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An assessment of local scour at floodplain and main channel of compound channel section

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Abstract

Scour around structure is a well known problem for engineers around the world. Most of the rivers in Bangladesh are compound and alluvial in nature. Pier like structures are often constructed at floodplain of compound channel, also subjected to local scour and may cause failure of structure. A compound channel of 22 m long and 20 cm deep having one adjacent floodplain of 80 cm wide with 165 cm wide main channel was constructed to conduct this study considering relative depth ratio (Y_r) 0.26. General behavior of local scour at floodplain and main channel have been investigated for commonly used circular and round nose shaped structures by using three locally available bed materials with three discharges and four length-width ratios. Scour map, bed profile, velocity profile, flow intensity contour map and 3D perspective plots were analysed for both floodplain and main channel to evaluate comparison between floodplain and main channel scour. Generally scour behaviour are near about same at flood plain and main channel for different bed materials, discharges, structure shapes and length width ratio. But flow velocity and scour depth are always higher in main channel than floodplain. The scour depth around circular structure was highest as compared with scour depth around other shapes of structures both at flood plain and main channel. Floodplain velocity distribution is associated with vortex generation as mid of channel.

Keywords: Local scour, compound channel, floodplain, main channel, pier-like structure

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1. Introduction

Scour is the problem that leaves infrastructure such as bridge piers and bridge abutments in unsafe conditions requiring maintenance and occasionally results in loss of life. Damage of hydraulic structure is a world wide concern which is mainly caused by local scouring. Problems of local scour have been studied extensively for several decades by many investigators like temporal and equilibrium scour (Melville and Chiew, 1999; Kothiary et al, 1992a), clear water and live bed scour (Vital et al, 1994; Jain, 1981;

Kothiary et al, 1992b; Laursen, 1962), scour in uniform and non uniform bed materials (Raudkivi and Ettema, 1977), scale effect in pier scour (Ettema et al, 1998; Kabir, 1984; Shen et al, 1969) and so on. Melville (1975), Breusers and Raudkivi (1991) described local scour mechanism and made observations on horseshoe vortex generation and scour hole formation. A compound channel refers to a two-stage channel composed of both main channel and side channel in floodplain. Relative depth (Y_r) of compound channel is expressed as ratio of flow depth in side channel (floodplain) to flow depth in main channel (Lyness and Myers, 1994). Cordoso and Bettess (1999) investigated local scour at bridge abutments that extended different distances on floodplain in a two-stage channel. Hasan (2003) also conducted similar work on protrusion scour at toe of abutment. Approach channel geometry is considered to represent collectively various influences on local scour depth that occur if approach channel is compound rather than rectangular (Melville and Coleman, 2000). Melville (1995) observed that approach channel geometry can have a very significant influence on local scour depth at abutments of bridge crossing compound river channels, particularly for longer abutments where abutment extending into main channel and channel geometry effects on local scour can be represented by a multiplying factor, *K*/dG. He also showed that *K*\dG, as determined by a simple expression involving cross-section geometry and roughness of main and flood channels, is consistent with experimental data and proposed an expression for equivalent length of abutment in a compound channel. But channel geometry effects are unimportant at bridge piers as long as velocity and depth of flow used to estimate local scour depth represent flow approaching pier under consideration (Melville and Coleman, 2000). In Bangladesh, Rivers are naturally compound, consisting of a main channel and adjoining floodplains. Abutment, bridge piers and river crossing towers are often constructed on floodplains which are also subjected to local scour. Khatun (2001) conducted an experiment on local scour around bridge pier in a single rectangular channel using cohesive and non cohesive bed materials and established an empirical relationship to estimate local scour.

A number of experiments have been carried out for this study in a compound section with floodplain to investigate general behaviors of local scour at floodplain and main channel. Comparative study also has been done to assess difference between floodplain scour and main channel scour. The outcomes shall provide necessary data and information on general behavior of scour in a compound channel. It will also be able to give a comparative view between floodplain and main channel scour.

2. Experimental setup and data collection

The experiments have been conducted in Physical model facility, Department of Water Resources Engineering, Bangladesh University of Engineering and Technology (BUET). A compound channel was constructed which was 22 m long, 20 cm deep and had 165 cm wide main channel and one adjacent floodplain of 80 cm wide (Fig.1 and Fig.2). In total 36 experimental runs have been carried out for three variable discharges and three different locally available bed materials with two shapes of structures and four length-width ratio.

General behavior of local scour at flood plain and main channel has been investigated for locally available three different bed materials having sediment size (d_{50}) 0.75 mm, 0.18 mm and 0.12 mm, respectively. Grain size distribution curves and properties of these bed materials are given in Fig.3 and Table 1, respectively. Circular and round nose shapes of structure were used for experiments similar to commonly used shapes in Bangladesh.

The experiments were conducted for four pier length to pier width ratio (l/b) in which l/b=1 for circular structure and l/b=2, l/b=3, l/b=4 for round nose structure. A constant pier width has been maintained. To investigate and compare general behavior of scour at floodplain and main channel, one pier was placed in flood plain when another one having same shape and same pier length to pier width ration (l/b) was placed in main channel. The ratio

Table 1
Properties of bed materials used in experiment

Bed material	d_{50} (mm)	$d_{84.1}$ (mm)	$d_{15.9}$ (mm)	$\sigma_g = \sqrt{\frac{d_{84.1}}{d_{15.9}}}$	Comment
1	0.75	1.2	0.45	1.63	Non uniform, Non ripple forming
2	0.18	0.26	0.094	1.66	Non uniform, Ripple forming
3	0.12	0.20	0.068	1.72	Non uniform, Ripple forming

