116	8	8.95	-	27.17	19.6	381	0.27	7.5	22.2	58.60	7.11	0.54	0.35
8/14.5/10.9/1	116	8	10.94	26.43	27.56	21.7	569	0.90	5.9	6.4	82.08	33.33	1.87	1.68
4/10.0/9.9/1	40	4	9.95	25.51	-	-	989	2.30	2.6	4.8	141.83	90.25	50.08	25.44
4/10.0/15.9/1	40	4	15.92	25.05	27.35	25.6	2533	7.44	4.2	5.4	81.77	20.54	1.57	0.45
4/29.0/25.9/2	116	4	25.86	25.37	-	-	795	1.65	8	15.4	106.55	69.90	22.16	15.51

and removal of chunks tended to become more infrequent as a test progressed.

Another type of erosion observed was the removal of individual particles, or surface erosion. This was seen in two tests at very high bed-shear stresses (260 and 400 Pa). It occurred only at the start of the tests and lasted at most 4 h before mass erosion occurred. This type of erosion resulted in a symmetrical shape of the scour hole through the scouring process.

Note that the bed-shear stresses reported above were calculated from the equation given by Beltaos and Rajaratnam [2] for a submerged vertical circular impinging jet on a smooth, rigid bed. They found the maximum shear stress τ_{om} created by a jet at a large impingement height (H/d>8.1) is

$$\tau_{om} = 0.16\rho U_o^2 \left(\frac{d}{H}\right)^2 \qquad (1)$$

where ρ is the density of the fluid. For the present work, since the particle size of the material tested was very fine and the surface was cut with a wire before testing, it was assumed that the soil surface could be taken to be smooth. The reported bed shear stress corresponds to the initial conditions of a test (a flat bed a distance H from the origin of the jet).

B. Time Development of Scour Holes

Since mass erosion was the only type of erosion that produced a significant amount of scour, the experiments were run under conditions to produce mass erosion. Due to the intermittent nature of mass erosion, the scour holes tended to be quite irregular in shape early on in a test (Fig. 4), but looked more symmetrical and smooth as they neared asymptotic state (Fig. 5). As well, with mass erosion of large particles, the maximum depth of scour did not necessarily fall along the jet centerline. The maximum depth of scour would remain constant for some time during a test when this occurred. This gave

Figure 3. Larger chunks removed during an experiment with H= 65 mm, d=8 mm, and a U_o=8.95 m/s over 68 h of testing

Figure 4. Scour hole growth (in plan view) after 15 min for test with H=65 mm, d=8 mm, and U_o= 8.95 m/s.

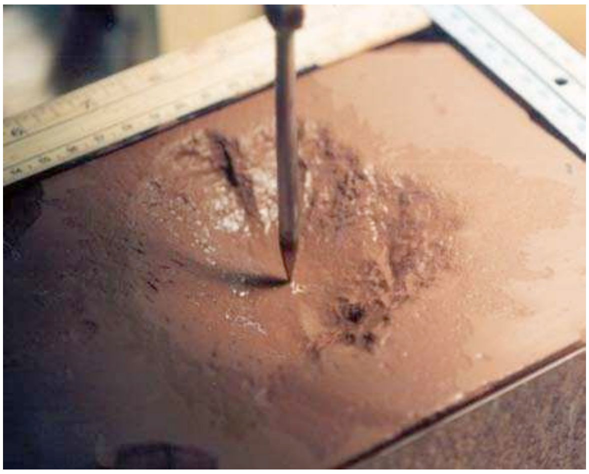

Figure 5. Typical shape of scour hole at asymptotic state (Expt. 8/14.5/10.9/1 after 93 h).

discontinuities in a plot of the maximum depth of scour with time, which was also seen by Moore and Masch [15]. Fig. 6 shows the observations from three experiments of the growth with time of the maximum depth of scour ε_m, centerline depth of scour ε_{cl}, and cube root of the scour hole volume $\sqrt[3]{\xi}$. It would appear from Fig. 6c that for Expts. 8.0/8.1/7.0/1 and 8.0/8.1/7.4/1 the centerline scour depth did not reach asymptotic state. However, this continued growth in the centerline depth of scour was attributed to the disturbance of the sample due to repeated measurements in that area, which would sometimes result in a small amount of erosion.

