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Scour downstream of a Broad Crested drowned Weir

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Abstract*: A detrimental problem of scour downstream of a Bagmari Syphon in the feeder canal off taking from Farakka Barrage on the Ganga River, West Bengal, India has kindled our interest in understanding the scour process downstream of a broad crested drowned weir. A river was syphoned across the Feeder canal at Bagmari, flushing the top of the syphon with canal bed. However, the canal bed degraded over the years and resulted in exposure and protrusion of the syphon barrel above the canal bed and acting as a broad crested drowned weir. Due to the acceleration of flow over the barrel, scour has developed downstream of the barrel. This problem has been formulated and studied in the laboratory to study the scour process and its mitigation measures using boulders. Experiments have been carried out in the Hydraulics Laboratory of IIT Roorkee, India in a flume of 12.5 m length, 0.46 m width, 0.70 m depth for the different protruding height of weir and flow intensity, keeping ratio of shear stress of approach flow to critical shear stress less than unity. Study on factors affecting maximum scour depth and its temporal variation were analyzed graphically. The scour depth increases with an increase in protruding height of weir and flow intensity. It has been found that maximum scour reduces significantly using boulder apron. The maximum reduction in scour depth with boulder apron lies in the 44% - 68% range and the range of shift in maximum scour depth from weir with boulder apron was 1.6-1.8 times from the original location of maximum scour depth without boulder apron.*

Keywords: *Broad crested weir, drowned, flow intensity, riprap, scour*

1. Introduction

Hydraulic structures constructed across a channel is always under a risk of failure due to uncertain hydraulic load. One of the risks associated with such structures is failure due to severe scour in its vicinity. Broad crested weir is one of the widely used hydraulic structures found across a channel as a flow regulating structure. Besides, it is also used for flow measurement. Severe local scour downstream of broad crested weir may become a reason for its failure. It is, therefore, important to have a thorough understanding of the mechanism of local scour downstream of a weir.

Flow over a weir is normally free flow but during extreme flood conditions flow depth downstream of weir may rise above the crest causing the weir to be drowned and resulting in submerged flow conditions. The local scour downstream of a broad crested weir in free flow condition is much larger than submerged flow condition since the flow intensity for free flow condition is higher than submerged flow condition. The local scour downstream of a weir like structures such as bed sills, check dam, grade control structures and submerged weirs have been extensively studied and several empirical equations have been proposed (Bormann and Julien 1991; Gaudio et al. 2000; Lenzi et al. 2002, 2003a, b; D'Agostino and Ferro 2004; Marion et al. 2004; Ben Meftah and Mossa 2006; Marion et al. 2006; Scurlock et al. 2012; Lu et al. 2013; Pagliara and Kurdistani 2013; Guan et al. 2014, 2015, 2016).

Sometimes, water conveying structures have to cross a river, such as pipelines, canal syphons etc. may behave as submerged weir if it gets exposed or flow becomes obstructed due to improper level of the river bed and crossing structures. A similar case is found downstream of Bagmari Syphon in the feeder canal off taking from Farakka Barrage on the Ganga River, West Bengal, India. A river was syphoned across the Feeder canal at Bagmari, flushing the top of the syphon with the canal bed. However, the canal bed degraded over the years and resulted in exposure and protrusion of the syphon barrel above the canal bed and acting as a broad crested drowned weir. The flow when reaches the top of the syphon barrel acting as a broad crested weir, gets retarded and as it passes over the weir, the flow gets accelerated and modified, which results in local scour. If precautions such as protection of the syphon barrel behaving as broad crested weir are not undertaken, the structures will no longer remain stable and leads to failure. Thus, it becomes imperative to have a thorough understanding of the local scour mechanism and its mitigation techniques.

The aforementioned problem was formulated in an experimental flume in order to understand the scour process, factors influencing the scour and its mitigation using boulder riprap under different flow intensities maintaining clear water scour. The results of this study are useful in the mitigation of local scour and the development of a numerical model for estimation of local scour downstream of broad crested weir like structures in the water resources projects.

