



Jul 1st, 12:00 AM

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Erosion of Sediment Beds by Turbulent Wall Jets in Combined-Sewer-Overflow Reservoirs

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Abstract: Sediment management with the help of water jets in combined-sewer-overflow (CSOs) reservoirs in the Chicago area has motivated this work. Erosion caused by single and multiple submerged circular turbulent wall jets on a granular (non cohesive) sediment bed of finite thickness laying on a fixed boundary was studied with the help of laboratory experiments. Plane turbulent wall jets were also tested on sewer sediment in order to determine its critical shear stress. Though not strongly cohesive this sewer sediment presented some flocculation. Regarding circular jets, different combinations of jet diameter, jet separation, and ratio between sediment thickness and jet diameter were tested. For granular sediments results show a relation between dimensionless parameters characterizing the steady state bed profile and the densimetric particle Froude number F_o given by the velocity at the nozzle, and the effective diameter and submerged specific density of the sediment. Sewer sediment is better characterized by the critical shear stress beyond which transport occurs. For both kinds of sediment, evolution of scour with time confirms previous studies where the erosion was found to initially grow with the logarithm of time up to a certain reference time. This time, made dimensionless with a time scale t_c involving the volume of sediment scoured and the rate of erosion, was also related to the densimetric Froude number in the studies involving granular (non cohesive) sediment.

Keywords: Submerged jets, Erosion, Scour, Cohesionless sediment, Sewer sediment.

1. INTRODUCTION

The use of jets to prevent sedimentation at the bottom of reservoirs and harbors is not a recent idea but it has not been frequently implemented. Depending on the area to be cleaned, an array of jets can be set to remove the newly deposited sediments.

Previous laboratory and field experiments have shown that the erosive action of a submerged wall jet is a function of the jet diameter, velocity, and orientation relative to the bottom [Van Dorn et al. 1975, Jenkins 1981]. The limit of the scour pattern can be considered to be an isoline of constant shear stress with a value equivalent to the threshold bottom stress.

However, estimating the threshold shear stress of a certain material presents uncertainties. An alternative approach to characterize the response of the sediment to jet flow, in the case of non-cohesive sediment, is to use the densimetric Froude number

associated with a representative diameter. The densimetric Froude number F_o is defined as $U_o/(gd_i\Delta\rho/\rho)^{1/2}$, where U_o is the jet velocity at the nozzle, g the acceleration due to gravity, d_i a representative size of the bed material, and $\Delta\rho$ is the difference between the density of the bed material ρ_s and the density of the fluid ρ . This approach was developed by several investigators studying a similar problem also found in hydraulic engineering, namely, the erosion of a semi-infinite layer of sediment due to submerged circular wall jets [Rajaratnam & Berry 1977]. The representative dimensions of the scoured bed were found to be function of F_o .

The research reported in this paper focused on: a) finding the characteristics of sediment typical of combined sewer overflow reservoirs, b) estimating the erosion of a layer of sediment of finite thickness resting upon a fixed boundary, with the goal of applying this technology to the projected McCook

reservoir for combined sewer overflows in Chicago, Illinois. Being the bottom of the reservoir of limestone rock, the use of a fixed boundary in the experiments was thought to be appropriate. Compared to the fast scour of the sediment bed, the erosion of the bottom by jets operating for a short period of time is considered to be negligible. This work extends previous research on jet scour from single to multiple jets. Jet diameter and separation were varied in order to test the validity of the dimensionless equations derived. The discharges were selected to cover a wide range of F_o mainly under highly turbulent conditions. The evolution of the scour with time is also addressed.

