

Prediction of Scour Profile Caused by Submerged Three-Dimensional Wall Jets

Abdullah Al Faruque, Ram Balachandar

Abstract—Series of laboratory tests were carried out to study the extent of scour caused by a three-dimensional wall jets exiting from a square cross-section nozzle and into a non-cohesive sand beds. Previous observations have indicated that the effect of the tail water depth was significant for densimetric Froude number greater than ten. However, the present results indicate that the cut off value could be lower depending on the value of grain size-to-nozzle width ratio. Numbers of equations are drawn out for a better scaling of numerous scour parameters. Also suggested the empirical prediction of scour to predict the scour centre line profile and plan view of scour profile at any particular time.

Keywords—Densimetric Froude Number, Jets, Nozzle, Sand, Scour, Tailwater, Time.

I. INTRODUCTION

THE prediction of scour is very important to design various hydraulic structures prone to scour. As in other fields of sediment transport, so far there is no entirely satisfactory theoretical solution which describes scour completely. The complexity of the non-steady flow patterns and the mechanisms by which the flow entrains an erodible sediment bed is presently not analytically solvable. The predictability of scour becomes more difficult because most of the flow related to scour is turbulent and turbulence is still an outstanding difficult subject to understand comprehensively. Consequently, most studies in this field involve systematic experimentation to delineate the significant variables and to develop empirical relationships between the flow patterns, the scour characteristics and the properties of the bed material.

II. EXPERIMENTAL SETUP

A schematic drawing of the open channel flume and experimental setup used in this study is shown in Fig. 1. The open channel flume is 8.0 m long, 1.1 m wide and 0.92 m high. The header tank is 1.2 m square and 3.0 m high. The sidewalls and bottom of the flume are made of transparent tempered glass to facilitate velocity measurements using a laser Doppler anemometer. The flume is a permanent facility and the quality of flow has been confirmed in previous studies. The channel bottom slope is adjustable. For the present

experiments, the channel bottom was set to be horizontal. A summary and details of test conditions can be found in [1] and avoided here for brevity.

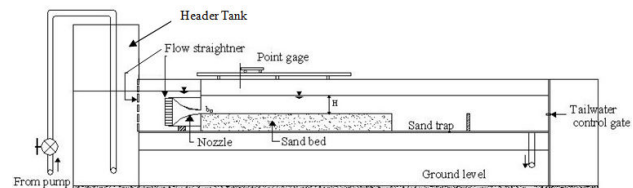


Fig. 1 Schematic of the open channel flume and experimental setup

III. RESULTS

A complete schematic of the scour hole and the ridge showing various scour parameters that is formed downstream of the scour hole is shown in Fig. 2.

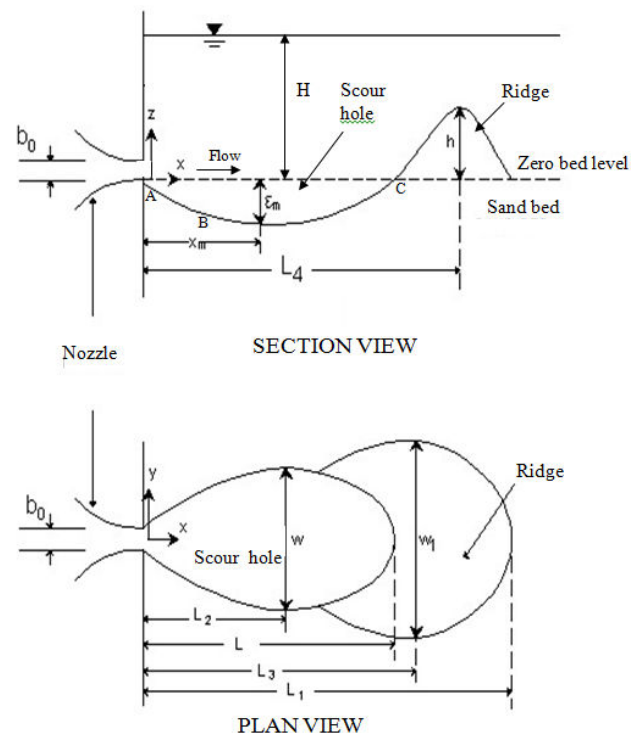


Fig. 2 Various scour parameters

In an effort to further understand the role of scaling variables, the variation of ϵ_m/b_0 with increasing time for several tests, including the scour generated by two-