Figure 1. Layout of compound channel reach

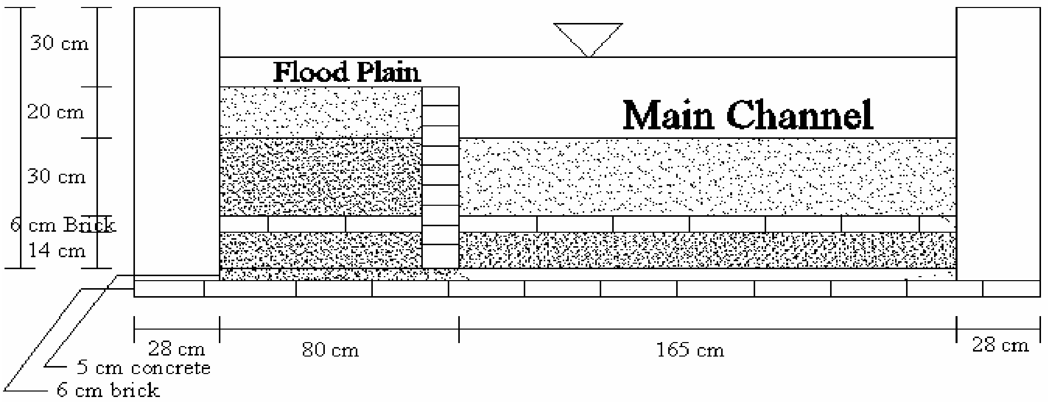


Figure 2. Schematic cross-section of constructed compound channel

V/V_a is a measure of flow intensity for scour with non uniform sediments (Raudkivi, 1986; Melville and Sutherland, 1988). The armour peak velocity, V_a, which marks transition from clear water to live bed conditions for non uniform sediments is equivalent to V_c for uniform sediments. Thus, for non uniform sediments, live bed conditions pertain when $V/V_a > 1$ (Melville and Coleman, 2000). In present study, all bed materials were non uniform. For this reason, V_a was considered as critical flow velocity (V_c) and it was determined by using following equations (Melville and Coleman, 2000):

$$d_{50a} = \frac{d_{\max}}{1.8} \tag{1}$$

$$u_{*ca} = 0.0115 + 0.0125 d_{50a}^{1.4} \text{ for } 0.1 \text{ mm} < d_{50a} < 1 \text{ mm} \tag{2}$$

$$u_{*ca} = 0.0305 d_{50a}^{0.5} - 0.0065 d_{50a}^{-1} \text{ for } 1 \text{ mm} < d_{50a} < 100 \text{ mm} \tag{3}$$

$$\frac{V_{ca}}{u_{*ca}} = 5.75 \log\left[5.53 \frac{y}{d_{50a}}\right] \tag{4}$$

$$V_a = 0.8 V_{ca} \tag{5}$$

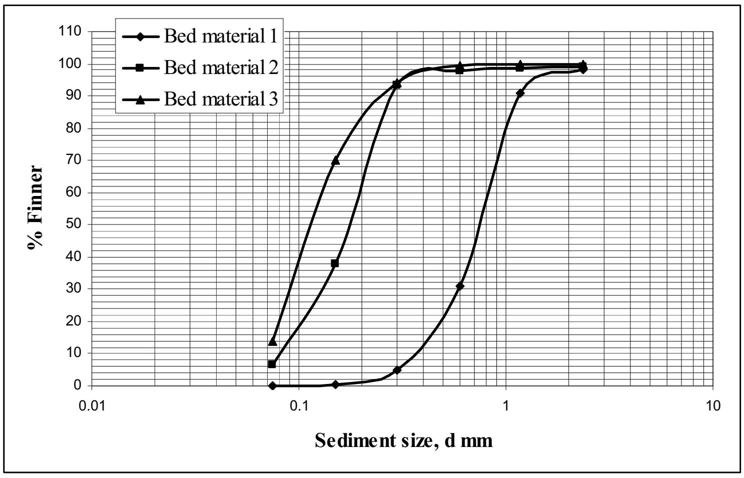


Figure 3. Grain size distribution curves

Maintaining different hydraulic parameters like velocity, bed shear stress, freeboard and water depth, three discharges (200 l /s, 175 l /s and 150 l /s, respectively) were taken into account. Uniform flow and live bed scour condition (Table 2) were maintained through out the experiment. Lyness and Myers (1994) showed that Manning's 'n' reaches a minimum value at a relative depth of 0.25 for over bank flow. Also Sturm (2004) investigated that relative depth ratio varied from 0.13 to 0.32 for compound channel having one floodplain and a main channel. A relative depth ratio (ratio of flow depth in side channel i.e. floodplain to flow depth in main channel, Y_r) of 0.26 was considered to maintain experimental condition in constructed compound channel. Total depth of flow on main channel and depth of flow on floodplain have been kept 27 cm and 7 cm, respectively. Some test runs were conducted before experiment to find out suitable test duration to attain quasi-equilibrium condition at flood plain and main channel for different bed materials and different discharges (Fig.4). Considering negligible rate of scour development and recommended maximum pump running time at a stretch, duration of each test run was selected as eight hours. Flows around circular structure and round nose structure during experimental run are shown in Fig.5.

Table 2
Experimental values of relative flow velocity with respect to critical flow velocity (V_a)

Sediment size (d_{50} mm)	Discharge (m^3/s)	Floodplain flow Velocity, (m/s)	Main channel flow Velocity, (m/s)	V/V_a	
				Floodplain	Main channel
0.75	0.200	0.224	0.425	1.12	1.50
	0.175	0.196	0.372	0.98	1.31
	0.150	0.179	0.339	0.90	1.20
0.18	0.200	0.224	0.425	1.32	1.90
	0.175	0.196	0.372	1.15	1.64
	0.150	0.179	0.339	1.10	1.50
0.12	0.200	0.224	0.425	1.30	1.86
	0.175	0.196	0.372	1.14	1.63
	0.150	0.179	0.339	1.04	1.48

Rehbock weir and accompanying point gauge in stilling basin in front of weir was used to measure discharge. Desired water level was maintained by adjusting tail gates after discharge reaching stable condition. Water level was monitored by point gauge reading, located in experimental reach.