There were also two series of tests where there were repeated tests under the same hydraulic conditions. The observations from these experiments are shown in Mazurek [11]. The scour holes produced by the same hydraulic conditions had approximately the same volume at asymptotic state, but there was substantial variation in the maximum and centerline scour depths. Also, the time evolution of the scour holes between experiments was quite different and appeared to depend mostly on the size particles eroded early in a test.

IV. ANALYSIS OF TIME EVOLUTION OF SCOUR

A. Rajaratnam and Beltaos (1977)

Rajaratnam and Beltaos [17] developed a method to analyze the time evolution of scour by a vertical circular turbulent impinging jet in cohesionless materials. Their experiments were performed with air jets impinging on a bed of either sand or polysterene particles. They evaluated the growth of the radius of the scour hole and maximum depth of scour. Note that the maximum depth of scour occurred along the jet centreline for all but very early times. It was shown that the data from the experiments could be collapsed onto one curve if the dimensionless scour depth $\varepsilon_m/\varepsilon_{m\infty}$ was plotted against a dimensionless time t/t_+. Here ε_m is the maximum depth of scour, $\varepsilon_{m\infty}$ is the maximum depth of scour at asymptotic state, t is the time from the start of the experiment, and t_+ is the time scale for scour. For their experiments, the most effective time scale for collapsing

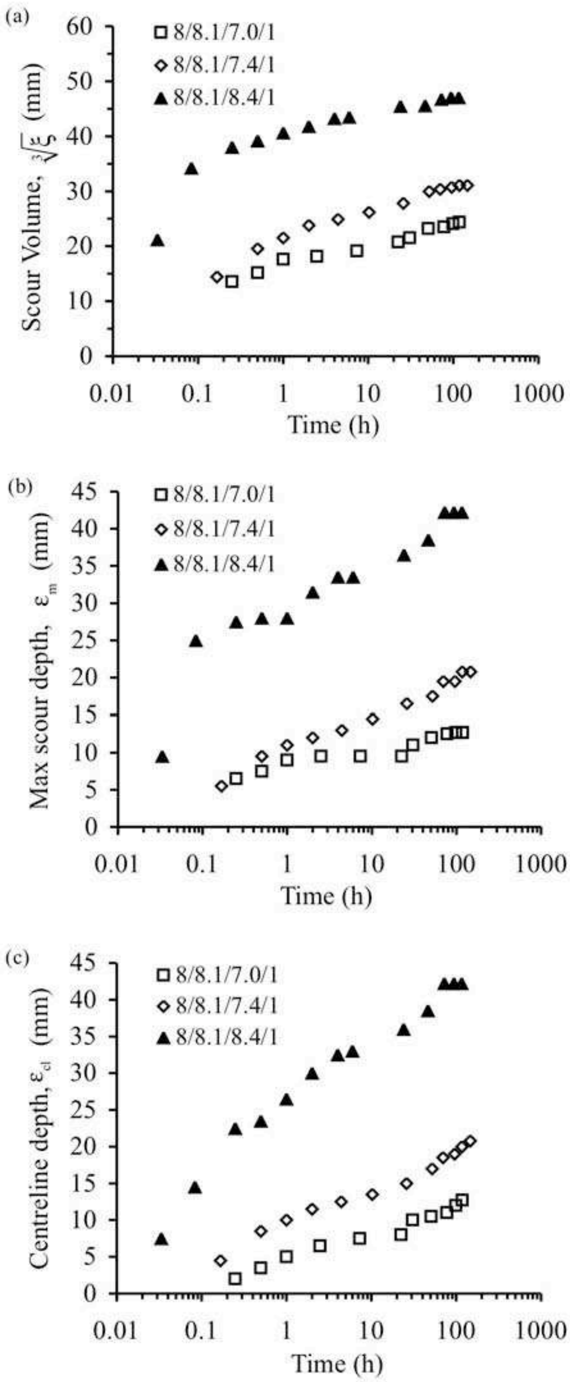

Figure 6. Examples of the growth of the (a) cube root of the scour hole volume (b) maximum depth of scour and (c) centerline depth of scour.

the data was the time to scour 50 % of the maximum depth of scour at asymptotic state.