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dimensional, circular and three-dimensional jets was plotted in Fig. 3, [1]. For those sets of data where the effect of time has been not reported in previous studies, the data is shown for asymptotic conditions. The scaling variables in Fig. 3 [1] resemble that suggested in several related studies. There is a fairly large scatter in the data. The same set of data is re-plotted in Fig. 4 [1] using a combination of the nozzle hydraulic radius, d_{50} and F_0 as the scaling variables. This is done to accommodate the effect of nozzle size (and shape), sand grain size and densimetric Froude number. $R^n d_{50}^{(1-n)} F_0^m$ is suggested as the scaling parameter. The value of exponent n is 0.75, while m is 0.65 in Fig. 4, [1]. With the exception of the two-dimensional jet scour results of [2], the other data more-or-less collapse on to a single curve. Compared to the other results, it should be noted that the circular jet scour data of [3] have a large $d_{50}/b_0 = 0.28$ (gravel). Given the wide variety of experimental conditions encountered in the various tests, the collapse of the data is fair. The solid line in the figure indicates the fit to the data from the present and previous studies where time variation of scour is available. Simple empirical relations are suggested for the various scour parameters and indicated in each of the figures. It should also be remarked that for $T = tU_0/H > 10^6$, an asymptotic state can be assumed. The role of the suggested combination of variables is also reflected in scaling the other scour hole variables (Figs. 5 to 14). The value of n changes slightly depending on the parameter (0.65 to 0.75) while m varies from 0.6 to 0.65. The only exception is for the parameter h , where the value of $m = 1$ produces the best fit to the experimental data. These figures indicate that the effect of tail water depth, sand grain size, nozzle shape, time since the start of the test and the prevailing densimetric Froude number are absorbed by the proper choice of the scaling variables. Legends for Figs. 3 to 14 are shown in Fig. 15.

An empirical prediction of scour profile at any particular time can be expressed as follows and shown in Fig. 16:

For $0 \leq x \leq x_m$

$$\frac{\varepsilon}{\varepsilon_m} = -0.0018 \left(\frac{x}{\varepsilon_m}\right)^3 + 0.054 \left(\frac{x}{\varepsilon_m}\right)^2 - 0.407 \left(\frac{x}{\varepsilon_m}\right) - 0.091 \quad (1a)$$

For $x_m < x \leq L$

$$\frac{\varepsilon}{\varepsilon_m} = -0.005 \left(\frac{x}{\varepsilon_m}\right)^4 + 0.15 \left(\frac{x}{\varepsilon_m}\right)^3 - 1.5 \left(\frac{x}{\varepsilon_m}\right)^2 + 6.3 \left(\frac{x}{\varepsilon_m}\right) - 11.12 \quad (1b)$$

Here, ε = depth of scour at any distance x from nozzle and ε_m = maximum scour depth at any particular time.

For any particular time, ε_m can be determined from the formula shown in Fig. 4.

Similarly, the width of the scour can be predicted as:

For $0 \leq x \leq L_2$

$$\frac{w'}{w} = -0.26 \left(\frac{x}{w}\right)^2 + 0.67 \left(\frac{x}{w}\right) + 0.063 \quad (2a)$$

For $L_2 < x \leq L$

$$\frac{w'}{w} = -0.64 \left(\frac{x}{w}\right)^2 + 1.72 \left(\frac{x}{w}\right) - 0.66 \quad (2b)$$

Here, w' = half width of scour at any distance x from nozzle and w = maximum width of scour hole at any particular time. For any particular time w can be determined from the formula shown in Fig. 8.

