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Local scour around submerged bell mouth groin for different orientations

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Abstract

Groins are the most popular techniques for riverbank stabilization that are constructed along the channel bank to locally change river conditions, thereby creating a flow condition that promotes navigability and diverts the flow away from the bank. An experimental study was undertaken in a 45.6m long and 2.45m wide laboratory water basin to investigate the local scour around a bell-mouth groin structure. A total number of 12 test runs were performed for different flow conditions. Three different discharges and four different angles with submerged groin condition were considered in the present study. Therefore, twelve tests were conducted with submerged condition of which six had a water depth of 22 cm and the rest six had a flow depth of 26 cm. All tests were conducted for 8 hours duration in clear water condition. In order to avoid the ripple formation, the coarse sand with d_{50} = 0.75 mm was selected as bed material. Scour depth for 90^o angled groins was observed to be the maximum and for 135^o it was the minimum. The time to reach maximum scour depth was found to vary with discharge and angle of attack. The study also revealed that maximum scour depth and deposition pattern is changed with changing the condition of flow and groin orientations. Scour depth varied with velocity variation of flow, and an increasing tendency of scour depth has been observed with increasing flow intensity. Maximum scour depth shows an increasing trend with increasing Froude number.

Keywords: Local Scour, Submerged Groin, Bell Mouth Groin

1. Introduction

Groins are structures constructed in rivers to maintain a suitable measure for bank protection and flood control. Recently groins have been received more attention from the standpoint of ecosystem. The design, location, orientation and length of groins are very important subjects for the hydraulic engineers in the field. Basically, it is important to have a clear picture of scour phenomenon around these structures in order to be able to make a safe and economic design. Also, hydraulic conditions such as velocity, water depth, bed shape, and bed material around groins are so diverse to provide the ecosystem with suitable habitat. The development and magnitude of local scour for different angle of attacks are still undefined, though local scour is of utmost importance to the design of any type of groin. The foundation should be able to sustain the maximum scour depth around the mouth of groin. In Bangladesh, failure of bell mouth groin often occurred due to excessive scouring. From the engineering point of view, one is always interested in determining the potential scour so that the provision can be made in design and construction (Chang, 1988). The engineer is often called to design bank protection and conveyance channels that must maintain stability while subject to scour. Groins are structures that are constructed along the channel bank to locally change river conditions, thereby creating a flow condition that promotes navigability and diverts the flow away from the bank. As one of the most popular techniques for riverbank stabilization, groins have already been enjoyed a wide use in a number of riverbank stabilization projects and with a strong tendency to increase its applicability (Shields et al., 1995).

Over the past several years, there has been a rapid expansion of literatures concerning groins under clear water scour condition in both laboratory experiment and numerical simulation (Rahman and Muramoto 1999, Ishigaki and Baba 2004, Zhang 2005, Raudkivi and Ettema 1977); Live-bed scour around spurdykes (Zhang et al. 2005); Local scour formulae around piers and groins (Anawaruzzaman 1998, Islam et al. 2002); River course stabilization by groin like structures (Khaleduzzaman 2004); River bank stabilization in a bend by groin (Hossain 1981, Khan 1983, Sarker 2001); Velocity distribution in groin fields (Muto et al. 2005); Exchange process between river & its groin fields (Uijttewaal et al. 2001) etc. Hasan (2003) investigated the local scour at the toe of protected embankment. Kabir (2007) investigated the scour reduction technique and flow pattern around abutment using bottom vanes. Khatun (2001) conducted an experiment on local scour around bridge pier using cohesive and non-cohesive bed materials and established an empirical relationship to estimate local scour. Rahman et al. (2001, 2002) investigated flow field and scouring around piers and abutments.

From the foregoing discussion it is apparent that most of the above studies were concerned with pier, embankment, abutment, groin and spur-dikes mainly for assessment of local scour which is very frequently used in Bangladesh. But the development of scientific guiding principles for the bell mouth groin design is yet not fully explained. The reason is that bell mouth groin is typical in the India subcontinent including Bangladesh. The flow structure and scour development around bell mouth groin is of great interest for the design of riverbank stabilization projects in Bangladesh. In the present study, which is exploratory and experimental in nature, the scour around the single groin is investigated for submerged condition.

Groins are classified according to the method and material of construction, i.e. permeable and impermeable. The permeable and impermeable are self explanatory are differentiated by the ability of the construction material to transmit flow. Permeable groin slow down the current while impermeable groins deflect the current. Permeable groins are most effective on alluvial streams with considerable bed load and high sediment concentration, which favour rapid deposition around the groins. Groins vary depending on their action on the stream flow. They may be classified as attracting, deflecting or repelling groins. Groins may be further classified according to their appearance of plan. Straight groin is set at some angle from the bank and has a head to provide extra volume and area for scour protection at the outer end. T-head groin has a straight shank with a rectangular guide vane at the outer end. The angle at the bank is normally 90^o. L-head groin or wing or trail groins have larger sediment deposits between groins, less scour at their head, provide greater protection to the banks and are more effective in channelization for navigation when the length closes 45 to 65 percent of the gap between the groins. Hockey shape groins have scour holes that are more extensive in area than the T-shape groins and do not appear to have any advantages over the other shapes (Richardson et al., 1975). Straight groin with pier head was designed and executed to dig and stabilize artificial pools for salmon and trout migration and fishing.