2. Experimental Set-up and Procedure

The experiments were conducted in a tilting flume with a dimension of 12.5 m length, 0.46 m width, 0.70 m depth with a slope of 3/8000 in the Hydraulics laboratory of Department of Civil Engineering, Indian Institute of Technology Roorkee, India. About 35 cm depth of fine sediment was filled to prepare the bed. The working section of the flume was made up of glass on side walls to facilitate visual observations as shown in Figure 1 (a). At the upstream end of the flume, water was fed into a tank to stabilize the water head through a pipe of 150 mm diameter. A flow straightener made of wood was installed at the inlet of the flume to suppress the turbulence in the flow. A small stretch of channel bed downstream of the flow straightener was filled with stones up to 15 cm thickness for stabilizing the flow. Flow passes over a weir model made of steel sheet and rectangular in shape with certain protrusions as shown in Figures 1(a)-(b). At the downstream end of the flume, a tailgate was installed to maintain desired tailwater level in the flume. There was a sharp-crested weir at the outlet of the flume to measure the discharge. A pointer gauge was used to measure initial and final water level to obtain head (H) over the weir. By measuring the head over the weir and knowing the C_d and width of weir, discharge was calculated using the general formula. The dimension of the broad-crested weir model was width, X=0.45 m, length, B=0.25 m and height, Y=0.35 m height as shown in Figure 1(a)-(b) and Figure 2.

The sand characteristics were: median size d_{50} = 0.30 mm; d_{60} = 0.31 mm, d_{10} = 0.23 mm, geometric standard deviation σ_g = 1.23 and coefficient of uniformity C_u = d_{60}/d_{10} = 1.34 respectively. Figure 2 shows a sketch of experimental parameters in the testing flume.

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Figure 1. (a) Photometric view of weir embedded in sand river bed in experimental flume & (b) Schematic diagram of the experimental setup in a flume.

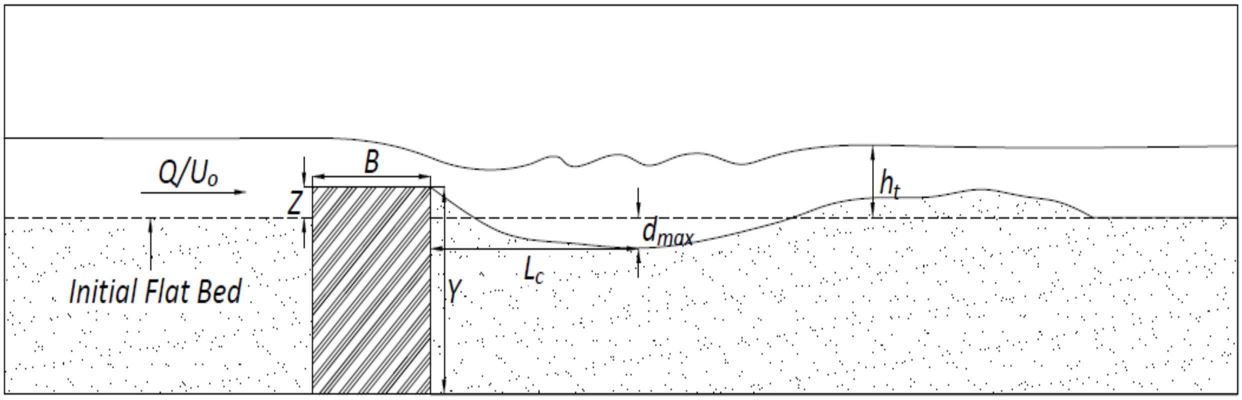

Figure 2. Definition sketch of experimental parameters in a testing flume

Taking all the basic parameters into account, scour depth d_s downstream of the broad-crested drowned weir can be written in a functional form as,

$$d_s = f\ (\rho, \rho_s, \mu, g, h_o, h_t, U_o, d_{50}, \sigma_g, U_c, B, z) \quad (1)$$

where, d_s = scour depth, ρ, ρ_s = densities of water and sediment respectively, μ = dynamic viscosity of water, g = acceleration of gravity, h_o = average approach flow depth, h_t = tailwater depth, U_o = average approach flow velocity, U_c = critical average flow velocity, (d_{50}, σ_g) are the sediment median size and geometric standard deviation of sediment material, B = weir crest width and z = protrusion height of weir.