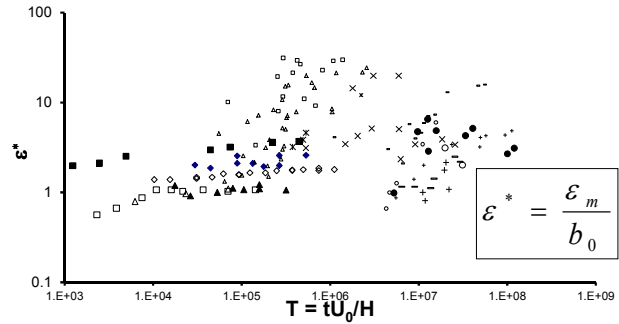


Fig. 3 Scaling variables on maximum depth of scour from several related studies

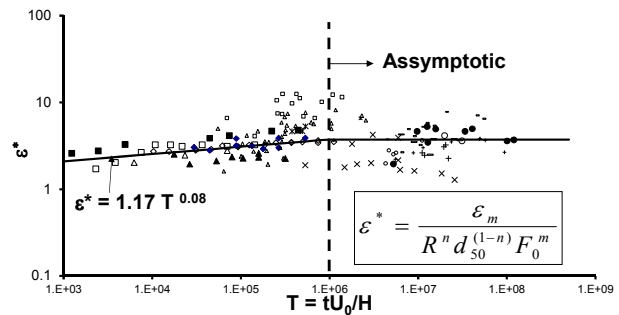


Fig. 4 Proposed scaling variables on maximum depth of scour

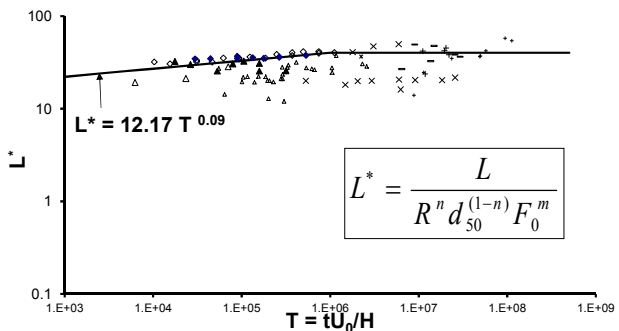


Fig. 5 Proposed scaling variables on maximum length of scour hole

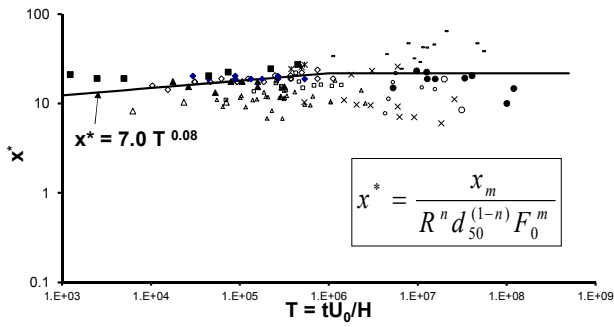


Fig. 6 Proposed scaling variables on distance of maximum scour depth from the nozzle

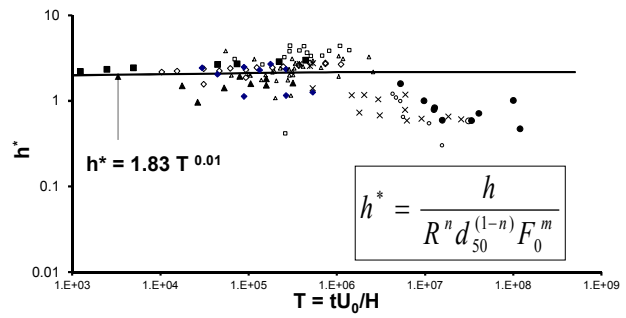


Fig. 10 Proposed scaling variables on maximum height of ridge

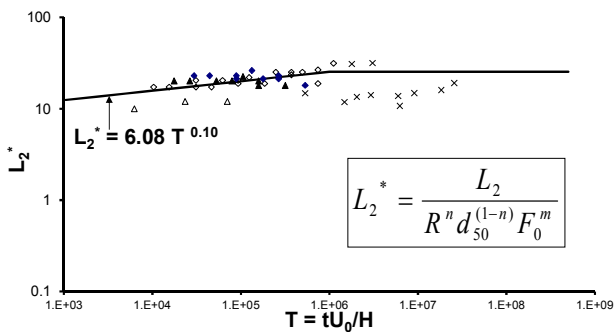


Fig. 7 Proposed scaling variables on distance of maximum width of scour hole from the nozzle