Velocities were measured with a programmable electromagnetic velocity meter (P-EMS). Area selected for velocity measurement was 0.20 m upstream and 0.20 m downstream form centre of pier in longitudinal direction and +0.20 m to -0.20 m in lateral direction. The area was divided into grid system at an interval of 0.05 m to 0.20 m and measurements were taken at each grid point. Average velocity was obtained by placing P-EMS probe at a constant 0.6 depth from top of water surface. To develop velocity profile, 0.2, 0.4, 0.6 and 0.8 depths velocity data were also collected at (-0.5, 0) grid point.

Scour depth measurements was made with bed level measurement instrument (BLMI). Numbers of sharp edged rods were fixed with BLMI, each spaced at a distance of 2.5 cm laterally and gap between two longitudinal sections varied between 2.5 cm to 20 cm depending on nature of bed deformation. Extents of measured areas were selected depending upon extents of scour holes. Average mobile bed level was used as reference. Any data found to be below this reference point was taken as negative value and indicated scour. Similarly, any data found to be above same reference point was taken as positive value and indicated deposition.

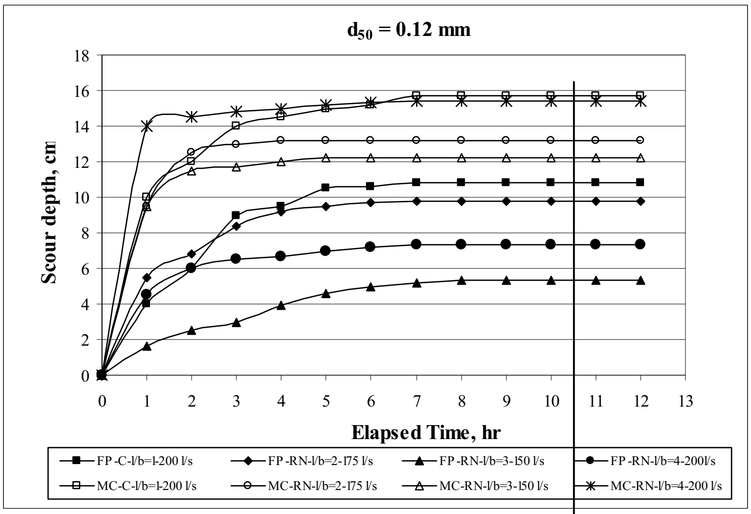


Fig.4. Scour development with time at floodplain and main channel

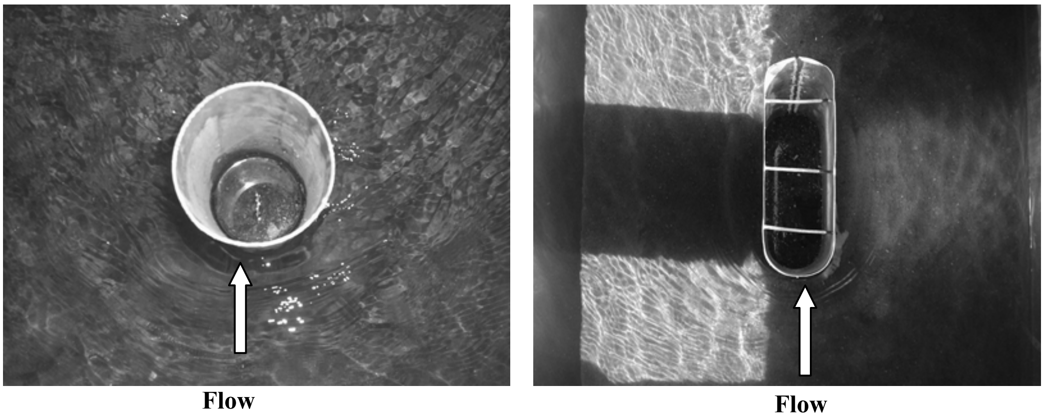


Figure 5. Flows around Circular structure and Round nose structure, respectively.

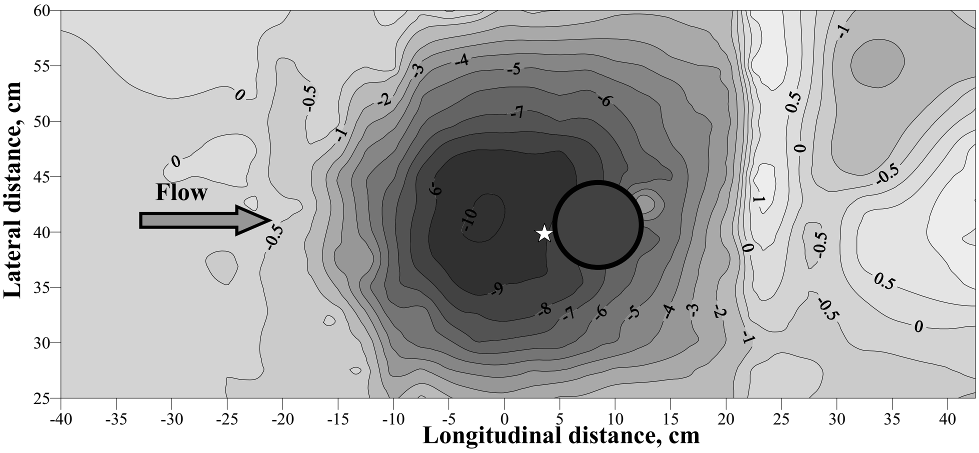


Figure 6. Scour contour map around Circular structure for d_{50} = 0.18 mm and 200 l/s discharge at floodplain