2. SEWER SEDIMENT EXPERIMENTS

2.1 Sewer Sediment Characterization

The sewer sediment was provided by the Metropolitan Water Reclamation District of Greater Chicago, the samples were taken from O'Hare reservoir. A LISST-ST laser-diffraction instrument was used to analyse its properties [Sequeiros et al. 2005]. Tests with and without disaggregated samples were made in order to estimate the size of aggregate formation. The mean size of particles belonging to the original samples (not disaggregated) was about 24 μm , while corresponding values for disaggregated samples were 10.8 μm . The mean size of the aggregates found in the original sediment samples was estimated to be about 84 μm . Given the range of particles sizes found in this study, the sediment may present some cohesivity. Nevertheless experiments performed in an annular flume showed that the sediment was easily eroded by shear stresses as low as 0.06 N/m^2 . These facts indicate that this sewer sediment can neither be classified as granular due to the small size of its particles and aggregates and the tendency to form flocks, nor as cohesive, because it lacks the strong cohesion that characterizes clay and other similar sediments.

2.2 Critical Shear Stress Determination

The determination of the critical shear stress was based on the tests performed by Sequeiros [2004] on the scour caused by plane wall jets upon a layer of finite thickness of sewer sediment (see Figure 1).

Following Mazurek et al. [2003] the asymptotic length of erosion, $x_{m\infty}$, can be expressed as:

$$x_{m\infty}/b_o = f_1 [(\lambda - \lambda_c)/\lambda_c] \quad (1)$$

where $\lambda = \rho U_o^2$ is related to the bottom shear stress, U_o is the velocity at the nozzle, b_o is the thickness of the nozzle, ρ is the density of the eroding fluid, λ_c is related to τ_c is the critical shear stress of the soil below which no significant erosion happens. The bottom shear stress τ_b is related to the velocity as $\tau_b = C_f \rho U_o^2 / 2$ where C_f represents the nondimensional

skin friction coefficient. It is related to the more common Darcy Weisbach friction factor f as $f = 4C_f$.

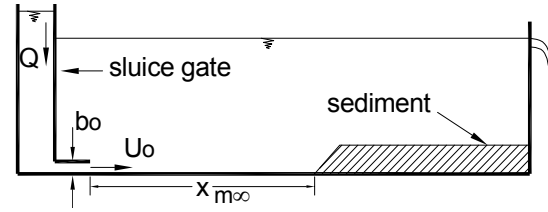


Figure 1: Plane wall jet tests on sewer sediment.

Figure 2 shows the dependence of the final scour length on λ . The asymptotic scour length $x_{m\infty}$ was averaged at three positions along the front. The critical value of λ can be estimated by extrapolating the data to the condition $x_{m\infty} = 0$. Close observation of Figure 2 indicates this extrapolation should be performed with care. In the proximity of the abscisses axis the points appear to follow a curve drifting away from the linear tendency corresponding to high Reynolds number tests. Applying the least square method the power law that yields the best fit is:

$$x_{m\infty}/b_o = 5.08 [(\lambda - \lambda_c)/\lambda_c]^{0.578} \quad (2)$$

where $\lambda_c = 3.3 \text{ Pa}$. This is shown in Figure 3. It should be mentioned that because of the limited set of data available it may be better to define a range of λ_c rather than a single value. In any case there is no need to change the analysis here pursued.

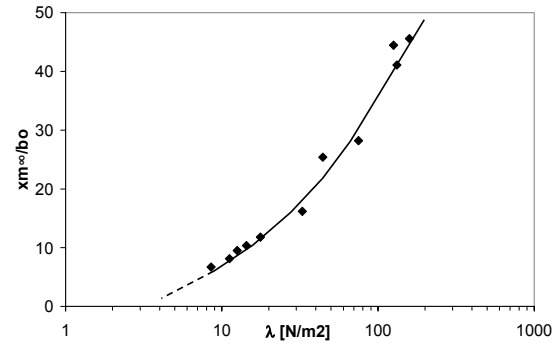


Figure 2: Dimensionless scour length as versus λ .