To test this method of analyzing time evolution of scour for cohesive soils, the data for the growth of the centerline scour depth were plotted in dimensionless form as $\varepsilon_{cl}/\varepsilon_{cl\infty}$ against t/t_+. A number of different time scales were tried for t_+, including t_{80}, t_{50}, and t_{35}, where t_n is the time to n % of the centerline scour depth at asymptotic state. These times scales were determined by one of two methods. First, if a linear fit data of the data for each experiment of the centerline scour depth to the logarithm of time did not show a lot of scatter, the curve fit was used to estimate the time to n % of the asymptotic state value. Otherwise, linear interpolation was used between data points. The estimates for these time scales are given in Table 1.

Fig. 7 shows the growth of the dimensionless centreline scour depth $\varepsilon_{cl}/\varepsilon_{cl\infty}$ with t/t_{80}, t/t_{50}, and t/t_{35}. The time scale corresponding to the time to 80 % of the asymptotic scour depth appears to provide the best fit to the overall data. It was seen the smaller time scales collapsed the data from the early part of the scour process effectively, but there was much scatter for later into the scouring process. Thus, for the present work, the analysis of the data will continue only for t_{80}. It was found the data was best fit by

$$\left(\frac{\varepsilon_{cl}}{\varepsilon_{cl\infty}}\right) = 0.10 \ln\left(\frac{t}{t_{80}}\right) + 0.79 \qquad (2)$$

with an r^2=0.82 and the fit of Eq. 2 to the data is shown in Fig. 7a.

To use the dimensionless curves presented in Fig. 7(a), one would need to predict both the asymptotic depth of scour and the time scale. Methods for predicting $\varepsilon_{cl\infty}$ are presented in Mazurek et al. [12] and Ansari et al. [1]. For t_{80}, one might write

$$t_n = f_1\left\{M_o, \rho, H, \mu, \tau_c\right\} \qquad (3)$$

where $M_o = \pi\rho U_o^2 d^2/4$ is the momentum flux of the jet, and τ_c is the critical shear stress of the soil. Eq. 3 is based on the analysis of Mazurek et al. [12], who found that when assessing scour by vertical circular jets in cohesive soils at asymptotic state, M_o, ρ, H, and μ could be used to describe the properties of a jet at large impingement height and the critical shear stress τ_c can be used to represent the erosion resistance of the soil. By dimensional analysis, it is then found

$$\frac{t_{80}U_o}{H}\left(\frac{d}{H}\right) = f_2\left\{\frac{\rho U_o^2}{\tau_c}\left(\frac{d}{H}\right)^2, R = \frac{\rho U_o d}{\mu}\right\} \qquad (4)$$

For jets with Reynolds number R greater than about 10000, the Reynolds number on scour at asymptotic state can be neglected [12,17]. It is assumed here that that is also the case for the time development of scour. Also, following Mazurek et al. [12], let $\chi = \rho U_o^2 (d/H)^2$. The parameter χ/τ_c represents the ratio of the shear stress on the bed to the critical shear stress of the soil. Since it can be shown that $\tau_c = 0.16\chi_c$, where χ_c is the value of χ below which (mass) erosion does not occur, χ/τ_c is proportional to χ/χ_c. Finally, χ/χ_c can be rewritten in the form of an excess stress $(\chi - \chi_c/\chi_c)$, so that

$$\frac{t_{80}U_o}{H}\left(\frac{d}{H}\right) = f_3\left\{\frac{\chi - \chi_c}{\chi_c}\right\} \qquad (5)$$