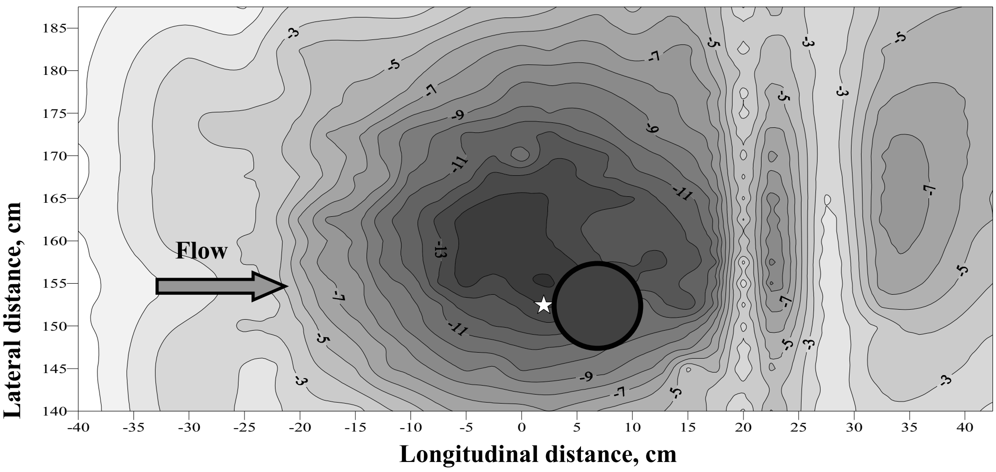


Figure 7. Scour contour map around Circular structure for d_{50} = 0.18 mm and 200 l/s discharge at main channel

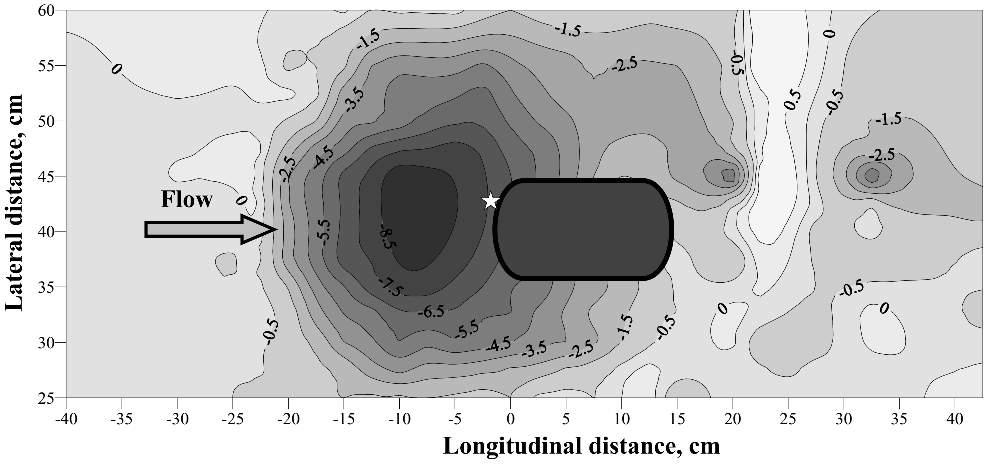


Figure 8. Scour contour map around Round nose structure for d_{50} = 0.18 mm and 200 l/s discharge at floodplain

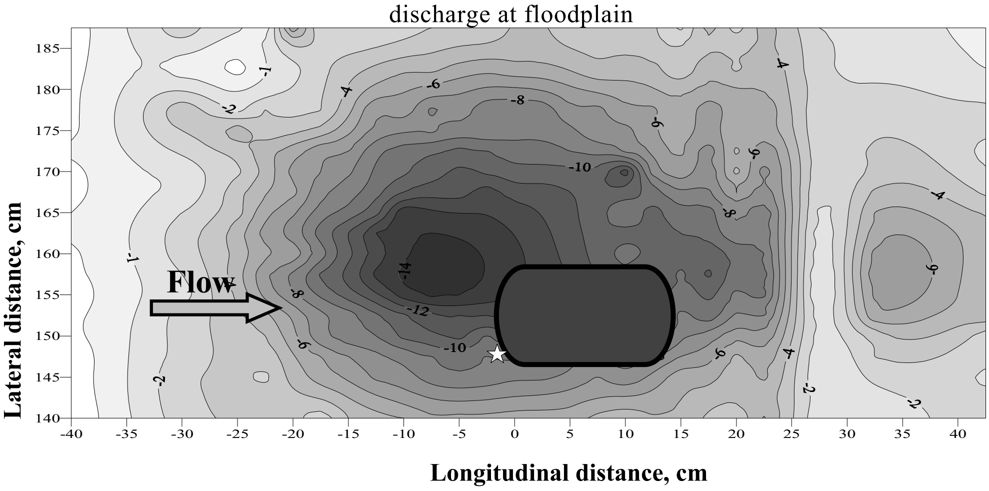
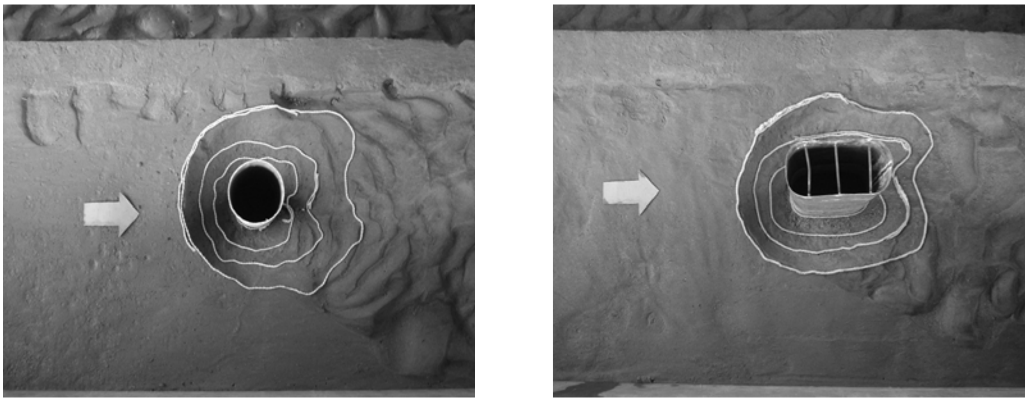
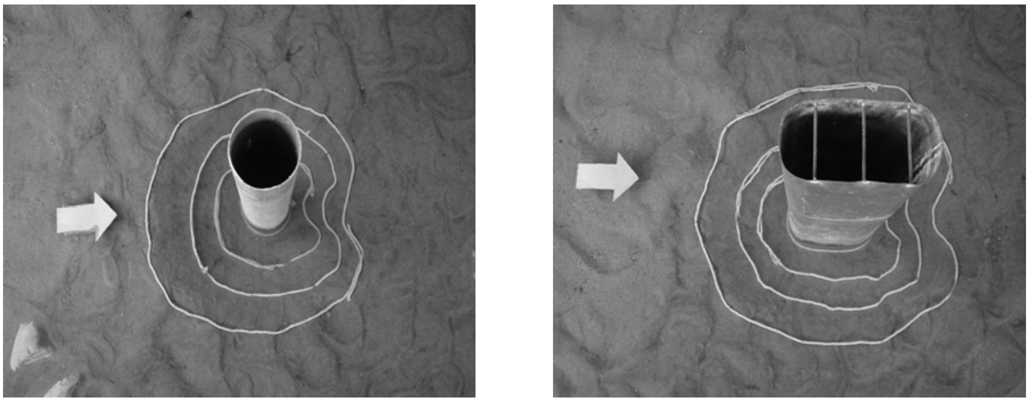


