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Experimental Study of Local Scour Downstream of Cylindrical Bridge Piers

Mohammed Tareq Shukri $^{1)}$***, Junaid Kameran Ahmed*** $^{2)}$ ***and Omer Muhie*** $^{3)}$

$^{1)}$ Ishik University, Iraq. E-Mail: mohammed.tareq@ishik.edu.iq
$^{2)}$ Ishik University, Iraq. E-Mail: Email: junaid.kameran@ishik.edu.iq
$^{3)}$ Ishik University, Iraq.

ABSTRACT

Scour is a natural phenomenon caused by the erosive action of flowing stream on alluvial beds, which removes the sediment around or near structures located in flowing water. It means the lowering of the riverbed level by water erosions, such that there is a tendency to expose the foundations of a structure. It is the result of the erosive action of flowing water, excavating and carrying away material from the bed and banks of streams and from around the piers of bridges. The failure of bridges due to excessive local scour during floods poses a challenging problem to hydraulic engineers. The failure of bridge piers is due to many reasons, such as localized scour combined with general riverbed degradation. In this paper, we tried to estimate the temporal variation of scour depth at non-uniform cylindrical bridge pier, by an experimental work carried out in the civil engineering hydraulic laboratories of Gaziantep University on a channel with dimensions of 8.3m length, 0.8m width and 0.9m depth. Experiments have been carried out at 20 cm depth of a sediment layer with d_{50}=0.4 mm. Three bridge pier shapes having different scaled models have been constructed in a 1.5m test section in the channel.

KEYWORDS: Scour, Local scour, Bridge piers, Scour depth, Vortex, Horseshoe vortex.

INTRODUCTION

Scour is defined as the erosion of streambed sediments around an obstruction in a flow field (Chang, 1988). It is due to movement and removal of sediments around bridge piers. Bridge scour is usually divided into general scour, contraction scour and local scour. General scour happens without the existence of a bridge. Contraction scour results from the acceleration of the flow due to the constriction of channel, while local scour happens by the turbulence around bridge obstacles such as piers and abutments. According to statistics, 60% of all bridge failures result from scour and other hydraulic related causes. In this regard, scour is the primary cause of bridge failure in the United States (NCHRP Report 396, 1997). Scour may happen at any time, especially flood time, causing collapse of bridges and loss of lives. As illustrated in Figure 1, strong vortex motion caused by the existence of piers entrains bed sediments within the vicinity of the pier base. The down flow rolls up as it continues to create a hole and, through interaction with the oncoming flow, develops into a complex vortex system. The vortex then extends downstream along the sides. This vortex is often referred to as horseshoe vortex because of its great similarity to a horseshoe. In spite of a lot of work, where both experimental and numerical studies have been conducted to predict the behavior of rivers and to quantify the equilibrium depth of scour, many researchers are still interested in the basic understanding of the scour's mechanism. Based on the difference of the approach flow sediment transportation pattern, local scour was divided into clear-water scour and live-bed scour (Chabert and Engeldinger, 1956).

Figure 2 shows that clear-water scour occurs where

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there is no transport of bed material upstream of the crossing or encroachment or the material being transported from the upstream reach is transported through the downstream reach at less than the capacity of the flow. Live-bed scour occurs where there is transport of bed material from the upstream reach into the crossing or encroachment. Therefore, studying the phenomenon of pier scour has become a topic of interest to investigators. After the pioneering work of Durand-Claye (1873) on the investigation of pier scour, numerous investigations on pier scour have been reported by various researchers. A review of important experiments and field studies was given by Breusers et al. (1977), Dargahi (1982), Breusers and Raudkivi (1991), Dey (1997), Hoffmans and Verheij (1997), Melville and Coleman (2000) and Richardson and Davis (2001).