In some locations groins are constructed higher than the high water level, which are called non-submerged groin. In other locations groins are submerged under the water surface. In rivers with unsteady flow conditions, groins can serve as non-submerged in ordinary state or submerged during flood. The area behind the groin is either a dead zone during non-submerged conditions or a slow flow zone during submerged flow conditions. Most of previous investigators published experimental data on the various aspects of the local scour around emerged spur dikes. In their experiments, they have used flow depths that were less than the height of the spur-dike model, (Ahmed 1953; Liu et al. 1961; Garde et al. 1961; Laursen 1963; and Gill 1972).Recent studies have included Rajaratnam and Nwachukwu (1983), Melville (1992). Many prototype spur dikes, however, were designed to regularly consider overtopping flow, submerged condition. A few studies were presented for submerged groin, such as the study of Kuhnle et al. (1999), Kuhnle et al. (2002). In the present study an attempt has been made to investigate the scour around submerged bell mouth groin with different discharges and different groin orientations.

2. Dimensional Analysis Approach

Dimensional analysis is a mathematical technique which makes use of the study of dimensions as an aid to the solution of several engineering problem. Each physical phenomenon can be expressed by an equation, composed of variable (or physical quantities) which may be dimensional and non-dimensional quantities. Dimensional analysis helps in determining a systematic arrangement of the variables in the physical relationship and combining dimensional variables to form non-dimensional parameters.

An attempt has been made to establish relationship between maximum scour around the head of bell mouth groin and various parameters that affect scour. Non-dimensional parameters that control predominantly the scour effects were developed using Rayleigh method. For this, the Rayleigh method has been used for dimensional analysis. The variables considered are the scour depth (h_s), water depth (y), groin angle of attack (α), the approach flow velocity (V_a) and acceleration due to gravity (g). But the groin angle of attack (α) is not a physical dimension and it was not considered in the dimensional analysis.

Let, $$h_s = f(V, y, g) \tag{1}$$

or, $$h_s = f(V)^a\,(y)^b(g)^c$$

where a, b, c are dimensional constant

Applying dimensions of the variables, the equation (1) can be written as:

$L = f\,(LT^{-1})^a\,(L)^a\,(LT^{-2})^b = f\,(L)^{a+b+c}\,(T)^{-a-2c}$

And solving for a, b, c, we get

$$h_s = f(V)^{-2c}(y)^{1+c}(g)^c$$

$$or\ \frac{h_s}{y} = f\left(\frac{gy}{V^2}\right)^c = f\left(\frac{1}{F_r^2}\right)^c$$

The final form of the non-dimensional functional relationship can be obtained

$$\frac{h_s}{y} = f\left(\frac{1}{F_r^2}\right) \tag{2}$$

Equation (2) shows that the relative scour depth (h_s/y) is a function of Froude number (F_r).

3. Experimental Procedures

The experiments have been carried out in a wide straight flume which is 45.60 m long, 2.45m wide and having a depth of 1m. The flume has a re-circulating water supply system with pre-pump storage pool, measuring devices, tail gates and stilling basin etc. The water passed through an approach upstream reservoir provided with a series of baffles. These baffles distributed the flow uniformly over the entire width of the flume and also helped in dissipating the excess energy of flow. The sand bed had a thickness of 30 cm. The sand used in the experiments reported herein has mean size of d_{50}= 0.75 mm and standard deviation of σ_g= 1.94. The groin models used in the study were fabricated by wood. The groin model was bell mouth type. The groin was positioned with different angle of inclination of θ = 60°, 90°, 135° and 150° with the downstream. Before the beginning of each run the sand bed was leveled corresponds to Z=0. Three different discharges were considered in the present study. Total 12 (twelve) tests were conducted with submerged condition of which 6 (six) had a water depth of 22 cm and the rest six had a flow depth of 26 cm. To obtain a specific discharge, water level was maintained by adjusting the tailgate on downstream. The water discharge has been measured on a routine basis at half hour intervals by sharp-crested Rehbock weir located at the re-circulating canal. The discharge has been calculated from reading of point gauge in the adjacent stilling basin using the following equation.

$$Q = \frac{2}{3} C_d L_{weir} \sqrt{2g}\,(\Delta H)^{\frac{3}{2}} \tag{3}$$

The free flow has been ensured only at the downstream weir and coefficient of discharge (C_d) has been calculated to be 0.6.

Table 1
Experimental Program

Test no.	Angle of inclination in degree (anti-clockwise)	Froude number (F_r)	Discharge Q (lit/sec)	Water depth y (cm)
S11		0.237	170	
S12	150	0.209	150	22
S13		0.182	130	
S21		0.201	170	
S22	135	0.177	150	26
S23		0.154	130	
S31		0.237	170	
S32	90	0.209	150	22
S33		0.182	130	
S41		0.201	170	
S42	60	0.177	150	26
S43		0.154	130	

3.1 Scour measuring technique

The changes in the bed topography around the groin were measured with the help of the bed level measuring instrument. Each run was ended after getting equilibrium state for local scour (8 hours). Details of selected experimental runs are given in Table 1. Each test was designated by certain notations. For example, test no.1 is designated by S11, it means that the test were conducted at a discharge of 170 l/s, submerged condition with the groin placed at 150^{o} angle in direction towards downstream. All others tests have been similarly designated.

Scour data have been collected forming grids in the selected area around bell mouth groin on the dry bed. In one test run, 1225 scour data have been collected hence for 12 test runs total scour data was 14700.

3.2 Velocity measurement

Flow velocity measurements were obtained by using programmable electromagnetic velocity meter (P-EMS) consisting of a 50 mm-diameter probe and a control unit, mounted on a movable measuring carriage. The sensor of this instrument measured two dimensional velocity fields. Water depths were measured at one-hour intervals by the help of a point-gauge mounted on a wooden frame.

3.3 Co-ordinate system

A Cartesian co-ordinate system has been chosen and used during the experimentation in the flume as shown in Fig. 1.