Figure 9. Scour contour map around Round nose structure for d_{50} = 0.18 mm and 200 l/s discharge at main channel



(a) Flood plain



(b) Main channel

Fig.10. Scour around Circular structure (l/b=1) and Round nose structure (l/b=2), respectively after 8 hours run for d_{50} = 0.18 mm and 200 l/s discharge at (a) floodplain and (b) main channel

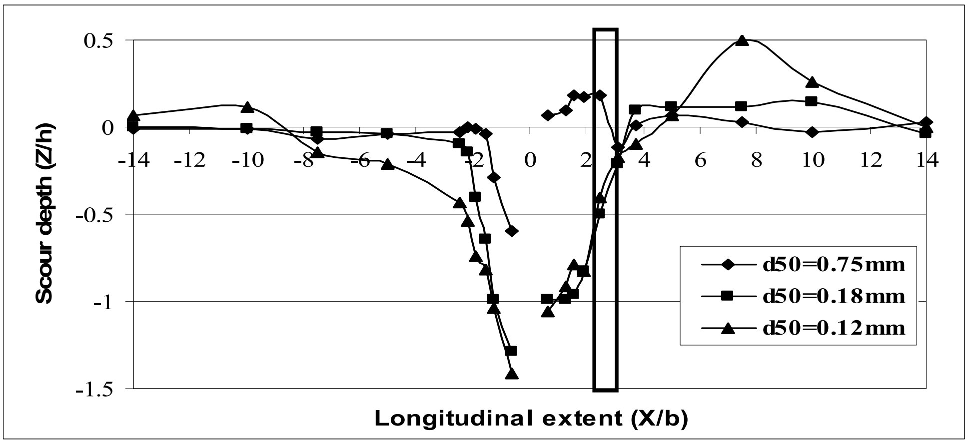


Figure 11. Bed profile variation in longitudinal direction (200 l/s discharge) at floodplain

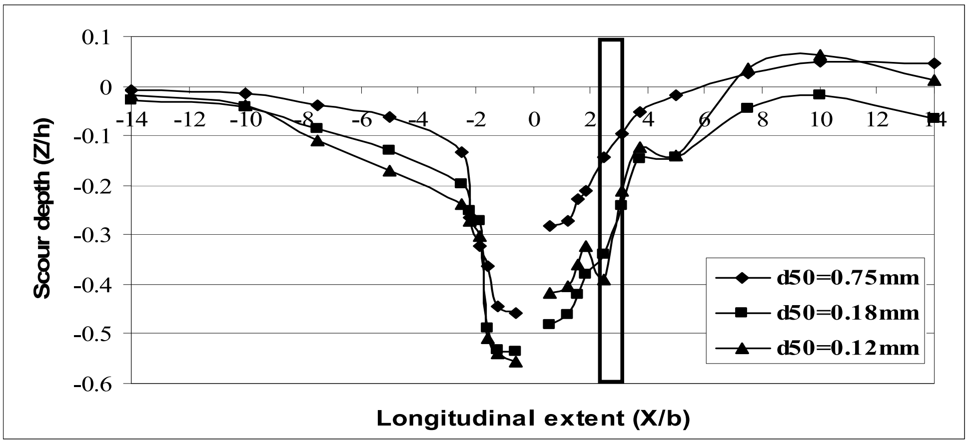


Figure 12. Bed profile variation in longitudinal direction (200 l/s discharge) at main channel