From plots of the variation of the volume of scour at

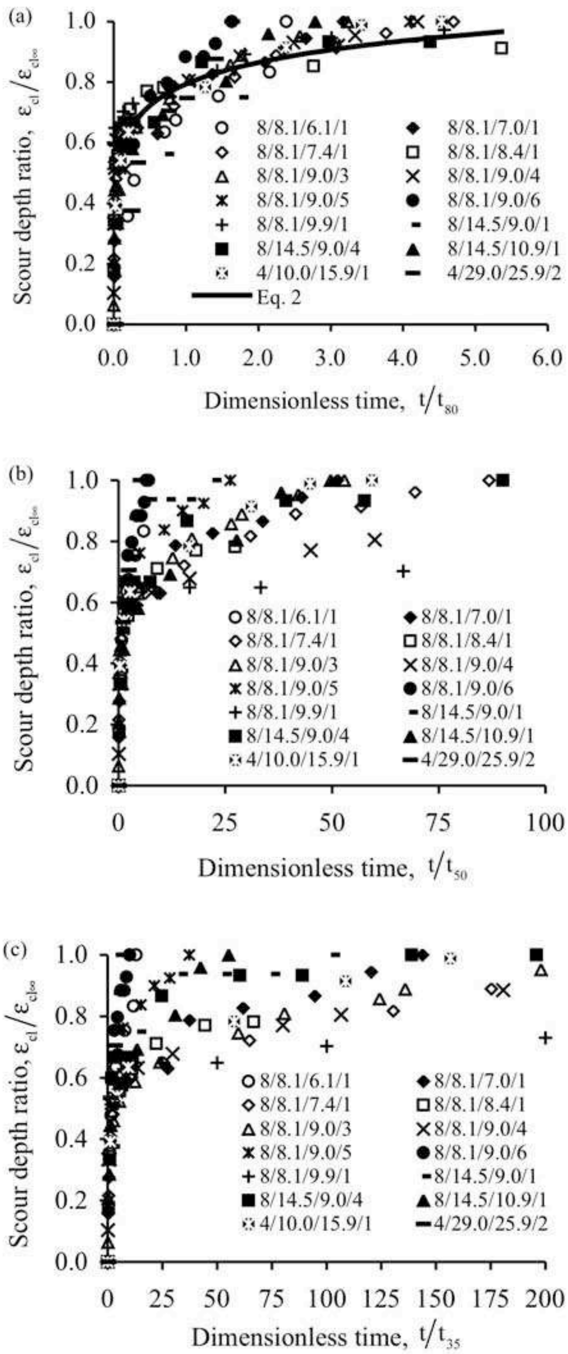

Figure 7. Dimensionless centerline scour depth with dimensionless time using a time scale corresponding to (a) 80 % (b) 50% and (c) 35 % of the asymptotic depth.

asymptotic state with χ, it was found that $\chi_c = 300$ Pa [12]. This corresponds to a critical shear stress for this soil of 48 Pa.

Fig. 8 shows the variation of the dimensionless time scale $(t_{80}U_o/H)(d/H)$ with the dimensionless excess stress $(\chi - \chi_c)/\chi_c$. Although there is a lot of scatter, an estimate for t_{80} might be made from

$$\frac{t_{80}U_o}{H}\left(\frac{d}{H}\right) = 788500\left(\frac{\chi - \chi_c}{\chi_c}\right) \qquad (6)$$

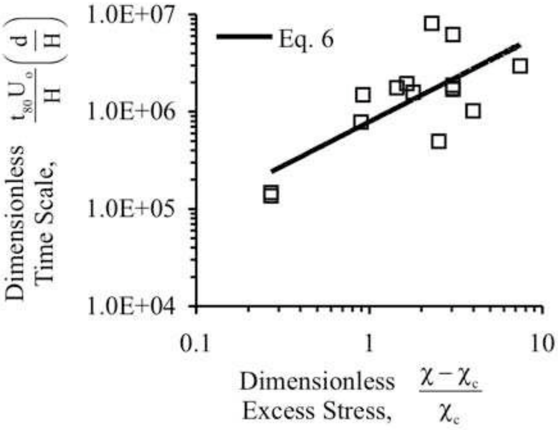

Figure 8. Variation of the dimensionless time scale with excess stress.

which gave an r^2=0.54.