The origin of this coordinate system has been set at the lengthwise midpoint of the flume right wall face at the initial bed level. The X-direction was defined along the length of the flume sidewalls. The positive direction was selected in the downstream direction from the origin, whereas, negative direction is in the upstream direction from the origin. The value of X was read from tapes fixed over both right and left wall of the flume.

The Y direction was defined along the direction perpendicular to the right wall at the origin towards the mid channel. Y=0 is situated precisely at the face of the right wall of the flume. The positive direction was directed towards the mid channel. The value of Y was measured with the help of tapes fixed with the bed level measuring instrument as well as with the measuring bridge.

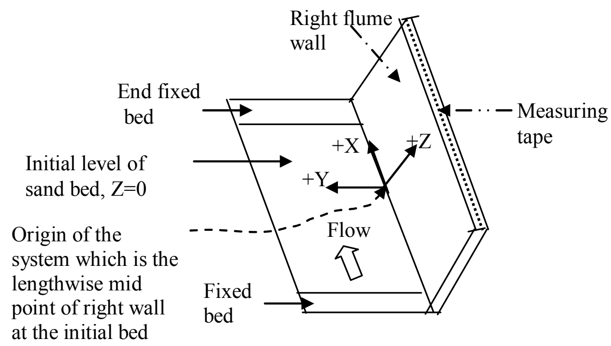

Figure 1. Coordinate system used in the experiment

The Z direction corresponds with the direction perpendicular from the initial bed level, where Z=0. The changes of the initial bed level, i.e. scouring and depositions were measured with respect to this level. It is to be mentioned that, all the levels could be compared to a pre-defined reference level which has been used in the previous researches as well. For this purpose, a bolt with a round head was mounted on the flume sidewall. The top of the head is at an elevation of 100 cm above the reference level. All other elevation used in this model setup is related to this reference level.

3.4 Bell mouth groin dimensions

Groin was installed on the bed surface with a width of 32.5 cm, is tapering vertically and the top width was lowered to 12.5 cm, shown as (Section 1-1 in Fig. 2). The height of groin above the bed surface is 20 cm and below the bed level was 40 cm. The top diameter at head of the groin is 15 cm and at the base on the bed level is 35 cm, shown as (Section 2-2 in Fig. 2). Shank and head slope is 2V:1H. The base of the groin at the bed level is extended up to 103.5 (63.5+40) cm towards the channel middle perpendicular to the right wall.

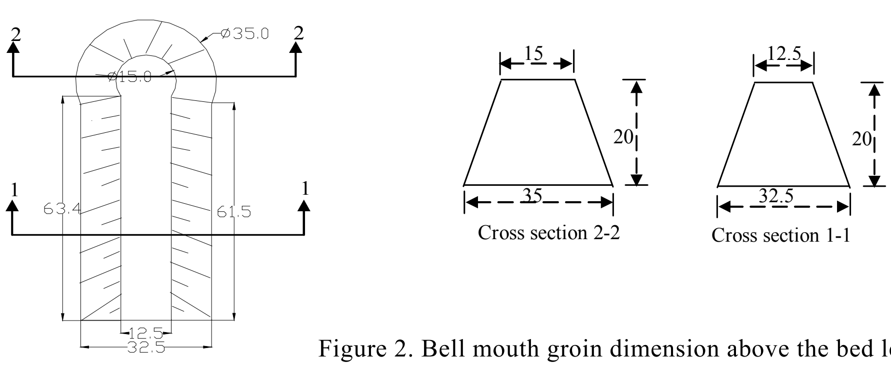

Figure 2. Bell mouth groin dimension above the bed level (all the dimensions are in cm)

3.5 Orientations of groin

Four types of bell mouth groin orientation were considered in the present study. These were 150°, 135°, 90° and 60° angles from the right bank of the channel (counter clockwise direction). Figures 3, 4, 5 and 6 shown the orientations and dimensions of the groin angled at 150°, 135°, 90° and 60° respectively.