In this study, sediment size, weir crest width B and fluid properties were kept constant. The approach flow depth h_o depends on weir protrusion height z, tailwater depth h_t and flow intensity U_o/U_c. Since, increase in weir height and approach flow velocity U_o increases flow resistance and discharge, respectively, the approach flow depth h_o also increases, i.e., h_o depends on U_o for constant channel slope. Thus, it is not considered in dimensional analysis. The tailwater depth was in controlled condition. Finally, dimensional analysis results (Guan et al. 2015) as,

$$\frac{d_s}{h_t} = f\ \left(\frac{U_o}{U_c}, \frac{z}{h_t}\right) \quad (2)$$

To analyze the local scour downstream of the weir in clear water conditions, U_o/U_c was kept < 1.0 throughout the experiment. Due to clear water conditions, there was no or minimal scour at the upstream of the structure, hence readings were not taken. The scour development at downstream of the weir was measured with a flat gauge, and readings were taken at center and two edges of the flume at 20 mm intervals along the flume. It usually took 2 hours for scour to reach at maximum scour stage. To analyze the temporal variance, readings were taken at 5 mins, 15 mins, 30 mins, 60 mins and 120 mins. It was observed that scour process attained maximum scour after 2 hours. Approach fow depth h_o, tail water depth h_t, head over weir, H_d were measured with pointer gauge.

For each protruding height of weir (z), discharge was controlled using the valve fitted at the inlet of the flume. Discharge was varied keeping the tail depth constant and the tail depth was controlled with the help of a tail gate provided at the end of the flume. Discharge was controlled in such a way that flow velocity at downstream of the structure, U_o should always be less than critical velocity, U_c corresponding to the approach flow depth, h_o, for this study, flow intensity ranges between $0.25 < U_o/U_c < 0.62$. Critical velocity, U_c is calculated from the equation $U_c/u_{*c} = 5.75\log(5.53\ h_o/d_{50})$, in which the average flow critical shear velocity, u_{*c} = 0.013 m/s was calculated using the Shields diagram for the particle size d_{50} = 0.30 mm. In this study, three different protruding heights of weir were used. i.e., z = 20, 30 and 50 mm and a total of 18 clear water scour tests were carried out. For each weir height, total 6 tests were carried out, 5 on sand bed and one with apron for discharge at which maximum scour was observed.

Sand bed was covered with wooden ply and plastic sheet till tail water depth reached the desired level. Ply and plastic sheet were removed safely to expose sand bed to flow. For each weir height and discharge, the sand bed was leveled to study the scour length and maximum scour depth corresponding to the flow. To analyze the effect of boulder raft/apron on the maximum scour depth and length, boulders of d_{50} = 10 mm were provided up to the 125% of length at which maximum scour is observed. For each weir height., flow conditions were replicated for the discharge value at which maximum scour depth was observed to determine the amount of reduction in scour depth and length in the presence of the apron.

3. Results and Discussion

3.1. Scouring Process

Scour downstream of drowned weir depends upon approach flow intensity and flow regimes (surface flow or impinging jet) (Guan et.al.,2015). Initially, just after the removal of plyboard cover, scour starts rapidly in a vertical and horizontal direction downstream of the submerged weir. The scour hole formed downstream of broad-crested weir exhibits 3D characteristics. The maximum scour hole occurred close to the flume sidewall rather than the center of the flume. This is due to the secondary flow to the transverse section of the flume. This secondary flow is a paired circular flow cells, which are quasi-symmetrically located on both sides of the centerline sand ridge (Guan et.al.,2015). At the beginning, the scour rate was higher for horizontal and vertical directions i.e., scour length and scour depth. Later on, it decreases asymptotically as depicted from Figure 4. Here the flow separation occurs at the end of crest of the weir, later on it rejoins at deepest point of scour hole and finally emerges from scour hole. The mode of sediment transport was suspended load and bed load in the scour hole. Figure 3 depicts two distinct parts, scour hole and dune. The digged material of scour hole gets transported downstream at such a location where there is no sufficient shear stress to carry the bed material further downstream. And this continuous deposition of bed material from scour hole gets piled up and forms dune. Initially, the dune's crest slope was steeper, later with continuous erosion process up to maximum scour depth, it becomes flatter, that can be clearly seen from Figure 3.