An advantage of the method of Rajaratnam and Beltaos [17] is that an estimate for the time to asymptotic state is not needed, as this can be difficult to determine. This is because of the small changes in the scour hole size over long times at the late in the scouring process. Prediction of the time scale t_{80} however, at least for the current experiments, seems to be somewhat problematic. This is likely because tests under the same hydraulic conditions did not show that same rates of scour hole development. There was a 73 h variation in the estimates for t_{80} for the experiments all carried out with U_o=8.95 m/s, d=8 mm, and H=65 mm. It is unlikely that the relatively small variation in soil properties could account for a variation this large. As well, although the time to 80 % of the centerline scour depth at asymptotic state the entire scour process to asymptotic state, ultimately what time scale is most appropriate is a function of the situation considered. A smaller time scale may be more appropriate for practical situations where the duration of scour is also short-term.

It should also be noted that a smooth curve to represent the time evolution of scour in cohesive soil will miss the discontinuities in the growth of the scour hole due to mass erosion. It is difficult to model a discrete process with a continuous function. An example of this is shown in Fig. 9 for Expt. 8/8.1/7.0/1. This is a particular problem early on in the scour process when the scour hole is small and the eroded chunks tend to be large.

B. Ansari et al (2003)

Ansari et al. [1] presented a method to analyze the time evolution of scour in cohesive soils. He suggested that the scour hole growth follows the following relation

$$\frac{\varepsilon_{cl}}{\varepsilon_{cl\infty}} = \left[\sin\left(\frac{\pi t}{2t_e}\right)\right]^m \quad (7)$$

where t_e is the time to asymptotic state. Ansari et al. [1] suggested the t_e and the power in Eq. 7, m, and t_e are a function of the soil antecedent moisture content, liquid limit (for soils with a plasticity), plasticity index, and dry unit weight. However, they did not have enough data to develop a relation to predict t_e and m.

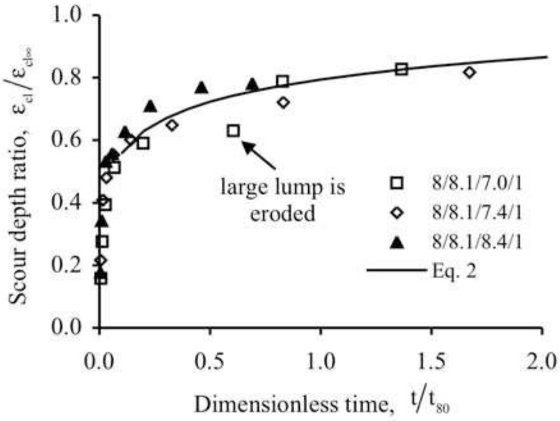

Figure 9. Variation in scour depths at early times due to mass erosion.

Fig. 10 shows the fit of the current experiments to Eq. 7. Note the time to asymptotic state was determined for each experiment from the change of slope on plots of the cube root of the scour volume with the logarithm of time, as it was constancy of the scour hole volume was used as the criteria for asymptotic state. For Eq. 7, an m=0.16 provided the best fit to the data. It is seen in Fig. 10 that there is more scatter than for Rajaratnam and Beltaos [17] method, likely due to the previously mentioned difficulties in assessing t_e.

V. CONCLUSIONS

For the time development of scour in a cohesive soil, mass erosion should be the expected scour process. Since this is the intermittent erosion of chunks or lumps of material, it is a discrete process. Modeling mass erosion by a continuous function can give a reasonable fit to the data for the time development of scour over the entire scour process. However, at very early times when the eroded chunks tend to be large and the scour hole is small