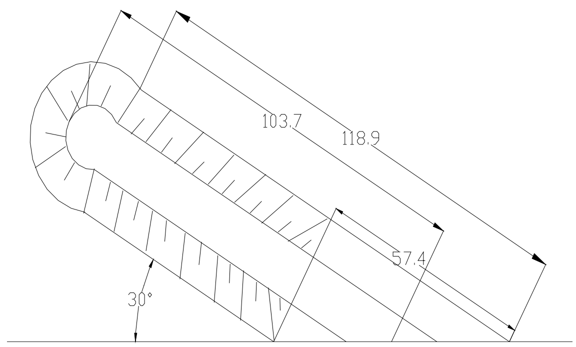

Figure 3. Bell mouth groin at 150^0 angle with right bank

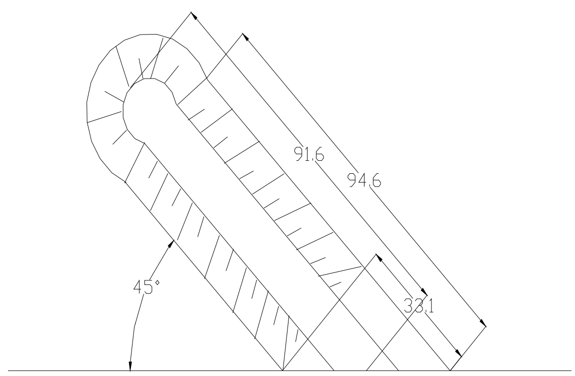

Figure 4. Bell mouth groin at 135^0 angle with right bank

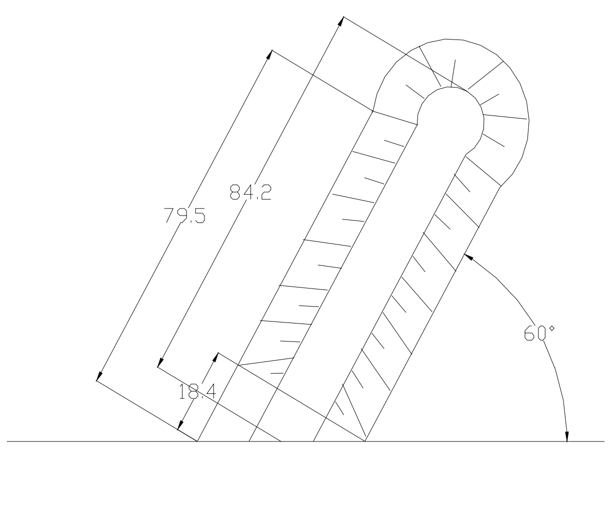

Figure 5. Bell mouth groin at 60^0 angle with right bank

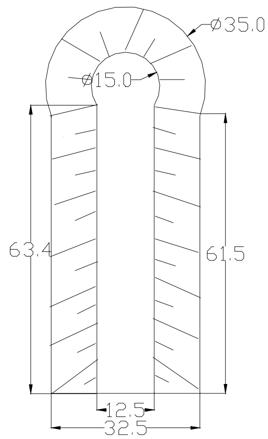

Figure 6. Bell mouth groin at 90^{0} angle with right bank.

4. Result and Discussion

4.1 Temporal variation of scour and equilibrium scour depth

Scour depth in clear water regime increases logarithmically with time upto limiting depth at equilibrium (Melville and Chiew, 1997). But in live bed regime, equilibrium depth is reached quickly. In this study, equilibrium scour depth has been observed at the defined location on the head of the bell mouth groin with the intervals of half an hour. The defined location of the equilibrium scour depth are for 150^o angle, X=-40 cm and Y=80 cm; for 135^o angle X=-10 cm and Y=90 cm; for 90^o angle, X=-25 cm and Y=90 cm; for 60^o angle X=-10 cm and Y=90 cm. Figures 7~9 show the temporal variation of scour depth and attainments of equilibrium scour for different discharges with different orientation of groins. For the entire 12 runs, scour depth for 90^o angle has been observed to be maximum and for 135^o is minimum. The case may be explained as, for 90^o angle flow velocity directly hit on the head of the groin and strong vortices were created around the head of the groin. These scour measurements with an interval of half an hour have been continued until the equilibrium has reached. In most of the cases it has been observed that the equilibrium scour has attained after a minimum of 4 to 4.5 hours of running. This equilibrium time has varied with discharge and angle of attack.

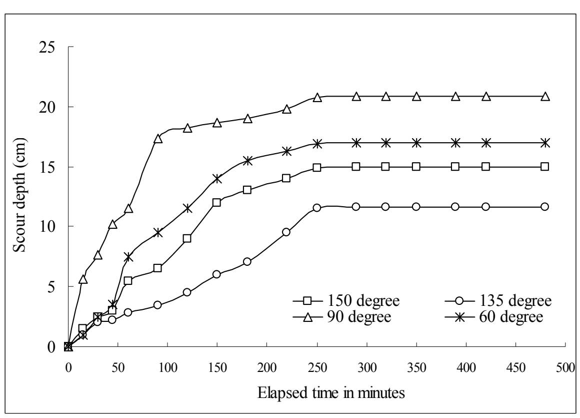

Figure 7. Temporal variation of scour depth for different groin orientations (Q=170 lit/s)

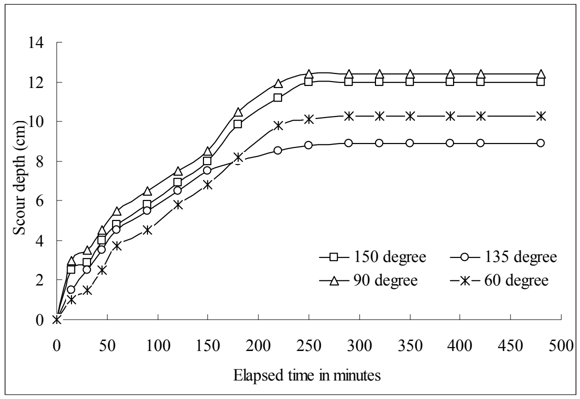

Figure 8. Temporal variation of scour depth for different groin orientations (Q=150 lit/s)

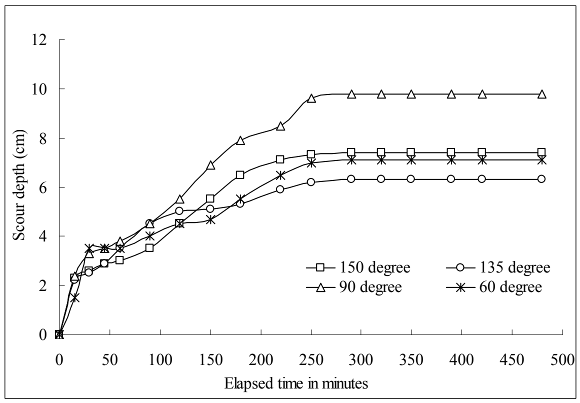

Figure 9. Temporal variation of scour depth for different groin orientations (Q=130 lit/s)

4.2 Scour and deposition contour map

2-D scour contour map indicating local scour around bell mouth groin for variable discharge are presented. Figures 10~12, 13~15, 16~18 and 19~21 represent scour maps for angles 150º (cases S11~S13), 135º (cases S21~S23), 90º (cases S31~S33) and 60º (cases S41~S43) respectively. With higher discharge scour hole slope is found steeper. Scour line intensity decreases with decreasing discharges and becomes flatter for lower discharge. In general scour hole slope is steepest around the head of the structure and gradually decreases sidewise. Slope of scour hole around head of bell mouth groin is more uniform for higher discharge than that of lower discharge. In the contour map, negative contour level indicates scour, positive value indicates the deposition, and zero indicates the original bed level.