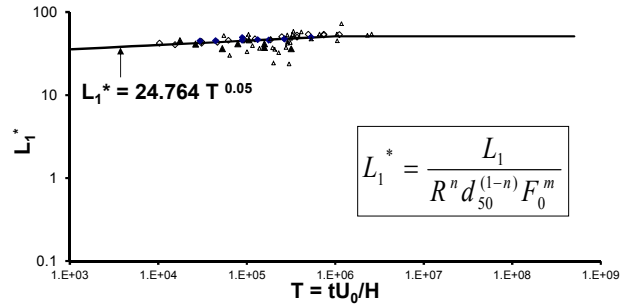


Fig. 11 Proposed scaling variables on distance of ridge end from the nozzle

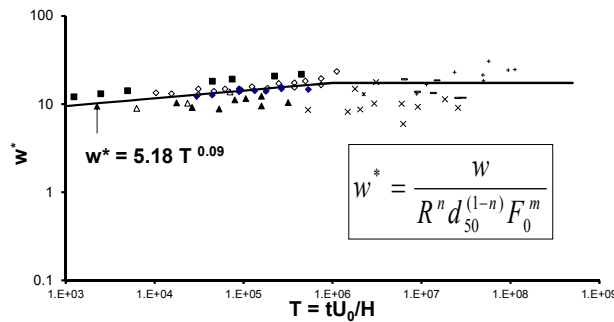


Fig. 8 Proposed scaling variables on maximum width of scour hole

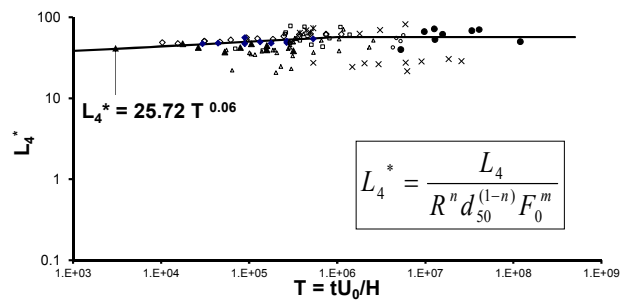


Fig. 12 Proposed scaling variables on distance of maximum ridge height from the nozzle

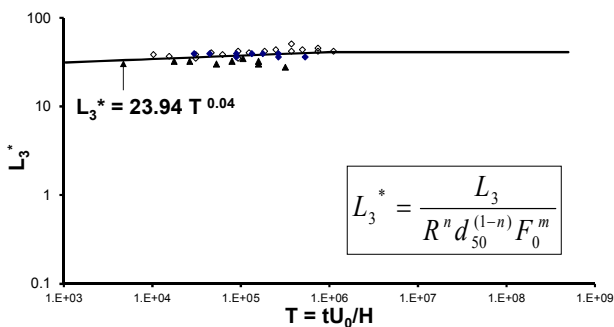


Fig. 9 Proposed scaling variables on distance of maximum ridge width from nozzle

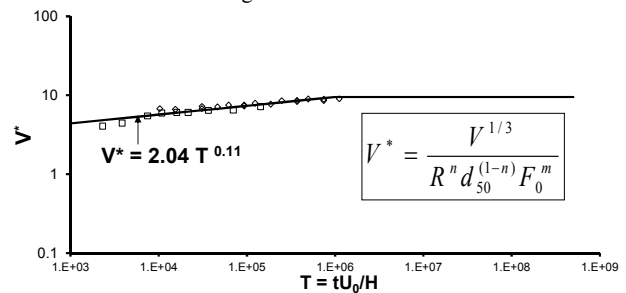


Fig. 13 Proposed scaling variables on volume of scour

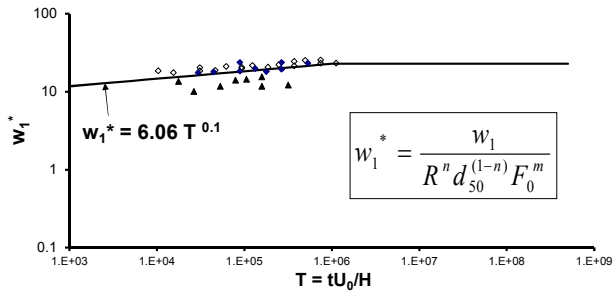


Fig. 14 Proposed scaling variables on maximum ridge width

- ◇ Present, Test A, B, C
- △ Present, Test J
- Reference [4], Ali & Lim (1986), Square=51mm
- Reference [2], Rajaratnam (1981), Plane
- + Reference [5], Lim (1995), B/d=67, Circular
- + Reference [5], Lim (1995), B/d=5, Circular
- × Reference [3], Ade & Rajaratnam (1998), Circular
- Reference [6], Rajaratnam & Diebel (1981), B/d=86, Circular
- Reference [6], Rajaratnam & Diebel (1981), B/d=1, Circular
- Present, Test D, F, H
- ▲ Present, Test E, G, I
- Reference [7], Rajaratnam & Macdougall (1983), Plane
- * Reference [8], Chiew & Lim (1996), Circular
- Reference [5], Lim (1995), B/d=10, Circular
- ◊ Reference [9], Aderibigbe & Rajaratnam (1998), Plane
- × Reference [10], Rajaratnam & Berry (1977), Circular
- Reference [6], Rajaratnam & Diebel (1981), B/d=3~3.5, Circular
- Reference [10], Rajaratnam & Berry (1977), Circular(Test 332)