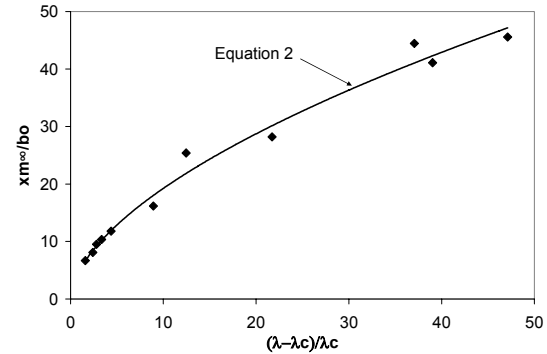


Figure 3: Asymptotic scour length as a function of $(\lambda - \lambda_c)/\lambda_c$ and power-law best fit (Eq. 2).

From Myers et al. [1963] the friction coefficient $C_f = 0.011$ for our range of Reynolds numbers. This gives

a value of critical shear stress $\tau_c = 0.02$ Pa, which results to be insignificant compared to results for cohesive soil obtained by Mazurek et al. [2003], but has the same order of magnitude as the results obtained in the annular flume.

The evolution of the scour with time was found to be analogous to that of circular jets and will be treated below.

3. GRANULAR SEDIMENT EXPERIMENTS

3.1 Multiple Jet Studies

The experiments involving sewer sediment were not extended to multiple jets mainly to avoid its hazardous manipulation in the laboratory large facilities. Fine granular mixtures were employed instead as a first approximation to the problem. Table 1 displays the characteristic sizes and the dimensionless geometric standard deviation, defined as $\sigma_g = (d_{84}/d_{16})^{0.5}$, for each material. The specific gravity of all materials was 2.65.

Material	d_{50} [μm]	d_{95} [μm]	d_{84} [μm]	d_{16} [μm]	σ_g	$d_{50}\sigma_g^{1.3}$ [μm]
1	19	86	56	5	3.28	89
2	45	196	118	7	4.26	296
3	250	360	325	196	1.29	348

Table 1: Characteristic diameters of the sediments

A linear array of submerged turbulent circular wall jets parallel to and resting on a fixed boundary was applied upon a layer of sediment resting on the same fixed boundary. The diameter of the jets and the distance between them were two of the variables studied. Single jet tests were also carried out to compare the scour patterns of jets acting alone and in parallel.

The experiments were carried out over a steel plate 5.4 m long and 2.6 m wide, located inside a water tank 7.3 m long, 2.7 m wide, and 2.3 m high. A pump conveyed the water from a secondary tank placed nearby to the jet array (see Figure 4). In most cases the discharge Q was measured using a magnetic flowmeter having a capacity of up to 20 l/s, located in the supply pipe. In the few experiments for which the discharge was lower than 0.10 l/s, the flow was obtained by measuring the time required to fill a certain volume of water. A 50.8 mm manifold having branches separated 0.13 m composed the jet system. The use of threaded joints facilitated the creation of different arrays, by modifying jet diameter and spacing. The manifold was comprised of up to 13 jets. The adjustable slope of the bottom plate was set at 1.5%. A layer of sediment of constant thickness, b_{so} , placed on the plate, set the initial condition. Figure 5 depicts a generic sketch for single jet experiment.

The water depth at the nozzle was fixed at 0.35 m for all the experiments. Once released, the jet drags the water above it, generating entrainment of

ambient fluid into the main flow. In a related study [Sequeiros 2004] velocity profiles were measured using acoustic Doppler velocimeters and showed a good fit to the wall jet empirical equation proposed by Verhoff [1963].

The experiments were run until a steady or approximate asymptotic state scour condition was reached. Once the jets were stopped, measurements of final scour were taken using a digital camera. A 3-mm definition grid was placed at the bottom to improve the accuracy of the data collection process. Some experiments were also recorded to study the evolution of the scour with time.