Mostly it is observed that scour hole has maximum extent around head of the structure for higher discharge and decreases gradually with decreasing discharge. Sediment deposition is found nearer to rear face of structure for lower discharge where as sediment is deposited slightly downstream for higher discharge. Table 2 shows the maximum scour depths and their locations for various cases.

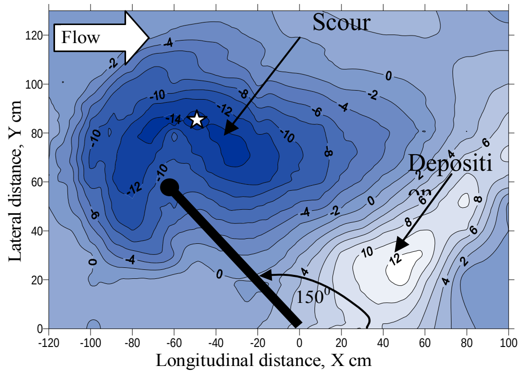

Figure 10. Final bed contour for test no. S11

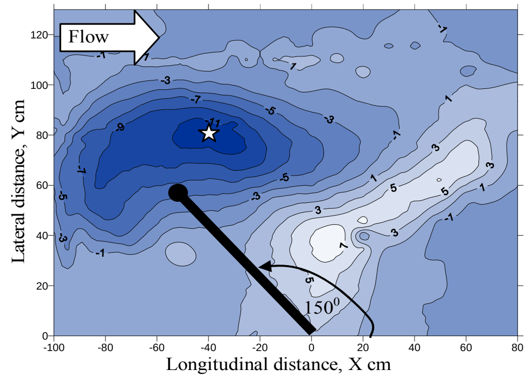

Figure 11. Final bed contour for test no.S12

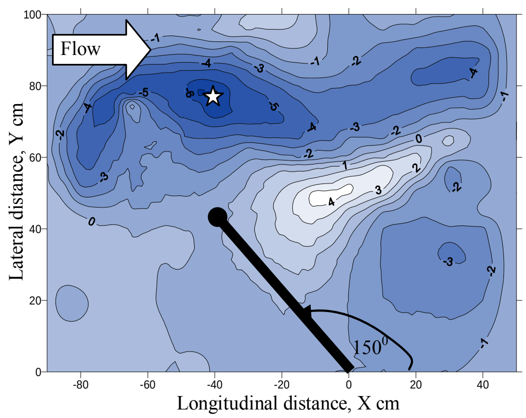

Figure 12. Final bed contour for test no. S13

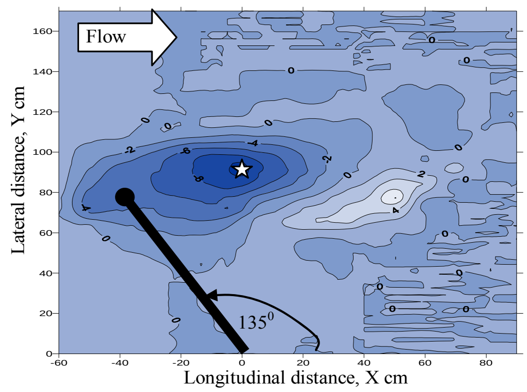

Figure 13. Final bed contour for test no. S21

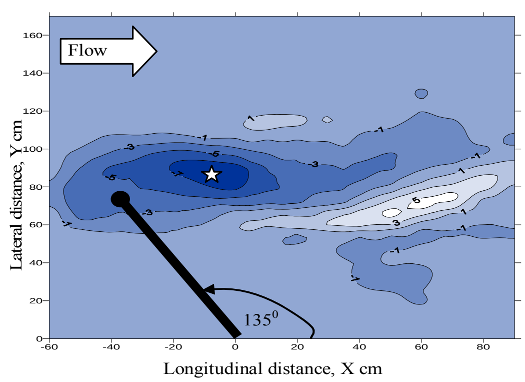

Figure 14. Final bed contour for test no. S22

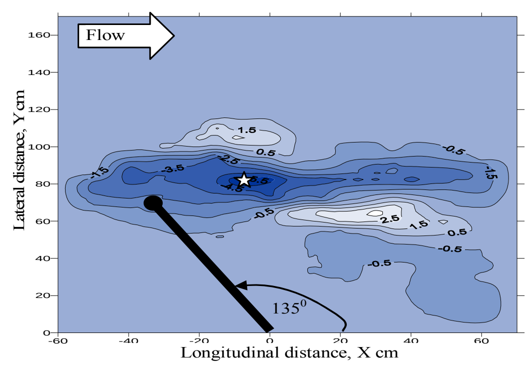

Figure 15. Final bed contour for test no. S23

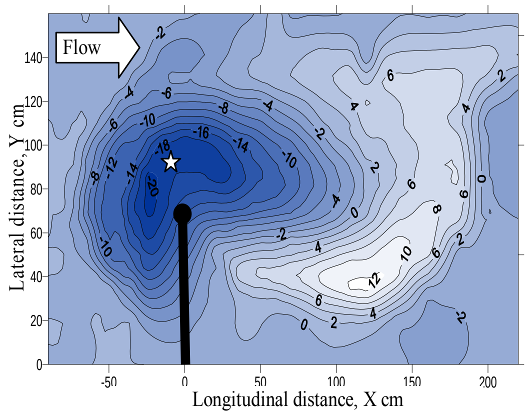

Figure 16. Final bed contour for test no. S31

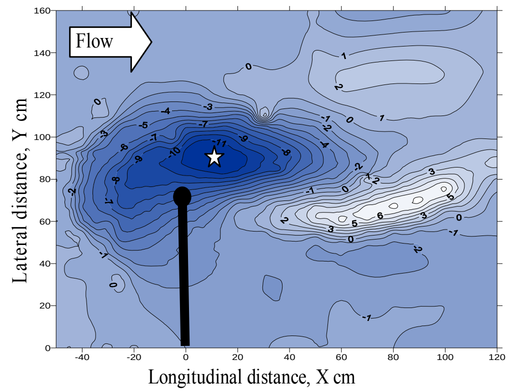

Figure 17. Final bed contour for test no. S32

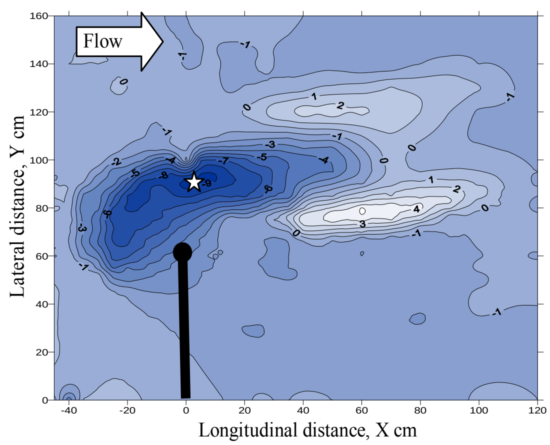

Figure 18. Final bed contour for test no. S33