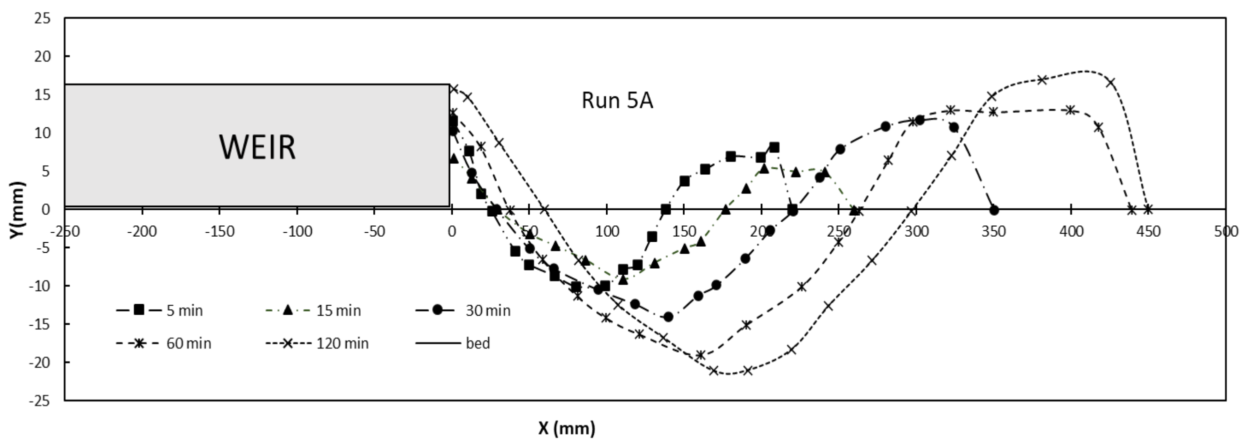

Figure 3. Temporal variation of scour profiles along longitudinal direction for Run 5A

3.2. Temporal variation of maximum scour depth

The temporal evolution of scour depth for all the three protrusions height of weir is shown in Figure 4. This shows that maximum scour occurs rapidly within short time. Later on the rate of scour decreases asymptotically. Here the time versus scour depth curve is divided in to three stages. For first 30 minutes the stage is initial fast stage (stage I) where scour depth increases instantly. It can be observed that at least 75% of maximum scour depth is achieved in Stage-I only. In stage stage-II ≈95% of maximum scour depth is achieved and remaining scour depth is achieved in Stage-III. The maximum scour depth is obtained in 2 hrs.