Fig. 15 Legends used in Figs. 3 to 14

IV. CONCLUSION

The present study deals with scour caused by three-dimensional jets issuing from a square nozzle onto a sand bed. The suggested set of scaling parameters based on nozzle hydraulic radius, grain size and densimetric Froude number provides for a better scaling of the time variation of the scour. The suggested empirical prediction of scour is useful to predict the scour centre line profile and plan view of scour profile at any particular time.

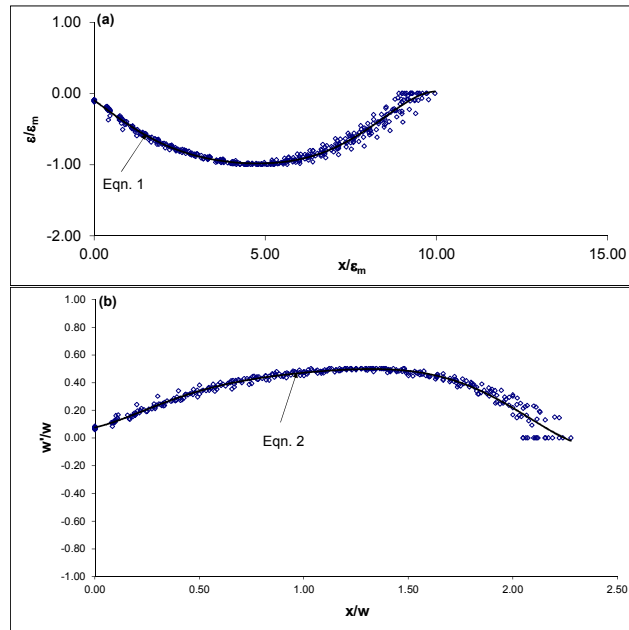


Fig. 16 Empirical prediction of scour profiles, (a) centre line profile. (b) plan view of scour hole

REFERENCES

- [1] Faruque, M. A. A., Sarathi, P., and Balachandar, R. (2006). "Clear water local scour by submerged three-dimensional wall jets: Effect of tailwater depth." *Journal of Hydraulic Engineering*, 132(6), 575-580.
- [2] Rajaratnam, N. (1981). "Erosion by plane turbulent jets." *Journal of Hydraulic Research*, Vol. 19, No. 4, pp.339-358.
- [3] Ade, F. and Rajaratnam, N. (1998), "Generalized study of erosion by circular horizontal turbulent jets", *Journal of Hydraulic Research*, Vol. 36, No. 4, pp.613-635.
- [4] Ali, K. H. M., and Lim, S. Y. (1986). "Local scour caused by submerged wall jets." *Proc. of the Instn. of Civil Engrs., Part 2*, 81, pp.607-645.
- [5] Lim, S. Y. (1995). "Scour below unsubmerged full-flowing culvert outlets." *Proc. of the Institution of Civil Engineers, Water Maritime and Energy*, Vol. 112, pp.136-149.
- [6] Rajaratnam, N., and Diebel, M. (1981). "Erosion below culvert-like structures." *Proc., 5th CanadianHydrotechnical Conf., May26-27, Canadian Society for Civil Engineering (CSCE)*, pp.469-484.
- [7] Rajaratnam, N. and Macdougall, R.K. (1983), "Erosion by plane wall jets with minimum tailwater", *Journal of Hydraulic Engineering*, Vol. 109, No. 7, pp.1061-1064.
- [8] Chiew, Y.M. and Lim, S.Y. (1996), "Local scour by a deeply submerged horizontal circular jet", *Journal of Hydraulic Engineering*, Vol. 122, No. 9, pp.529-532.
- [9] Aderibigbe, O., and Rajaratnam, N. (1998). "Effect of sediment gradation on erosion by plane turbulent wall jets." *Journal of Hydraulic Engineering*, Vol. 124, No. 10, pp.1034-1042.
- [10] Rajaratnam, N., and Berry, B.(1977). "Erosion by circular turbulent wall jets." *Journal of Hydraulic Research*, Vol. 15, No. 3, pp.277-289.