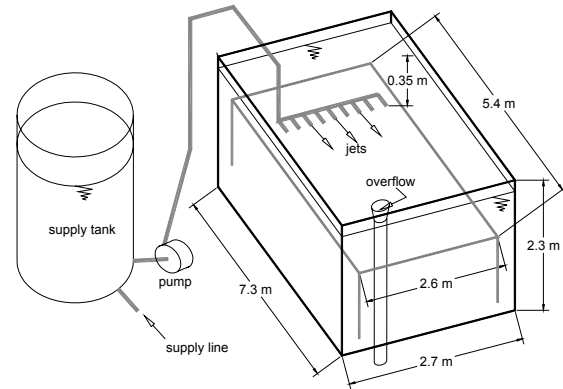


Figure 4: Set-up for the experiments

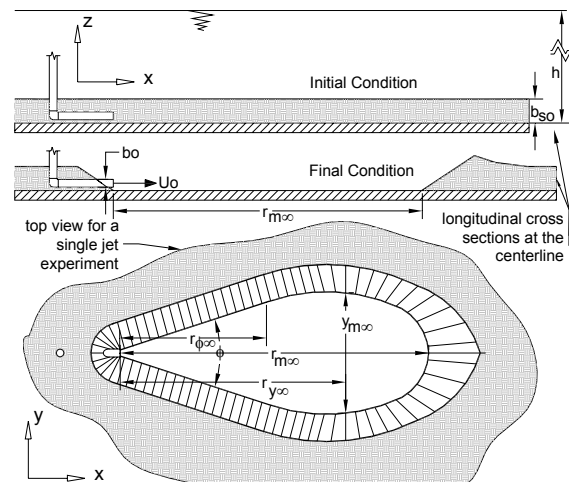


Figure 5: Sketch for a single jet experiment

The thickness of the sediment layer was changed in different experiments to study the influence of the ratio between jet diameter and bed sediment thickness. Different discharges were used in order to determine the scour pattern for a wide range of densimetric Froude numbers. A detailed tabulated summary of the conditions of all 58 experiments can be found at Sequeiros et al. [in press].

3.2 Asymptotic values analysis

The scour pattern created by a single jet can be characterized by measuring certain parameters, e.g., the maximum scour length, r_m ; the maximum scour width, y_m ; the distance from the nozzle to the point

where the maximum width occurs, r_y ; the angle ϕ formed by the jet downstream of the nozzle. Starting from the nozzle there is a region in the pattern of erosion where the scour width grows linearly as twice the distance from the nozzle times the tangent of $\phi/2$. This rate of increase in scour width is maintained up to a certain distance from the nozzle, r_ϕ . Beyond this point, due to lateral dissipation of momentum, the jet is no longer able to keep the linear rate of lateral erosion and the scour width grows at a lower rate until it reaches its maximum value, y_m , at r_y . Downstream from this point the width decreases until it vanishes at the tip of the scour hole. All these parameters used to define the geometry and dimensions of the scour hole created by the jets can be seen in Figure 5. At the asymptotic state the jet can no longer transport sediment because its momentum has been dissipated through friction, and the scour boundaries remain unmoved. At this point r_m , y_m , r_ϕ and r_y , become $r_{m\infty}$, $y_{m\infty}$, $r_{\phi\infty}$, and $r_{y\infty}$, respectively.

In case of multiple jets, the distance between jet nozzles is denoted d_j . The other parameters remain the same, noting that, depending on the distance between nozzles and the Froude number, the scour of different jets may or may not be in superposition.

The maximum length of erosion for a single jet at the steady state, denoted $r_{m\infty}$, can be expressed as the following functional relationship:

$$r_{m\infty} = f_1(U_o, b_o, \rho, \mu, g\Delta\rho, d_{95}, b_{so}, h) \quad (3)$$