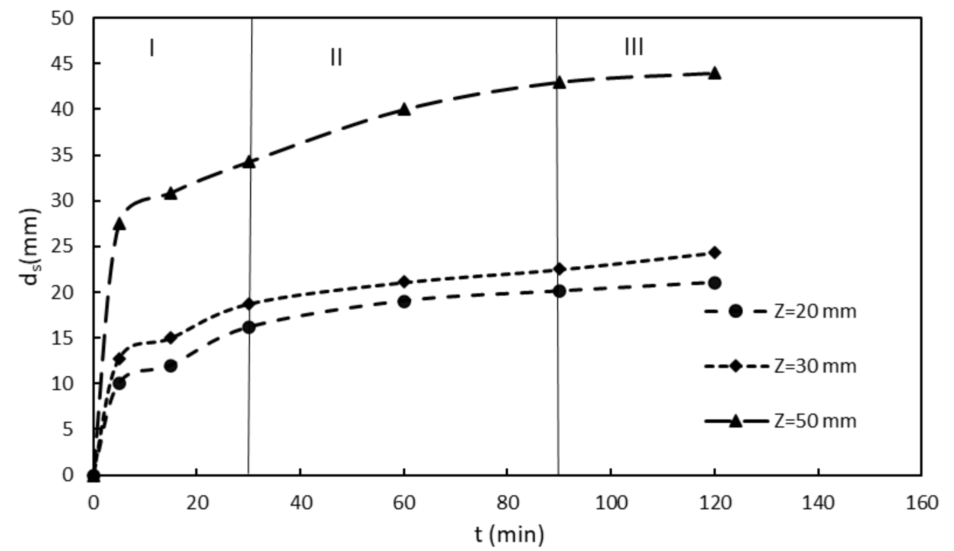

Figure 4. Various stages of scour with respect to time

3.3. Factors affecting maximum scour depth

3.3.1. Flow-Intensity

As in clear-water condition, flow does not bring sediment with it to replenish the scour hole at downstream of the weir, therefore, the relationship between flow intensity and maximum scour depth comes out to be a linear relation. Figure 5 represents a linear relation between d_s/h_t and U_o/U_c. This figure indicates that, for each weir height, the downstream scour depth increases linearly with velocity when $0<U_o/U_c<1$. For clear-water scour, there is no sediment transport upstream of the submerged weir to replenish the downstream scour hole, and the maximum downstream scour depth is determined only by the strength of the overflow. Therefore, for a given weir height and sediment size, an increase in U_o/U_c, which leads to a stronger overflow without bringing more sediment replenishment, results in a deeper downstream scour hole.

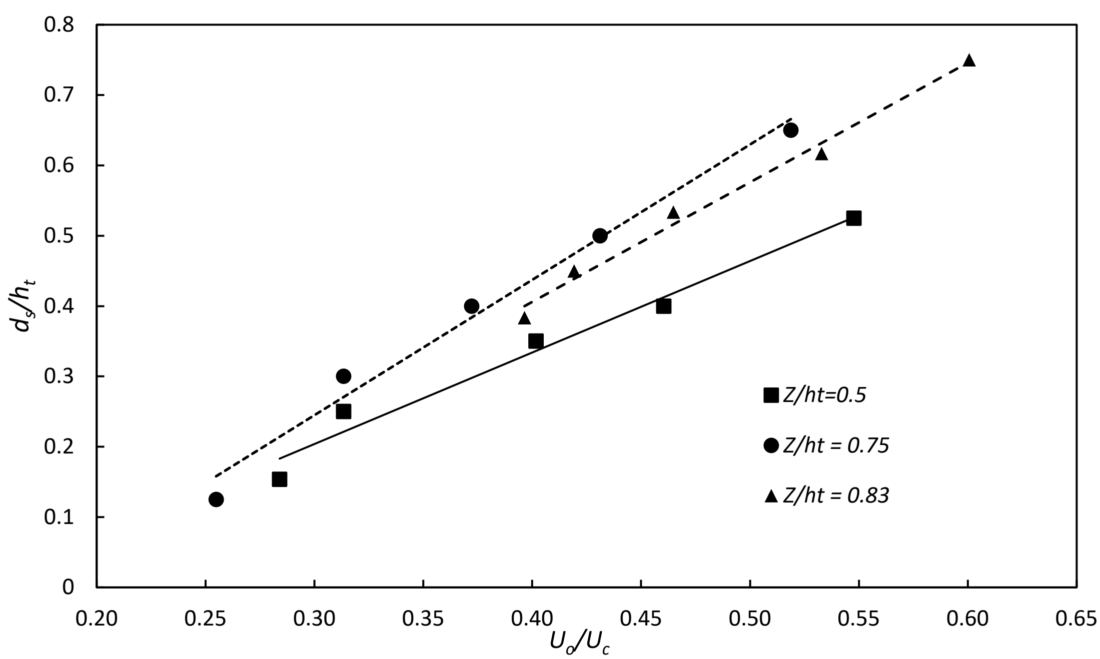

Figure 5. Variation of dimensionless maximum scour depth with flow intensity

3.3.2. Protrusion height of the weir

Figure 6 shows that the maximum downstream clear-water scour depth increases with z/h_t while h_t and U_o/U_c are held constant. For clear-water scour, the upstream sediment bed does not move. With an installed submerged weir, the flow over the weir crest is accelerated, destabilize the downstream sediment bed and generates a scour hole. As the protruding height of weir increases, the velocity head over the weir crest also increases resulting in higher value of approach Froude number. This causes the higher overflow impact on the downstream bed resulting in a deeper downstream scour hole. For zero weir height, no constriction of flow occurs, and the uniform approach flow is not able to move the sediment when $U_o/U_c<1$, resulting in zero scour depth.