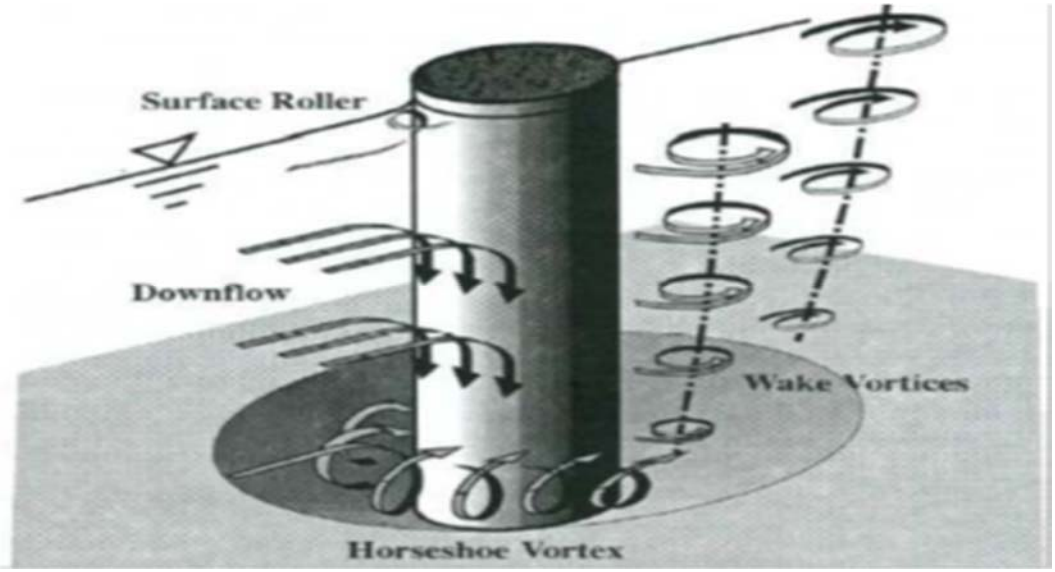

Figure (1): Vortex motion around a pier (Melville and Coleman, 2000)

Figure (2): General view of the laboratory flume

Scour Process

Upon reaching a certain flow velocity in the channel, the sediment particles close to the pier begin to move; scour is initiated. The eroded particles will follow the flow pattern, being carried from the front of the pier towards the downstream. Upon increase in the flow velocity, more and more particles will get dislodged, forming a scour hole increasing in size and depth. Eventually, a maximum scour depth, $(d_s)_{\max}$, is attained which corresponds to a flow velocity being close to the critical velocity $U=U_{cr}$, for initiation of sediment transport in the channel. For non-uniform sediments, a larger size is less likely to be eroded and an armoring layer forms in the scour hole. A subsequent further increase in the flow velocity, $U>U_{cr}$, is responsible for transport of sediments *in* and *out* of the scour hole, but the scour depth remains essentially constant. Thus, an average equilibrium scour depth, d_s, establishes itself, being slightly smaller than the maximum scour depth, $(d_s)_{\max}$.

Experimental Setup

The experiment in this study was conducted in a circulating flume as shown in Figure 2. Length of the flume was about 8.3 m, its width 0.8 m and its depth 0.9 m, with glass sides and an iron bottom. The study section was set about 2.8 m from the inlet of the flume which was filled with sand with medium size of particles d_{50}= 4mm and gradation coefficient σ_g=1.15. The thickness of the sand was 20 cm with a test section of 1.5m. The shape of the samples was circular with a diameter of 5cm, 7.5 cm and 11.1cm, respectively. The circulating flow system was served by a pump with a capacity of 25 l/sec located at the right of the flume and there was a valve to control the flow in the flume. The pump withdraws water from a sump at the downstream of the flume. At the end of the flume, there is a rectangular weir to measure the flow rate and a point gage to measure the depth of the scour hole.

