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Prediction of Progressive Penetration of Scour Hole into the Tributary Channel in Laboratory Channel Confluences

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Abstract: Confluences are basic building blocks in river networks at all scales. When two rivers merge at a confluence, rapid changes in fluid velocity and turbulence intensity cause changes in the bed geometry. Usually, a deep scour hole and a depositional point bar are present at the confluence. One important phenomenon that has been overlooked in previous studies is the progressive penetration of the scour hole into the tributary channel. This progressive penetration may jeopardize the structural safety of the lateral channel in the proximity of the main channel. In this study, dimensional analysis techniques are used to develop a general equation for the prediction of maximum scour hole penetration (P_{sc}) into the tributary. Eventhough, the penetration of the scour hole into the lateral channel is a time-dependent process, in developing the formula the maximum value after the equilibrium condition has been achieved is used. A series of 73 experimental tests with different confluence angle (θ), lateral to downstream channel discharge ratio (Q_r), lateral to main channel width ratio (B_r) and downstream densimetric Froude number (F_g) in an asymmetrical confluence has been conducted to test the proposed formulation. The results show that P_{sc} increases with Q_r, θ and F_g and decreases with B_r. The degree of penetration defines two types of scour holes: In the first type the scour hole penetration only reaches the toe of the lateral channel wall closer to the downstream junction corner whereas in the second type the scour hole reaches both lateral channel walls. The second type is associated with higher values of Q_r, θ and F_g and lower values of B_r. Statistical analysis showed that the mean error of the developed formula is of the order of 24%.

Key words: River confluence, scour hole, laboratory experiments, sediment transport

INTRODUCTION

Confluences are basic building blocks in river networks at all scales. When, two rivers merge at a confluence, rapid changes in fluid velocity and turbulence intensity cause changes in the bed geometry. Usually, a deep scour hole and a depositional point bar are present at the confluence. One important phenomenon that has been overlooked in previous studies is the progressive penetration of the scour hole into the tributary channel. This progressive penetration may jeopardize the structural safety of the lateral channel in the proximity of the main channel. The flow pattern, scour and sedimentation in confluences is complex and has attracted the attention of many researchers.

Past work on river channel confluences can be classified into two main groups. The first group consists on theoretical and experimental studies focusing on flow characteristic without the inclusion of sediment transport, such as Webber and Greated (1966), Lin and Soong (1979), Best and Reid (1984), Ramamurthy *et al.* (1988), Hager (1989), Gurram *et al.* (1997), Hsu *et al.* (1998a, b), Bradbrook *et al.* (1998), Lane *et al.* (1999), Weerakoon *et al.* (1991), Biron *et al.* (1996), Weber *et al.* (2001) and Huang *et al.* (2002). These studies have considered parameters such as depth ratio, separation zone dimensions, hydraulic jump conditions or three-dimensional flow effects. The second group includes the analysis of sediment transport (Mosley, 1976; Best, 1988; Roy *et al.*, 1988; Biron *et al.*, 1993, 2002; Rhoads and Kenworthy, 1995, 1998; Rhoads and Sukhodolov, 2001; Bryan and Kuhn, 2002; Boyer *et al.*, 2006; Parsons *et al.*, 2007; Ghobadian and Shafai Bejestan, 2007; Ghobadian *et al.*, 2007). Concentrating on confluence scour, sediment transport and bed morphology, effects of bed discordance, shear layer turbulence and mixing.

The effects of confluence angle and momentum and discharge ratios have been taken into account in several studies but the effects of tail water depth and bed grain size have received less attention. None of the previous studies has concentrated on progressive penetration of scour hole into the tributary channel and developed a relation for prediction of the maximum value of it, as proposed herein.

DIMENSIONAL ANALYSIS

In river confluence, many variables can affect the scour hole and point bar dimensions and maximum penetration of scour hole into the tributary channel. To developed general relation for predicting maximum value of penetration of scour hole into the tributary channel, one may consider the following dependence:

$$P_{sc} = f(Q_2, Q_3, B_2, B_3, \theta, S_o, V_3, \rho_s, \rho, g, \mu, \Delta Z) \tag{1}$$

Applying dimensional analysis theory, the following non-dimensional equations can be developed (Ghobadian, 2007):

$$\frac{P_{sc}}{B_3} = f\left(\frac{Q_2}{Q_3}, \frac{B_2}{B_3}, \theta, S_o, F_g, Re, \frac{\Delta z}{B_2}\right) \tag{2}$$