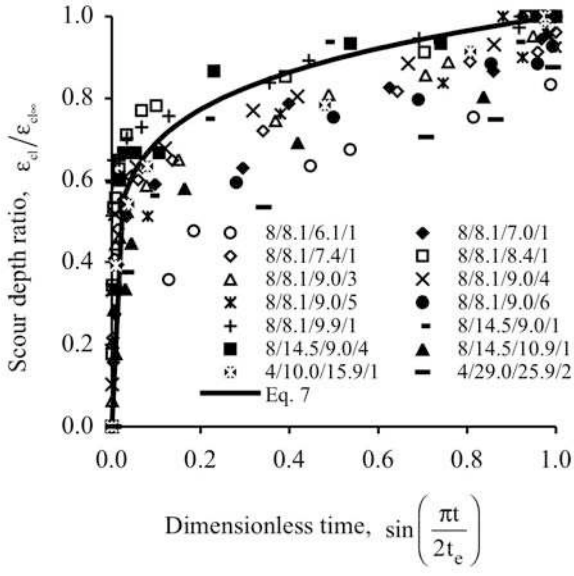

Figure 10. Time evolution of scour data based on Ansari et al. [1]

good prediction by a continuous model is less likely. A better understanding of the mechanics of mass erosion is needed for improved assessment of the time development of scour in cohesive material.

Acknowledgments

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References

[1] Ansari, S.A., U.C. Kothyari, and K.G. Ranga Ragu, 2003, Influence of cohesion on scour under submerged circular vertical jets, *J. Hydr. Engrg.*, ASCE, 129(12), 1014-1019.

[2] Beltaos, S., and N. Rajaratnam, 1974, Impinging circular turbulent jets, *J. Hydr. Div.*, ASCE, 100(HY10), 1313-1328.

[3] Beltaos, S., and N. Rajaratnam,1977, Impingement of axisymmetric developing jets, *J. Hydr. Res.*. IAHR, 15(4), 311-326."

[4] Dash, U., 1968, Erosive Behavior of Cohesive Soils, Ph.D. Thesis, Purdue University, West Lafayette, Indiana, USA.

[5] Dunn, I.S., 1959, Tractive resistance of cohesive channels, *J. Soil Mechanics and Foundations Div.,* 85(SM3), ASCE, 1-24.

[6] Hanson, G.J., 1991, Development of a jet index to characterize erosion resistance of soils in earthern spillways, *Trans. ASAE*, 34(5), 2015-2020.

[7] Hanson, G.J., and K.R. Cook, 1997, Development of excess shear stress parameters for circular jet testing, ASAE Paper No. 972227, St. Joseph, Michigan, USA.

[8] Hedges, J.D., 1990, The Scour of Cohesive Soils by an Inclined Submerged Water Jet, M.Sc. Thesis, Texas A & M University, College Station, Texas, USA.

[9] Hollick, M., 1976, Towards a routine assessment of the critical tractive forces of cohesive soils, *Trans. ASAE*, 19, 1076-1081.

[10] Mazurek, K.A., 2001, Scour of Clay by Jets, Ph.D. Thesis, University of Alberta, Edmonton, Alberta, Canada.

[11] Mazurek, K.A., 2005, Discussion of "Influence of Cohesion on Scour under Submerged Circular Vertical Jets," by S.A. Ansari, U.C. Kothyari, and K.G. Ranga Ragu, *J. Hydr. Engrg.*, ASCE, 131(8), 737-738.

[12] Mazurek, K.A., N. Rajaratnam, and D.C. Sego, 2001, Scour of cohesive soil by submerged circular turbulent impinging jets, *J. Hydr. Engrg.,* ASCE, 127(7), 598-606.

[13] Mehta, A.J., 1991, Review notes on cohesive sediment erosion, *Coastal Sediments '91*, 1, 40-53.

[14] Mirtskhulava, Ts.E., I.V. Dolidze, and A.V. Magomedova, 1967, Mechanisms and computation of local and general scour in non-cohesive, cohesive soils, and rock beds." Proceedings of 12th Congress of the IAHR, Fort Collins, Colorado, September, 1967, 3, 169-176.

[15] Moore, W.L., and F.D. Masch, Jr., 1962, Experiments on the scour resistance of cohesive sediments, *J. Geophys. Res*., 67(4), 1437-1449.

[16] Perigaud, C., 1984, Erosion of cohesive sediments by a turbulent flow: Part II - High mud concentration, *J. Mecanique Theorique et Appliquee*, 3(4), 505-519.

[17] Rajaratnam, N., and S. Beltaos, 1977, Erosion by impinging circular turbulent jets, *J. Hydr. Div.,* ASCE, 103(HY10), 1191-1205.