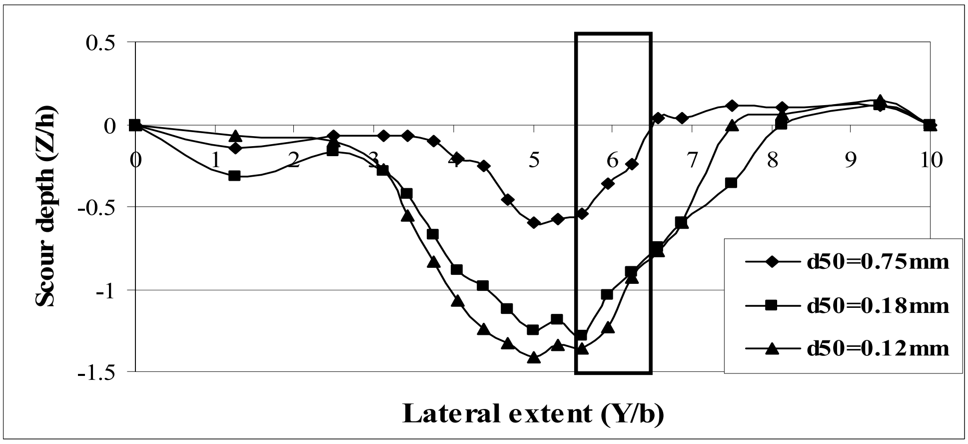


Figure 13. Bed profile variation in lateral direction (200 l/s discharge) at floodplain

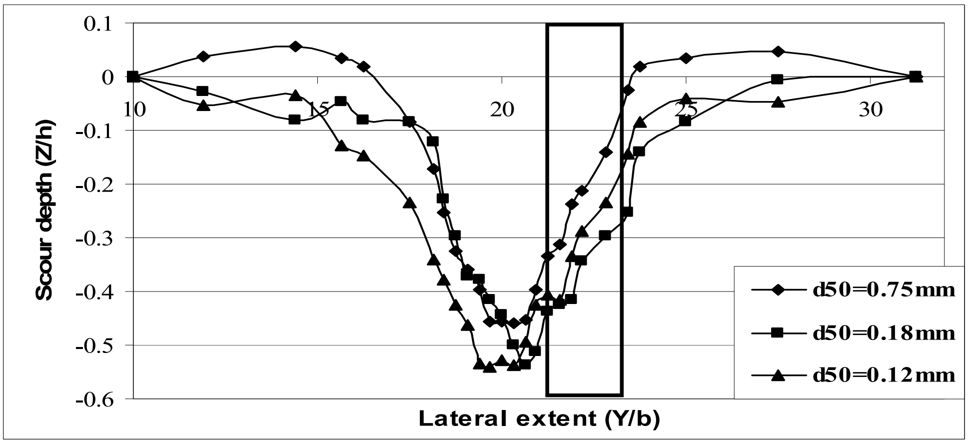


Figure 14. Bed profile variation in lateral direction (200 l/s discharge) at main channel

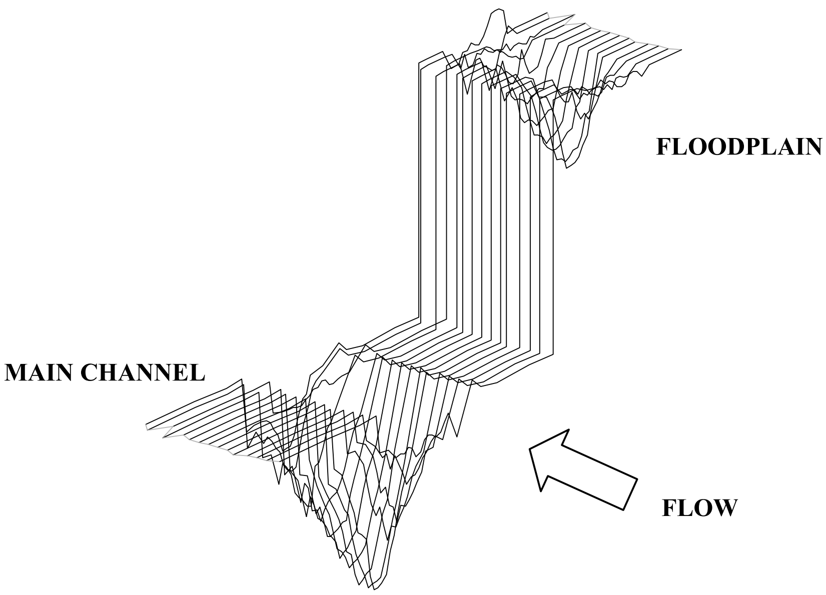


Figure 15. Three dimensional perspective plot of scour around Round nose structure (l/b=3) for d_{50} = 0.12 mm and 200 l/s discharge at floodplain and main channel