In order to have uniform flow before and after the bridge pier, a ramp was constructed and fixed to the upstream and downstream of the test section of the flume. Experiments were carried out at fixed discharges. Details of the experimental conditions are given in Table 1. Long time duration of 1 hour has been chosen in the experiments for each run. The variation of local scour depth with time was measured at various times by stopping the experiment and running it again.

In this study, different sizes of sediments were tested to determine d_{50}. Sieve analysis of the sediments was used in the present experiments.

Table 1. Results of experimental work

run	D (cm)	h (cm)	t (min)	Q (m/sec)	A	V
A1	5	2.5	15	0.00629	0.02	0.3145
A2	5	4.4	30	0.0166	0.0352	0.471590909
A3	5	5.4	30	0.02263	0.044	0.514318182
A4	5	5.7	30	0.02519	0.0464	0.542887931
B1	11	2.5	30	0.00629	0.02	0.3145
B2	11	4.4	40	0.0166	0.0352	0.471590909
B3	11	5.4	35	0.02263	0.044	0.514318182
B4	11	5.8	30	0.02519	0.0464	0.542887931
C1	7.5	2.5	50	0.00629	0.02	0.3145
C2	7.5	4.4	30	0.0166	0.0352	0.471590909
C3	7.5	5.4	30	0.02263	0.044	0.514318182
C4	7.5	5.8	50	0.02519	0.0464	0.542887931

A: code for 5 cm circular pier; B: code for 11.1 cm circular pier; C: code for 7.5 cm circular pier.

RESULTS AND DISCUSSION

In this study, experiments were carried out with 5cm and 11.1cm circular piers with four discharges. Experimental conditions are shown in Table 1. The present experimental results are compared with the results of Breusers et al. (1977). They have derived the following empirical equation for predicting the maximum equilibrium local scour depth by using the experimental results of Laursen and Toch (1956).

$d_{se} = 1.35K\ D^{0.7}\ Y^{0.3}$ (1)

where d_s = equilibrium scour depth; K=1 for circular piers; D= pier diameter; Y= depth of flow.

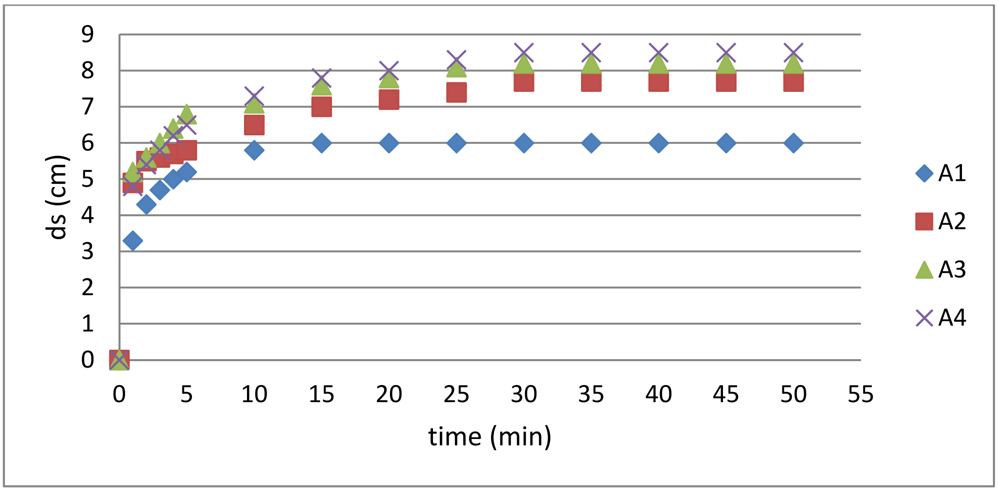

Figure (3): Evolution in scour depth according to different times for sample (A)

In Figure 3, there are four experimental runs for each pier at different discharges. Figure 3 shows that maximum scour depth reaches equilibrium after 15 minutes for lower discharge and increases by the increase of discharge for the pier diameter of 5cm.