In these equations Q_2 and Q_3 are flow discharges in the lateral channel and in the main channel downstream of the confluence, respectively, B_2 and B_3 are the corresponding channel widths, θ is the confluence angle, S_o is the bed slope, F_g is the densimetric Froude number and R_e is the Reynolds number downstream of the river confluence. F_g is computed as $V_3/[g\,(G_s-1)\,D_{50}]^{0.5}$, with V_3 being the flow velocity downstream of the confluence, g the acceleration of gravity. G_s the specific gravity of the sediment and D_{50} the median particle size, while R_e is equal to $\rho V_3 Y_3/\mu$ with ρ and μ representing density and dynamic viscosity of water, respectively. Δz is the bed elevation difference.

All experimental tests in this study have been carried out under subcritical conditions and therefore the bed slope has no significant effects on the flow patterns (Gurram *et al.*, 1997). For high Reynolds number and rough boundaries, the Reynolds number effect can also be disregarded. In this study B_2 and B_3 were kept constant and Δz was set equal to zero. Therefore, Eq. 2 is reduced to the following form:

$$\frac{P_{sc}}{B_3} = f\left(\frac{Q_2}{Q_3}, F_g, \theta, \frac{B_2}{B_3}\right) \tag{3}$$

Equation 3 is the basis for the analysis of the experimental data.

EXPERIMENTAL SETUP AND METHODOLOGY

The experimental setup consists of a main flume 9 m long with 75 cm deep for the first 2 m and 45 cm for remaining 7 m and 35 cm wide and a lateral flume 3 m long, 45 cm deep and either 15, 25 or 35 cm wide. Both flumes had a horizontal slope. At the upstream end of each flume a stilling box was installed to reduce the kinetic energy of the entrance flow. A head tank provides a

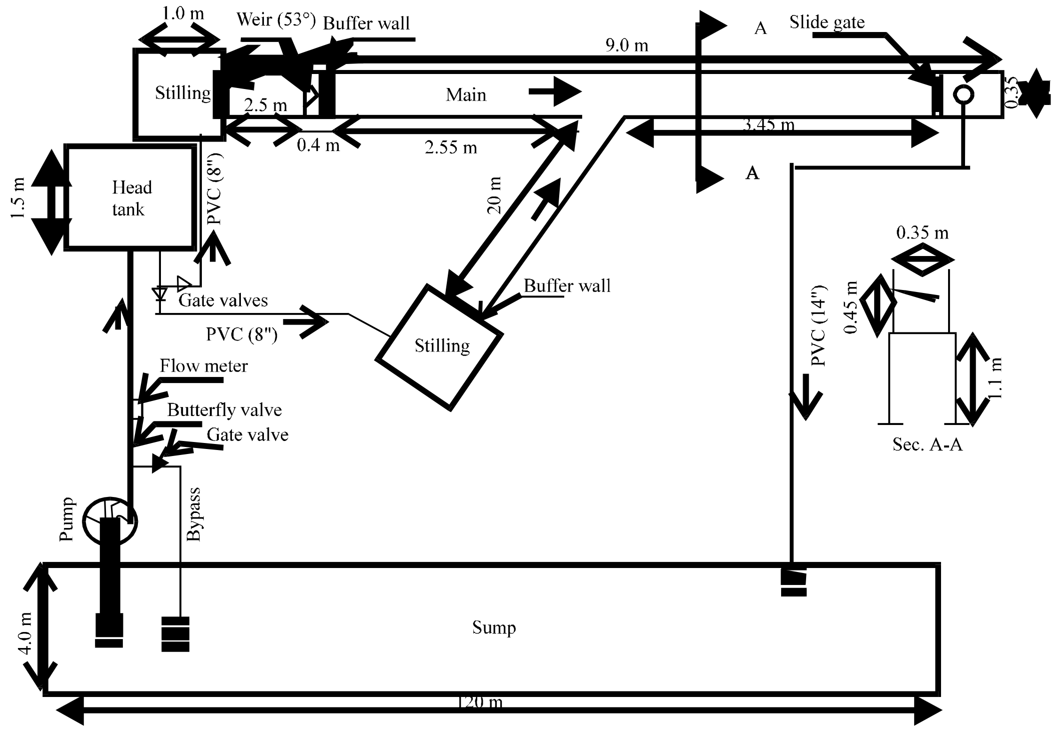

Fig. 1: Plan view of experimental set up

constant discharge to both stilling boxes. Discharge is measured by an electronic flow meter with an accuracy of 0.01 L sec^{-1}. At the end of the main flume, a sluice gate controls the downstream water depth. The lateral flume was connected to the main flume at three different confluence angles, i.e., 60°, 75° and 90°. This study was conducted in hydraulic laboratory at Shahid Chamran University, Ahvaz, Iran during 2005-2007. Figure 1 shows a plan view of the experimental setup.