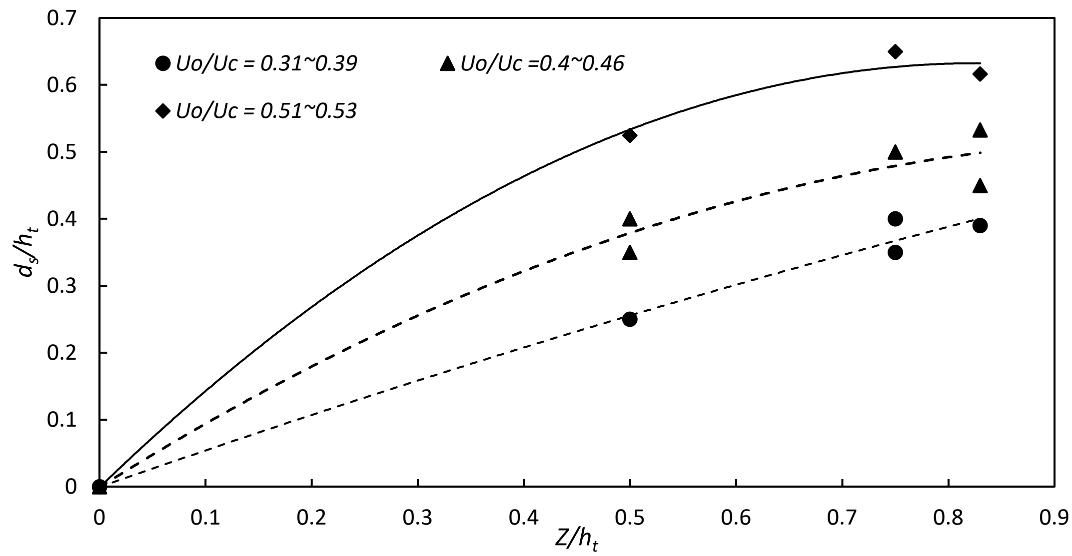

Figure 6. Variation of dimensionless maximum scour depth with dimensionless height of weir

3.4. Scour reduction using boulder apron

An apron of boulders of d_{50} = 10 mm was provided up to 125% of length where maximum scour depth was observed. Test runs were done for same discharge at which maximum scour depths were observed. Figure 7(a) shows the boulder apron placed downstream of the broad crested weir and Figure 7(b) shows scour profile through sidewall at different time interval by using boulder apron. Similarly, Figure 8 represents the comparison of scour pattern with and without apron at same discharge for z = 20mm, 30mm and 50mm, respectively.

Figure 7. (a) boulder apron placed downstream of weir and (b) Maximum scour profile obtained after using apron.

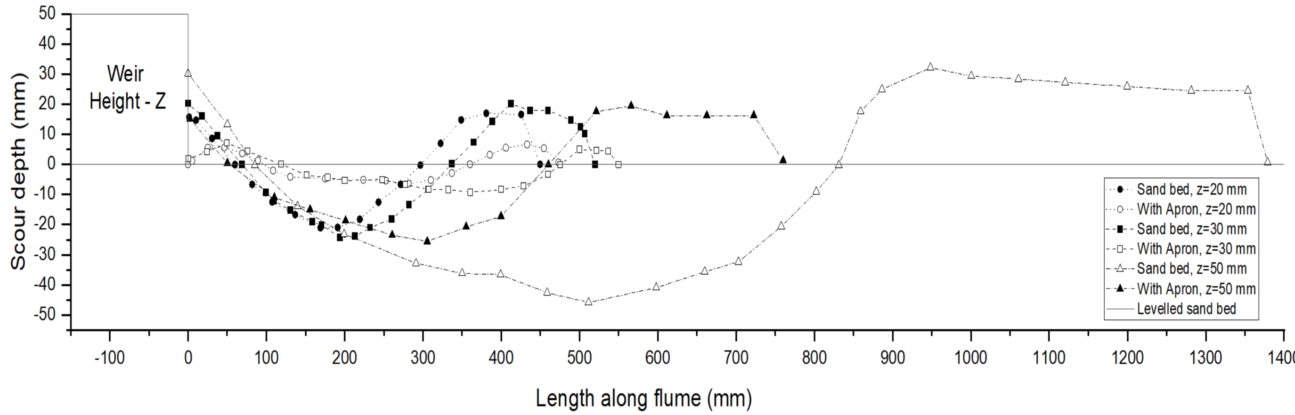

Figure 8. Comparison of scour pattern with and without apron for z =20mm, 30mm and 50mm

3.4.1. Maximum scour depth

With the use of apron excess resistance can be added to prevent scouring of bed sediment. Figure 9 indicates that with use of apron, a significant reduction in maximum scour depth was observed. Maximum scour reduced by 44% in case of *z* =50 mm and 68% in case of *z* =20 mm, for *z* =30 mm it was reduced by 60%.