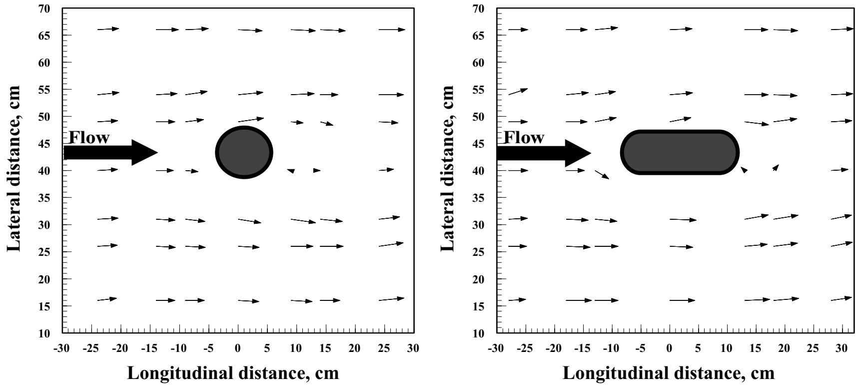
3. Results and discussions

3.1 Scour contour map

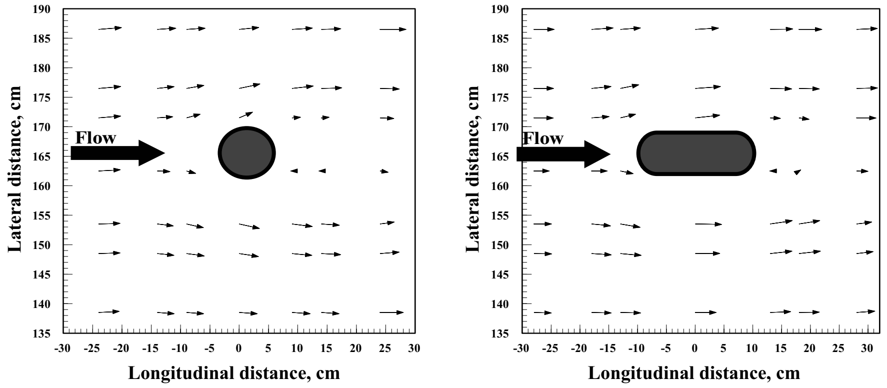
Both floodplain and main channel 2-D scour contour maps (Fig.6, Fig.7, Fig.8 and Fig.9) and corresponding photographs (Fig.10), indicating local scour around structure, were analyzed for variable discharges, shape of structures and length-width ratio. In all cases, generally with higher discharge, scour hole slope was found steeper at upstream face. Scour line intensity decreases with decreasing discharges and becomes flatter for lower discharge. Some times, in main channel, a secondary scour hole is observed at the end of rare face scour extent. Uniformity of scour slopes is observed more or less equal at upstream side and lateral sides of structure both at floodplain and main channel. At floodplain, sediment deposition was found nearer to rear face of structure for lower discharge and gradually shifted downstream for higher discharges but in main channel, sediment deposited comparatively far downstream than floodplain. Both at floodplain and main channel, scour extent at rear side of structure decreased with greater length-width ratio. But in case of main channel, scour extent is much larger than floodplain.

3.2 Longitudinal and lateral bed profile

Higher discharge caused higher scour depth and scour depth decreased with lower discharges in longitudinal bed profile both at floodplain and main channel. From main channel longitudinal cross section bed profile, all scour depth is found so higher and extent of scour hole is found greater than that of floodplain in all cases (Fig.11 and Fig.12). Generally, no sediment deposition is observed in main channel within same floodplain longitudinal distance. Higher velocity of main channel in comparison with floodplain velocity may be responsible for this occurrence as it carries sediment scoured around structure to a far downstream distance of main channel. Both floodplain and main channel, deeper scour depth was obtained for circular structure (l/b=1) and scour depth reduced with increasing of length-width ratio (l/b) for same discharge. Comparatively, scour depth has been observed less in coarse bed material than that of fine bed material (Fig.11, Fig.12, Fig.13 and Fig.14). In lateral direction, uniform extent and slope of scour hole has been observed both at floodplain and main channel except depth is found greater as usual in main channel than that of floodplain (Fig.13 and Fig.14). A significant and clear view of shape, extent, slope, deposition etc of scour around different shapes of structure with variable length-width ratio both at floodplain and main channel together can be obtained from three dimensional (3D) perspective plots of bed profile (Fig.15). Comparative idea about difference between floodplain and main channel scour can also be achieved at a glance as these 3 dimensional figures present both floodplain and main channel scouring situation at a time.