An 11 cm layer of uniform sediment was laid on both channel beds. There was no sediment feeding or recirculation in these experiments. In order to extended the densimetric Froude number range, three different sizes of sediment (D_{50} = 1.05, 1.95 and 3.41 mm) were used. At the start of each run the flumes were filled slowly, keeping the tailwater gate closed. When, the flow depth was high enough to avoid initial disturbances on the bed, the flow discharges were increased to the desired values and the tailwater gate was gradually opened until the desired flow depth was achieved. This situation was kept unchanged for 5 h or until the scour hole dimensions remained constant. At the end of the run the pump was shut down, the water was drained and the bed topography was measured using surveying equipment.

RESULTS AND DISCUSSION

Maximum penetrations of scour hole into the tributary channel from 73 experiments were gathered during this study. Penetration is defined as the distance from the main channel of the furthest point in the tributary where any appreciable scour can be observed. Table 1 shows the range of the relevant dimensionless variables covered by the experiments.

As has shown in Fig. 2, the degree of penetration defines two types of scour holes, in the first type the scour hole penetration only reaches the toe of the lateral channel wall closer to the downstream junction corner (Fig. 2a) whereas, in the second type the scour hole reaches both lateral channel walls (Fig. 2b). The second type is associated with higher values of Q_r, θ and F_g and lower values of B_r.

Figure 3 shows that the penetration of the scour hole into the lateral channel is a time-dependent process, as the scour hole depth increase with time during the experiment. Parallel lines in Fig. 3 show the slope of scour hole during the experiment is almost constant and

Table 1: Range of variables in this study

Parameter	Value
Width ratio (B_r)	0.428, 0.714, 1.0
Confluence angle (θ)	60°, 75°, 90°
Discharge ratio (Q_r)	0.2, 0.33, 0.5, 0.66, 0.8
Densimetric Froude number (F_g)	1.79-4.4

Fig. 2(a-b): Penetration of scour hole into tributary channel. (a): Scour hole reaches the toe of the lateral channel wall closer to the downstream junction corner and (b): Scour hole reaches both lateral channel walls

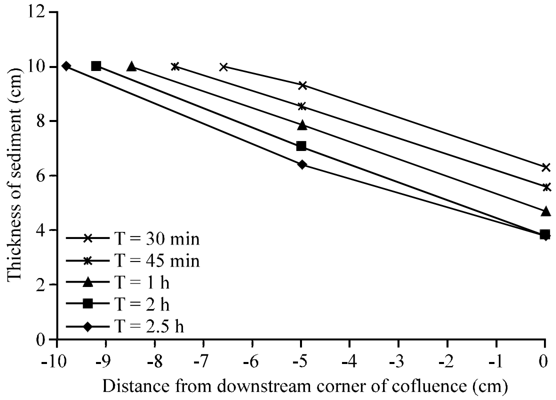

Fig. 3: Time-dependent penetration of scour hole into tributary channel

it is not time dependent. Maximum values of penetration where recorded after equilibrium of the scour was achieved.

The results corresponding to one set of the experimental tests are presented in Fig. 4-6. All other sets showed similar trends. In this study five different discharge ratios $Q_r = Q_2/Q_3$ were analyzed and it can be seen that the discharge ratio has a significant effect on the scour hole penetration development. Figure 4a shows the variation of relative penetration (P_{sc}/B_3) with the discharge ratio Q_r showing that as Q_r increases, the ratio of (P_{sc}/B_3) increases. This is because as the scour hole becomes larger, the equilibrium condition of its slope results in more penetration into the tributary.