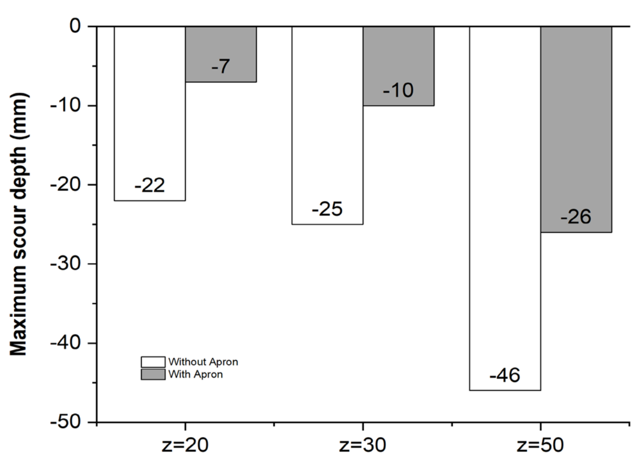

Figure 9. Comparison of reduction in maximum scour depth with use of boulder's apron

3.4.2. Location of maximum scour

The use of boulder apron shifted point of maximum scour depth downstream form toe of the weir. Since the apron roughness placed up to 125 % length of scour moderated the flow intensity resulting reduction in the scour depth. As far as maximum scour depth is concerned from the structure, safer the structure will be from the detrimental problem of scour. For z = 20mm, maximum scour depth was shifted by 1.6 times away from the original location of maximum scour depth without apron and similarly it was 1.8 times for z =30 mm. But it was reduced by 0.6 times for z = 50mm. Figure 10 clearly illustrates the above discussed matter in bar chart format. Thus, the application of boulder apron minimizes the local scour. It can be considered as a good preventive measure since it is successful to reduce scour depth near the structure of weir.

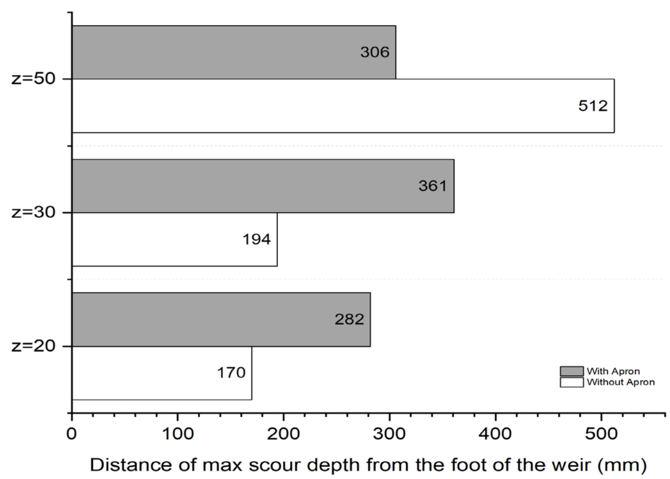

Figure 10. Comparison of location of max scour depth with and without apron

4. Conclusion

Following observations were made from experimental study.

- Maximum scour depth increases proportionally with flow intensity. i.e., maximum scour depth increases with increase of flow intensity (U_o/U_c) for tested range. Similarly, Maximum scour depth increases with increase in protruding height of weir *z* for three different range of flow intensity (U_o/U_c). At lower range of flow intensity, maximum scour depth increases slowly with increase in protruding height of weir. The rate of maximum scour depth increases with an increase in protruding height of weir at higher range of flow intensity (U_o/U_c).
- The maximum scour reduces significantly using boulder apron. The maximum reduction in scour depth with boulder apron lies in the 44% - 68% range and the range of shift in maximum scour depth from weir with boulder apron was 1.6-1.8 times from the original location of maximum scour depth without boulder apron.
- The results obtained from this study can be used for analyzing the proper length of apron required for protection works of Baghmari syphon of Feeder canal, Farraka Barrage having same tested range of dimensionless parameters.

Further, experimental findings can be substantiated with analytical methods, and two-phase 3D CFD modelling could be done to visualize flow behavior and shear stresses to better understand the phenomenon.

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