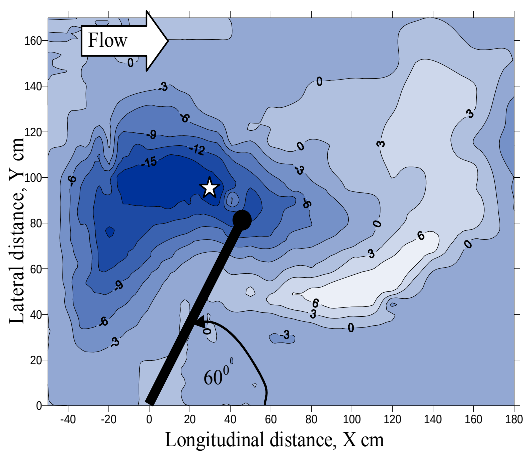

Figure 19. Final bed contour for test no. S41

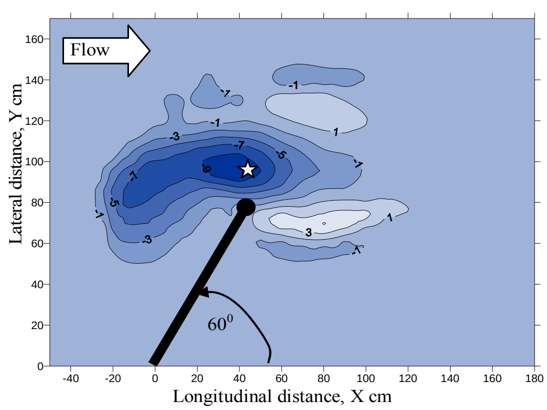

Figure 20. Final bed contour for test no. S42

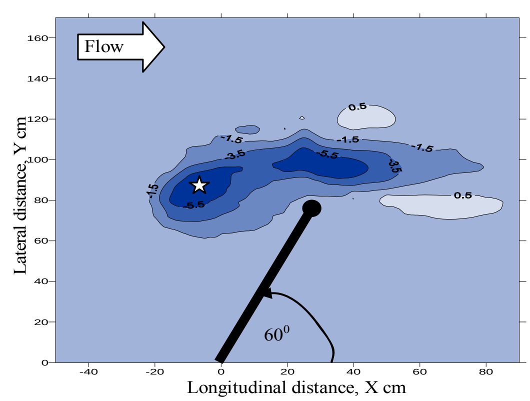

Figure 21. Final bed contour for test no. S43

Table 2
Maximum scour depth with position for various cases

Cases no.	Maximum scour depth (cm)	Position X , Y (cm)
S11	15	-30, 72.5
S12	12.6	-40, 77.5
S13	7.4	-40, 77.5
S21	11.6	0, 90
S22	8.9	-10, 90
S23	6.3	-10, 82.5
S31	20.9	-25, 72.5
S32	11.9	5, 95
S33	9.8	0, 90
S41	17	-10, 100
S42	10.3	30, 95
S43	7.1	-10, 87.5

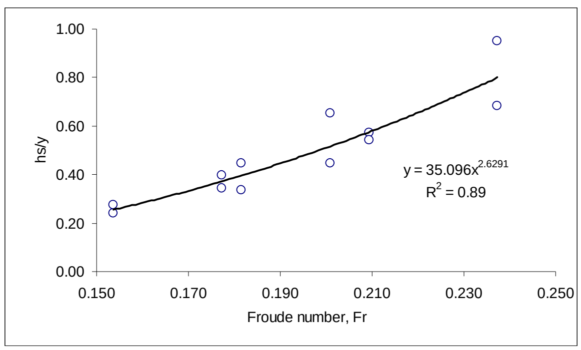

Figure 22. Variation of relative scour depth with Froude number

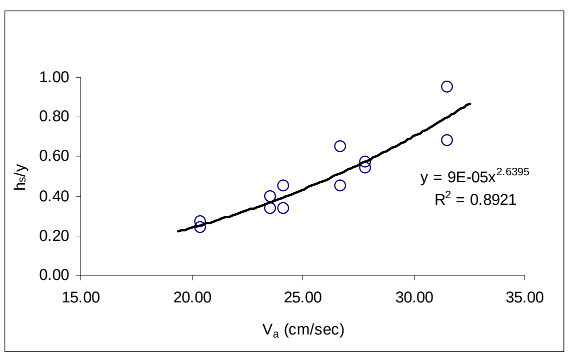

Figure 23. Variation of relative scour depth with approach flow velocity

4.2.1 Variation of maximum scour depth with Froude number

Variations of dimensionless maximum scour depth (h_s/y) with Froude number (F_r) are shown in Fig. 22. From trend line of this graphical presentation, the scour depth bears a good relationship with Froude number and it has been found that scour depth increases with increasing Froude number.