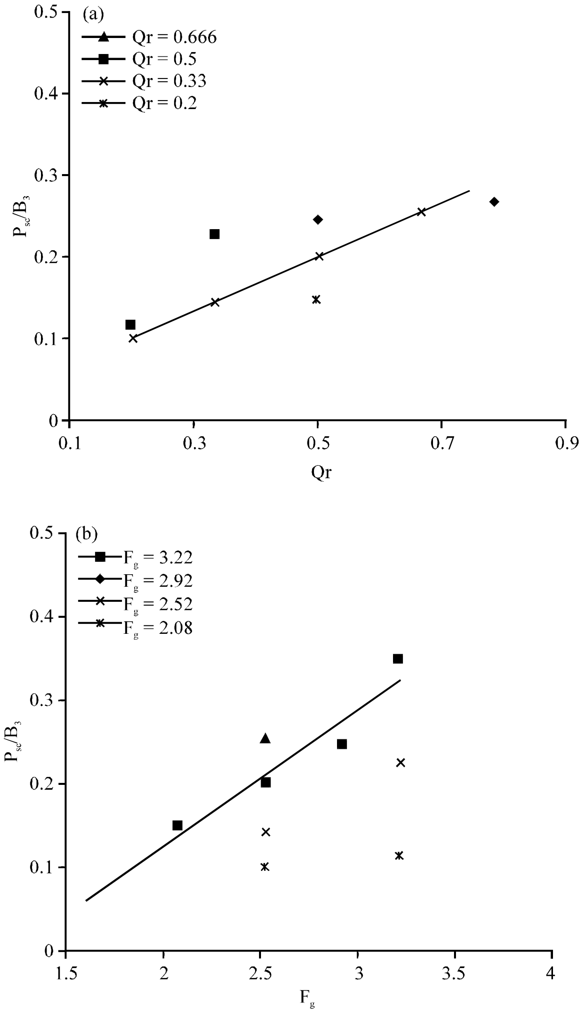

Fig. 4: (a-b) Variation of relative penetration (P_{sc}/B_3) with densimetric Froude number F_g; (a) with the discharge ratio Q_r and (b) with the discharge ration of F_g

The effect of the downstream densimetric Froude number on (P_{sc}/B_3) is shown in Fig. 4b, where it can be observed that the maximum penetration of scour hole into the tributary channel increases as F_g increases. This behavior is due to an increase on the flow transport capacity for smaller sediment sizes (which decreased in sized as F_g increased) and results in a larger (and deeper) scour hole.

The variation of the maximum penetration of scour hole into the tributary channel with confluence angle is presented in Fig. 5, showing an increase of P_{sc}/B_3 with θ. This can be explained by the size of the separation zone that forms downstream of the confluence, which is minimal for small confluence angles and increases as the tributary becomes more perpendicular to the main channel. For larger separation zones the effective wide of the postconfluence channel is reduced and increased flow velocity causes more scour.

Figure 6 shows the variation of (P_{sc}/B_3) with the width ratio B_2/B_3, showing a reduction of bar height with

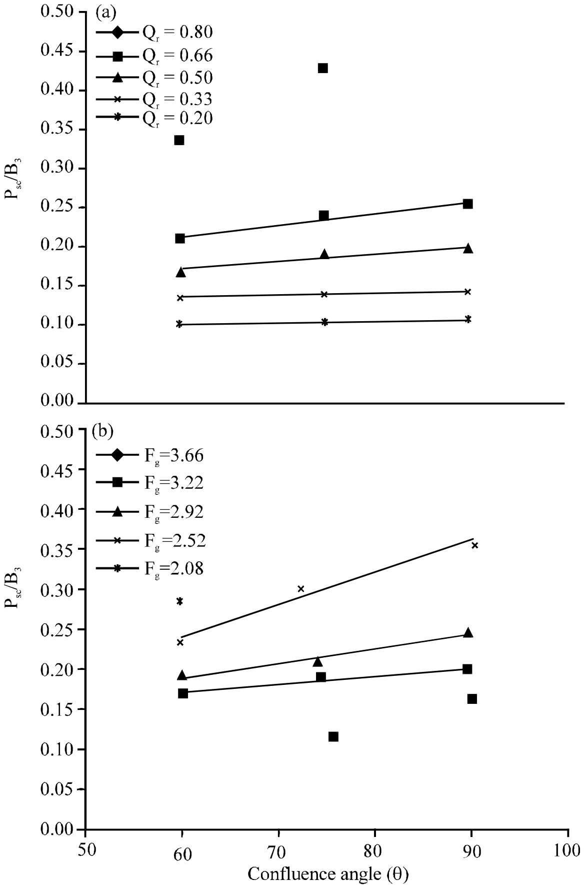

Fig. 5(a-b): Variation of relative penetration (P_{sc}/B_3) with confluence angle θ, (a): in different Q_r and (b): in different F_g