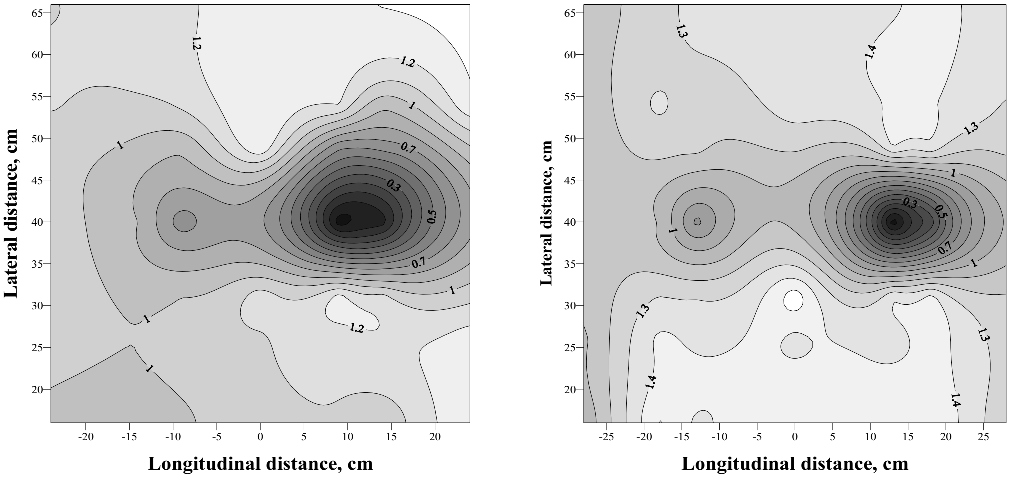


(a) Floodplain

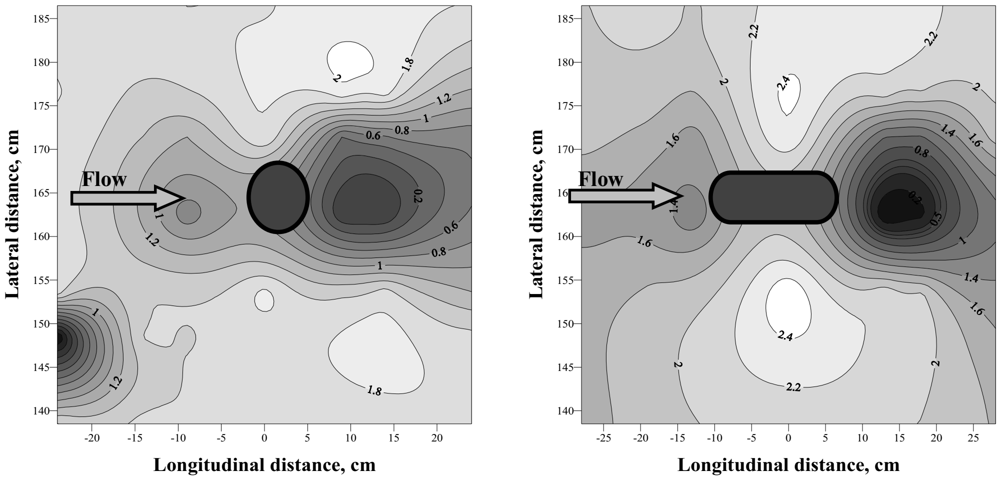


(b) Main channel

Fig.16. Velocity vector diagrams for Circular structure and Round nose structure, respectively for d_{50} = 0.12 mm and 200 l/s discharge at equilibrium condition at floodplain and main channel



(a) Floodplain



(b) Main channel

Fig.17. Flow intensity (V/V_a) contour map around Circular and Round nose structure, respectively for $d_{50} = 0.12$ mm and 200 l/s discharge at equilibrium condition at floodplain and main channel

3.3 Velocity variation

Same observations and trends of velocity variations have been found for discharge variation and for length-width ratio variation in both floodplain and main channel except velocities are found higher in main channel than that of floodplain. Velocity varied from higher to lower with decreasing discharges. No significant difference has been found in case of flow separation, flow circulation and horseshoe vortex formation between floodplain and main channel. A general reduction of velocity has been observed in front of structure for downward movement of flow due to separation of flow at upstream face of structure. Velocity was negligible at rear face of structure and gradually regained its original velocity after traveling downstream distance. Velocity vectors (Fig.16) indicated flow separation at structure front and flow velocity reached near about zero there. After dividing of flow, flow circulation has been observed due to horse shoe vortex around structure. Wake vortices were also occurred at rear front of structure that was responsible for downstream scour. From flow intensity (V/V_a) contour maps (Fig.17), V/V_a lines less than unity both in front and rear face of structure indicated reduction of flow intensity due to flow separation at front face and weak flow generation at rear face of structure. V/V_a line equals to unity or grater existed around upstream face of structure in case of higher discharge and shifted away with lower discharges. In comparison between floodplain and main channel V/V_a contour maps, it is observed that values of V/V_a lines are greater than that of floodplain. It is happened due to difference between velocity of floodplain and main channel. Velocity is found higher in main channel than that of floodplain for same discharge as depth of flow is more than that of floodplain. It may also affect scour because, scour depth is found higher in main channel than that of floodplain for same discharge in case of same bed material.

In general, it has been observed from Fig.18 that scour in main channel is deeper than that in floodplain. Increasing or decreasing tendency of scour depth in main channel in different bed materials is nearly same as floodplain scour trend. It has been measured that depth of scour around circular shape of structure is highest than that of scour around any other shapes of structures both in floodplain and main channel. A lowering trend with higher l/b ratio for round nose pier also has been observed.

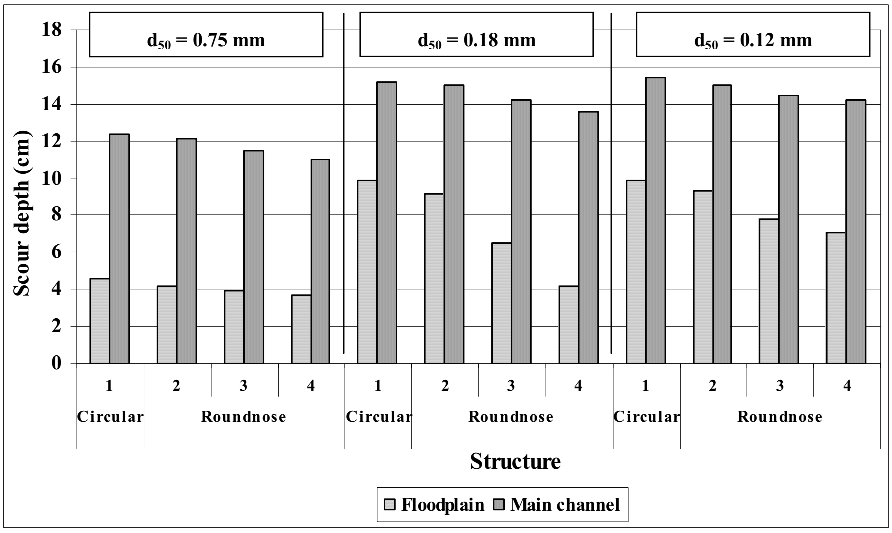


Fig.18. Comparison between floodplain and main channel scour depths in different bed materials

4. Conclusion

Scour depth varies with velocity variation of flow and an increasing tendency of scour depth has been observed with increasing flow intensity. Main channel scour is always higher than floodplain scour. Flow velocity is higher in main channel than that of floodplain and responsible for deeper scour in main channel than floodplain. Flow velocity reduces at front face of structure due to flow separation and downward movement of flow causes scour. Upward and reverse flow occurs at rear side of structure that causes scour behind structure. At floodplain, velocity distribution is associated with vortex generation as mid of channel. Scour around circular structure is highest than scour around any other shapes of structure both at floodplain and main channel. In both cases, highest scour depth is located just adjacent to structure and close to front face of structure at upstream. At floodplain, scour hole slope is steepest and uniform for higher discharge and shows a declining trend with lower discharges. A relatively flatter scour hole at rear side of structure is occurred in finer bed materials. Sediment is deposited near rear side of structures and shifts adjacent to rear face for lower discharges and grater length-width ratio. Generally main channel scour shows similar characteristics as floodplain but magnitudes considerably differ from floodplain scour.

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