Applying dimensional analysis, it can be shown that:

$$\frac{r_{m\infty}}{b_o} = f_2\left(U_o \sqrt{\frac{g\Delta\rho}{\rho}}, \frac{U_o b_o}{\nu}, \frac{b_{so}}{b_o}, \frac{b_o}{d_{95}}, \frac{h}{b_o}\right) \quad (4)$$

where U_o is the velocity at the nozzle, b_o is the thickness of the nozzle, ρ and μ are the density and dynamic viscosity of the eroding fluid respectively, $\Delta\rho$ is the difference between the density of the bed material and that of the fluid ρ , d_{95} is the representative size of the bed material in this situation, b_{so} is the initial thickness or the sediment layer, and h is the water depth, $F_o = U_o/(gd_{95}\Delta\rho/\rho)^{1/2}$, and $R_o = U_o b_o/\nu$ are the densimetric particle Froude number and the Reynolds number at the nozzle, respectively. The densimetric Froude number, was defined using, not the median d_{50} as the effective diameter, but d_{95} .

Aderibigbe and Rajaratnam [1998] showed that on the erosion of well-graded mixtures the most significant grains are the coarser ones and not those of sizes comparable to the median diameter that could be used to characterize the grain size distribution. Exposed to a certain flow, the smaller grains are more easily moved while the coarser grains remain in place. This is known as armoring, because the top layer of the bed will eventually become a region formed mainly by coarser grains

with just a few smaller grains. The size of the original sediment mixture that best correlates with the scour length was found to be d_{95} by Aderibigbe and Rajaratnam [1998], which according to them is equivalent to the median size of the armor coat.

An alternative approach is to include the geometric standard deviation in the computation of F_o , Aderibigbe and Rajaratnam [1998] noted that using $d_{50} \sigma_g^{1.3}$ as a substitute for d_{95} in the definition of the densimetric Froude number yields an equivalent correlation of the experimental data. Table 1 shows the alternative variable $d_{50} \sigma_g^{1.3}$ that could be used instead of d_{95} to take account of the sediment gradation in the present experiments. Breusers and Raudkivi [1991] set the limit of the geometric standard deviation beyond which a mixture can be considered to be non-uniform as 1.35. Materials 1 and 2 employed here were thus expected to armor and that was confirmed when building the dimensionless curves. Material 3 was not expected to armor given its uniformity, and, indeed, no significant differences were found when choosing either d_{95} or d_{50} as the effective diameter.

Rajaratnam [1976] showed that the effect of the Reynolds number can be neglected if it is larger than a few thousands ($R_o > 3000 - 10000$). Experiments conducted by Rajaratnam and Berry [1977] proved that the effect of b_o/d_{95} can be neglected for large enough values of this ratio, such as, and even lower than, those in the present experiments. Aderibigbe and Rajaratnam [1998] found that the effect of submergence is not important when the mean velocity field in the flow is similar to that of a classical (infinitely submerged) wall jet [Rajaratnam, 1976] and the flow depth, on average, is at least four times the dune height. In the current study the effect of the submergence was neglected based on similar reasons. The velocity field was similar to that of the classical wall jet as explained previously. The flow depth h was at least 5.8 times the initial thickness of the sediment bed b_{so} , 14.6 times the jet diameter b_o , and, in the experiments where longitudinal profiles were measured, at least 4.6 times the ridge height. Finally it was found that the ratio b_{so}/b_o has no influence on the steady state profiles as long as it is kept at least below 5. Under these conditions Equation 4 can be reduced to:

$$r_{m\infty}/b_o = f_3(F_o) \quad (5)$$

A similar analysis can be done to find analogous dimensionless relations for the other characteristic dimensions of the scour hole, $y_{m\infty}$, $r_{y\infty}$, and $r_{\phi\infty}$.

Materials 1 and 2 have certain amount of silt, which is prone to some kind of cohesive behavior, like erosion of chunks rather than just particles [Mazurek et al. 2003]. During the current experiments not such cohesive behavior was observed. As a result cohesive effects were neglected. For cohesion

dominated soils a dimensional analysis using the critical shear stress of the soil rather than a characteristic grain size should be carried out.