4.2.2 Variation of relative scour depth with approach flow velocity (V_a)

Variation of relative scour depth (h_s/y) with approach flow velocity (V_a) is shown in Fig. 23. From trend line of this graphical presentation, it was found that relative scour depth increases with increasing approach flow velocity.

4.3 Scour and deposition

Figure 24 shows the comparison between maximum scour depths with maximum height of depositions for each test run. Following three observations can be made from this Fig.: (i) for the same discharge, the maximum scour is occurred for 90^o angled groin. For example S11, S21, S31 & S41 has same discharge of Q=170 lit/sec and S31 represents 90^o angled groin. This scenario is also true for other discharges. (ii) The maximum depth of scour and deposition are decreases with decreasing discharge for a particular orientation. For example cases S11, S12 & S13 has same value of θ but different discharge. (iii) It is found that for 90^o orientation of groin case S31 the scour depth is relatively higher than the maximum height of deposition. As in this case, the groin is fully exposed to upstream flow, that strikes the groin in perpendicular direction the scour increases and more sediment deposited downstream of the structure. Figure 25 shows the relation between the maximum scour and the maximum deposition for all test runs. The trend line of this graphical presentation shows the linear relationship with slope less than 1. It reveals that the depth of deposition is always less than scour depth.

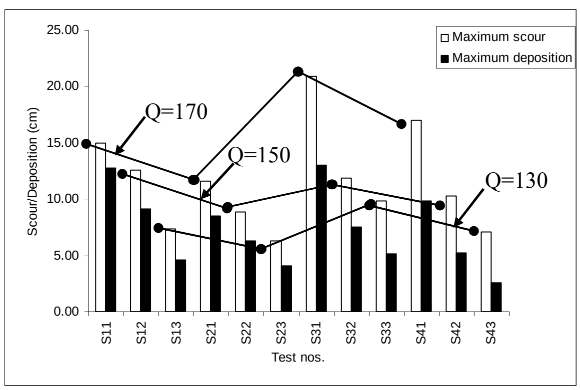

Figure 24. Scour and deposition pattern for all tests runs

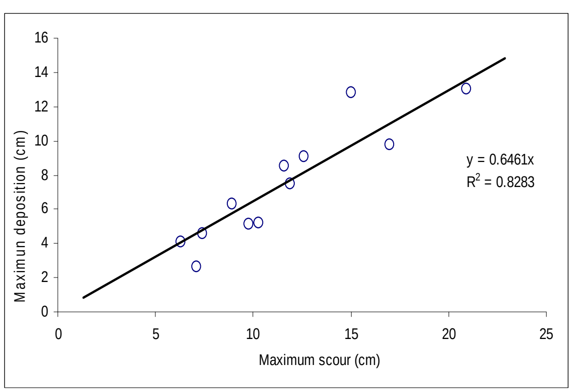

Figure 25. Relationship between maximum scour and deposition

4.4 Cross sectional bed profile

The experimental observations for the cross-sectional profiles of scour & deposition for different orientations are shown in Figs. 26~29. In order to make dimensionless, the X and Y co-ordinates has been divided by the height of the bell mouth groin (h) above the bed level.
The general scenario observed from all the Figs. is the maximum scour depth lies between Y/h=3 to 5 and the scour depth is observed to be increased with increasing discharge.

Figure 26 for 150° angle, It was found that there is no scour occurs at X/h=-4.5 for Q=130 lit/s, although scour in other flow conditions (for Q= 170 & 150 lit/s). This is because, X/h=-4.5 (90 cm upstream from the centre of the groin) is beyond the scour region for this case and the velocity is almost uniform at this section. It reveals that the scour region is shifted downstream with increasing discharge.

For 60° angle, Fig. 29 shows both deposition and scour around the bell mouth groin. Deposition starts at Y/h=0 and ends at Y/h=3 for this case. Deposition at about Y/h=2 and 6 are also observed in Fig. 28.