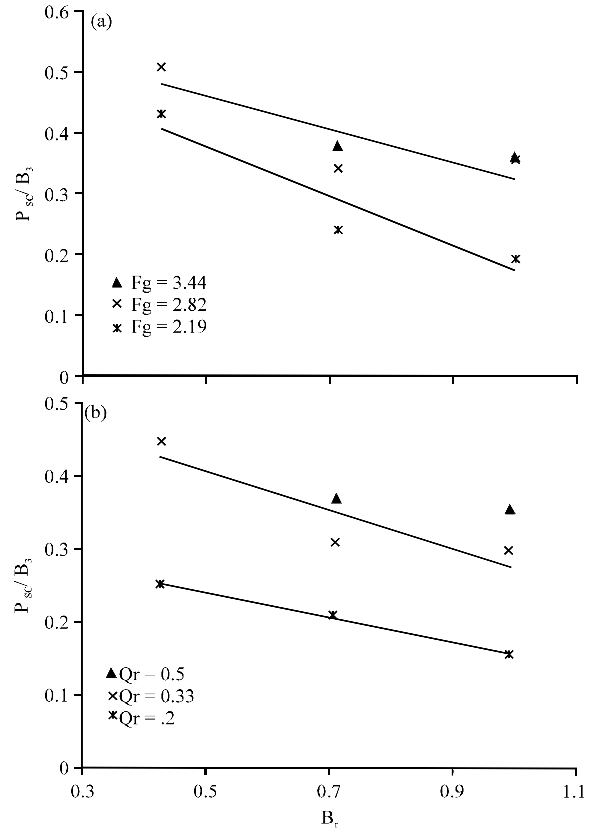

Fig. 6(a-b): Variation of relative penetration (P_{sc}/B_3) with ratio B_2/B_3; (a): In different Q_r and (b): In different F_g

an increase in B_2/B_3. This trend results from a decrease in the momentum of the lateral channel when the width ratio increases (all other parameters being constant) and a consequent reduction of scour hole depth and penetration.

SCOUR HOLE PENETRATION EQUATION

To develop a relation for the prediction of the maximum penetration of scour hole into the tributary channel at river confluences, the following equation was obtained by multiple regressions on the experimental data (r = 75.96%):

$$\frac{P_{sc}}{B_3} = 0.08Qr^{1.182}F_g^{1.505}B_r^{-1.1}(\frac{\theta}{90})^{1.556} + 0.048 \tag{4}$$

The range of applicability of Eq. 4 is given by the values of Table 1 and it must be noted that it is valid when there is no movement of bed material upstream of the channel confluence.

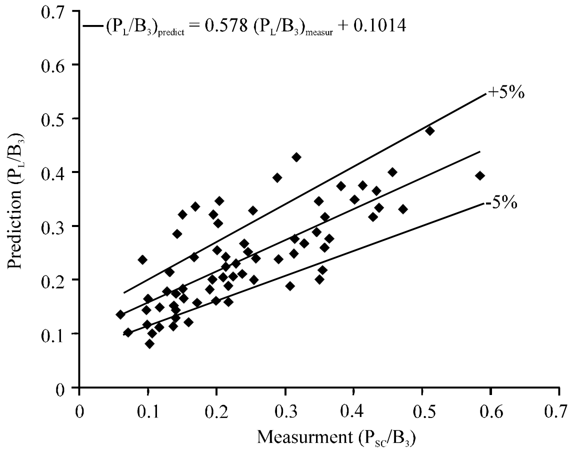

Fig. 7: Observed values of relative penetration of scour hole versus predicted values by Eq. 4

To investigating the accuracy of Eq. 4, observed values of relative depositional bar height have been plotted against the predicted values and the results are presented in Fig. 7. As, it can be seen from this figure most of data are between the 95% confidence bands statistical analyses. The relative error of the equation is about 24%. This means that Eq. 4 can be applied for as a guide in the prediction of maximum penetration of scour hole into the tributary channel in river confluences. The form of Eq. 4 clearly shows that the width ratio has a negative effect while the other parameters have positive effect on the relative penetration of the scour hole.

CONCLUSIONS

In this study and for the first time, a general dimensionless equation for the prediction of maximum penetration of scour hole into the tributary channel at river confluence has been developed. A series of 73 experimental tests with different confluence angle (θ), discharge ratio (Q_r), width ratio (B_r) and downstream densimetric Froude number (F_g) in an asymmetrical confluence have been conducted to test the proposed formulation. The results showed that the maximum penetration of scour hole into the tributary channel increases with increasing ratio of lateral channel discharge to total discharge. confluence angle and downstream densimetric Froude number. while it decreases with increasing width ratio. A relationship has also been developed that has a 24% relative error for prediction of scour hole penetration in to the tributary channel.

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