In case of studying not a single jet but an array of them, the same analysis just presented holds, except that there is another variable that must be incorporated, i.e., the jet spacing, d_j . It can be expressed in dimensionless form as d_j/b_o . Figure 6 shows the dimensionless maximum scour length versus F_o computed with d_{95} sorted using the ratio d_j/b_o . Tests corresponding to different effective diameters d_{95} and different jet nozzle diameters b_o collapse fairly well to a single curve. This confirms the validity of neglecting the effect of the dimensionless parameter b_o/d_{95} on jet scour.

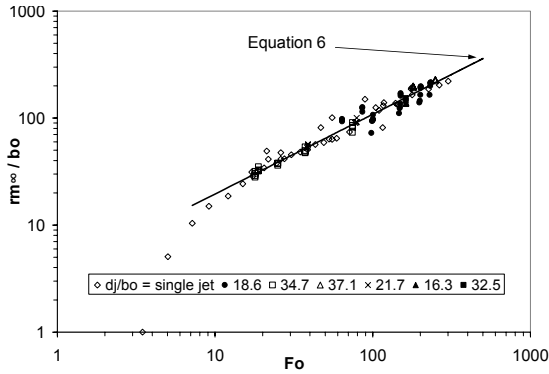


Figure 6: Asymptotic dimensionless value of maximum scour length as a function of F_o .

The tests with low F_o whose collapse is poor correspond to $3.5 < F_o < 9.1$ and have a Reynolds number range of $2900 < R_o < 7700$. This range is within that found by Rajaratnam [1976] for which the viscous effects are still considerable, which could help explaining the poor collapse. Hence low F_o tests were excluded from the analysis. Equation 6 fits the present data for F_o larger than 9.

$$r_{m\infty}/b_o = 3.51F_o^{0.75} \quad (6)$$

The behavior of $y_{m\infty}/b_o$, $r_{y\infty}/b_o$, and $r_{\phi\infty}/b_o$, is represented by $y_{m\infty}/b_o = 0.47F_o^{0.96}$, $r_{y\infty}/b_o = 2.41F_o^{0.74}$, $r_{\phi\infty}/b_o = 1.87F_o^{0.65}$ respectively.

When more than one jet is combined, a new variable enters the scene, the distance between outlets. Depending on how close the nozzles are located to each other, the flow field might be altered enough to cause a significant increment in the erosive capacity. The closer the jets are to each other, the closer to the nozzle the single velocity fields will start to be affected by neighboring jets and, consequently, the closer the flow will tend to be 2D. Pani and Dash [1983] experimented with ratios d_j/b_o lower than 3. For these low ratios the flow decays like that of the plane wall jet, providing there are enough jets to prevent the 2D flow from spreading laterally.

Values of the dimensionless separation length in the present experiments ($16.3 < d_j/b_o < 37.1$) are higher

than those of Pani and Dash ($d_j/b_o < 3$). This fact is important to understand why, in the present tests, the maximum longitudinal extent of the scour achieved by a single jet is, on average, no longer than the maximum longitudinal extent of the scour produced by multiple jets under the same conditions (see Figure 6). If the outlets are spaced beyond a certain distance, the flow field of a single jet will be only affected far away from the nozzle and in just a small amount, not enough to increase the bottom shear stress beyond the threshold value. Tests involving lower jet spacing were not conducted. Being the scope of this study the feasibility of using wall jet arrays to manage sediment deposits on reservoirs, the interest was placed on how far the jets could be located to efficiently clean a certain area with the lowest possible discharge minimizing overlapping between jet scours.

3.3 Evolution of scour with time

The development of scour with time was studied for some tests. As Rajaratnam and Berry [1977] noted the erosion length increases with the logarithm of time before the asymptotic state is reached. The scour length, thus, is proportional to the logarithm of time up to a time t^* beyond which the slope of the scour-time curve starts decreasing and finally becomes zero at the asymptotic or steady state. This same behavior was also observed in the present study, even though the erosion pattern is different.