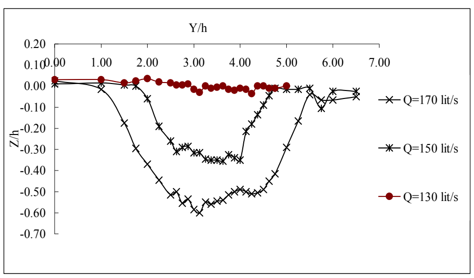

Figure 26. Transverse bed profiles at X=-90 cm for 150^0 angle

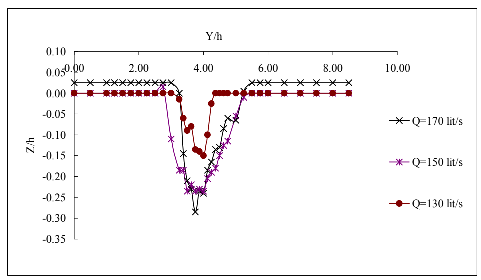

Figure 27. Transverse bed profiles at X=-50 cm for 135^0 angle

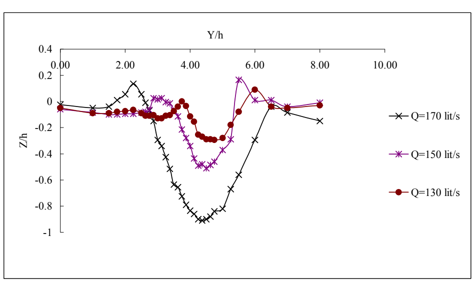

Figure 28. Transverse bed profiles at X/h=30 cm for 90^0 angle

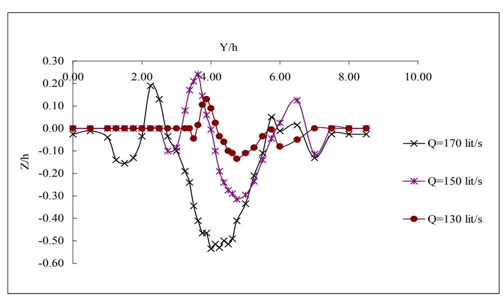

Figure 29. Transverse bed profiles at X=60 cm for 60^0 angle

4.5 Bed profiles along the longitudinal section

The longitudinal bed profile has been plotted to observe the change in bed profile along the stream wise direction at the vicinity of the head of the bell mouth groin for different discharges. These have been shown in Figs. 30-33. In these Figs. the horizontal line corresponding to Z/h=0 represents the initial bed level.

Figure 30 shows the variation of longitudinal bed profile at Y=85cm (away from the right bank) for 150^{o} angle. It shows that maximum scours starts from -7h distance and end 3h distance. After 3h distance it rises above the initial bed level i.e. starts deposition. Minimum scours starts from -3.5h distance and end at X/h=0.

Figure 31 shows the variation of longitudinal bed profile at Y/h=105 cm (cm away from the right bank) for 135^{o} angle. It shows that maximum scours starts from -4.5h distance and end 3.5h distance. After 3.5h distance it rises above the initial bed level i.e. starts deposition. Minimum scours starts from 1h and end at 3h distance.

Figure 32 shows the variation of longitudinal bed profile at Y/h=100 cm (away from the right bank) for 90^{o} angle. It shows that maximum scours starts from -5h distance and end 8h distance. After 8h distance it rises above the initial bed level i.e. starts deposition. Minimum scours starts from -1.5h distance and end at 3.5h distance.

Figure 33 shows the variation of longitudinal bed profile at Y/h=100 cm (away from the right bank) for 60^{o} angle. It shows that maximum scours starts from -4h distance and end 8h distance. After 8h distance it rises above the initial bed level i.e. starts deposition. Minimum scours starts from -1h distance and end at 3h distance.

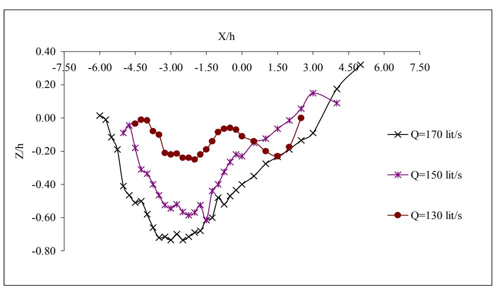

Figure 30. Longitudinal bed profiles at Y=85 cm for 150^{0} angle

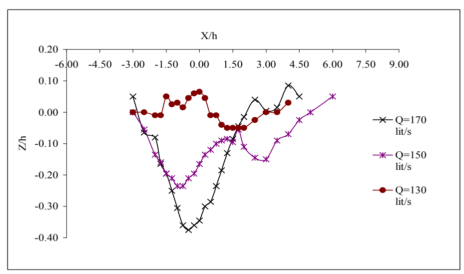

Figure 31. Longitudinal bed profiles at Y=105 cm for 135^{0} angle

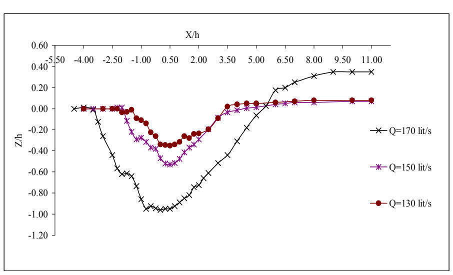

Figure 32. Longitudinal bed profiles at Y=100 cm for 90^{0} angle

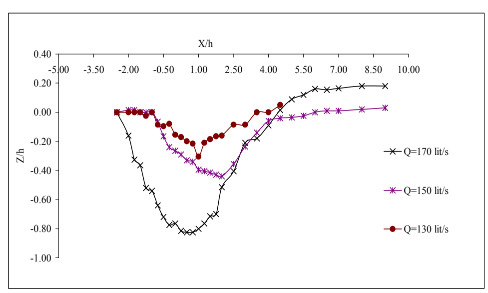

Figure 33. Longitudinal bed profiles at Y=100 cm for 60^{0} angle

5. Conclusions

Based on the detailed experimental investigation, analysis and discussion the following conclusions may be drawn:

i) Equilibrium scour depth measured around the head of the bell mouth groin shows that the scour depth for 90^o angle was the maximum while for 135^o it was the minimum. The equilibrium time to reach the maximum scour depth was found to vary with discharge and angle of attack for different test runs.

ii) From scour and deposition contour maps and their transverse and longitudinal sections, it is observed that scour hole has maximum extent around head of the structure for higher discharge and decreases gradually with decreasing discharge. Sediment deposition is found nearer to rear face of structure for lower discharge where as sediment is deposited slightly downstream for higher discharge.

iii) For the same discharge, the maximum scour is occurred for 90^o angled groin. Because in this case, the groin is fully exposed to upstream flow, that strikes the groin in perpendicular direction the scour increases and more sediment deposited downstream of the structure.

iv) The maximum deposition shows the linear relationship with slope less than 1. It reveals that the depth of deposition is always less than scour depth.

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