The length used to evaluate the front movement along time was r_m . To collapse the individual profiles to a general curve, the scour scale was chosen as $r_{m\infty}$. The time scale was taken as t^* , the time where the scour stops growing proportionally to the logarithmic of time. Figure 7 shows a plot of $r_m/r_{m\infty}$ versus t/t^* for the tests where t^* could be obtained. When t equals t^* , r_m is approximately $0.95 r_{m\infty}$; and r_m is $r_{m\infty}$ when t is approximately 5 times t^* ($t_\infty/t^* \approx 5$). This means that it is possible to predict the asymptotic time t_∞ by knowing t^* without the need to run the whole experiment. Thus t^* gives a measure of how long the scour process may last before reaching the asymptotic state.

In order to make the t^* dimensionless, a time scale is required. The time it takes the jet to scour the asymptotic profile can be defined as $t_c = V/Q_s$, where V is the total scoured volume and Q_s is an average scour rate. An estimation of the excavated volume per unit width is $b_{so}r_{m\infty}$, where b_{so} is the initial thickness of the bed and $r_{m\infty}$ is the asymptotic scour length. The characteristic time is then given by $t_c = b_{so}r_{m\infty}/q_s$ where q_s is the average bedload rate per unit width. Sequeiros et al. [in press] proposed the following equation for t_c :

$$t_c = \left[\frac{r_{m\infty}}{b_o} \frac{(\beta - 1)}{c_f} \right]^{3/2} \frac{b_{so} r_{m\infty} gR}{8U_o^3} \quad (7)$$

The parameter β depends on the nature of the jet. For circular wall jets it can be taken as 2.1 [Jenkins, 1981]. The friction coefficient c_f for smooth boundaries can be estimated from Myers et al. [1963] as $c_f = 0.005$.

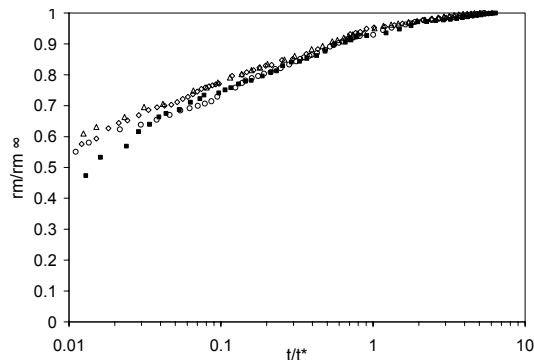


Figure 7: Dimensionless evolution of maximum scour length with dimensionless time.

Because t^* and t_c were found to be in the same order of magnitude, it can be inferred that the characteristic time t_c is a reasonable time scale for the jet scouring process. This result is relevant for design purposes, as the operation time of the jet array system to clean a given bed area should be small enough to keep associated costs reasonably low, particularly in the case of large bed areas.

4. CONCLUSIONS

The critical shear stress of typical sewer sediment was estimated studying the scour of plane wall jets. This material has special characteristic being neither cohesive nor granular. The erosion caused by single and multiple circular wall jets acting parallel to a fixed bottom over a granular layer of sediment of finite thickness was studied extensively and found to be a function of the jet velocity, jet diameter, density of the eroding fluid, and the properties of the sediment to be eroded, in particular its size and critical shear stress. Three kinds of granular sediment were employed in the tests. In the asymptotic state, the maximum scour length and other representative dimensions of the final scour hole seem to depend on F_o . A set of equations was proposed for these parameters to predict the main dimensions of the scour given F_o and the diameter of the jet. Other variables were found not to affect the final dimensionless extent of the scour hole for the ranges of governing parameters employed in these experiments. The scour was found to initially grow with the logarithm of time, until a reference time denoted t^* , and then to tend slowly towards and asymptotic value at a time t_c . An equation for the time scale t_c involving the volume of sediment scoured and the rate of erosion was also proposed.

5. ACKNOWLEDGEMENTS

This research was supported by grants from the Metropolitan Water Reclamation District of Greater Chicago and the U.S. Army Corps of Engineers (Chicago District). This support is gratefully acknowledged.

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