Figure 4 shows time variation of local scour depth for pier diameter of 7.5 cm at different discharges. It's clear that there is a variation in maximum scour depth, but the effect of diameter is small on scour depth in that test.

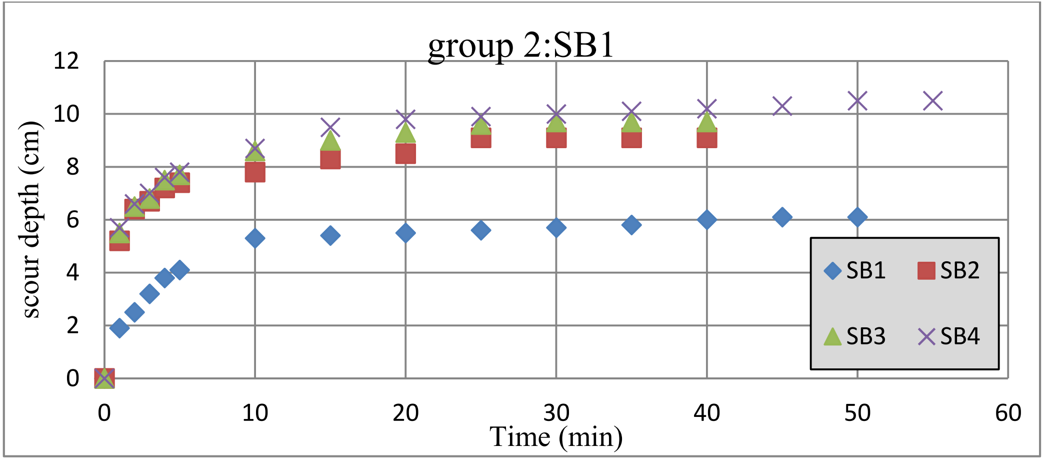

Figure (4): Evolution in scour depth according to different times for sample (B)

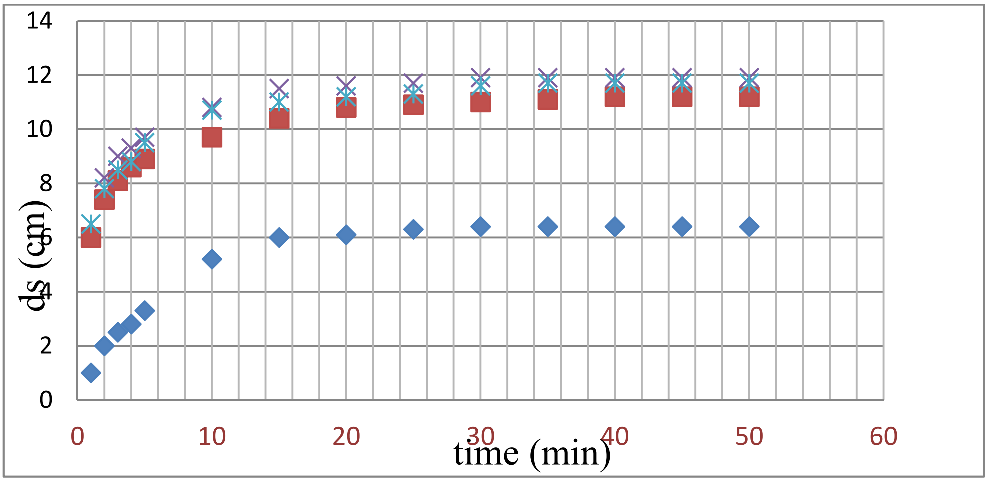

Figure (5): Evolution in scour depth according to different times for sample (C)

Figure 5 shows time variation of local scour depth for pier diameter of 11.1 cm at different discharges. It can be concluded that local scour depth increases with increasing discharge.

Figures 3, 4 and 5 show that equilibrium scour depth increases when approaching discharge to the pier increases. The reason is that the kinetic energy of the flow increases and the destructive effect of the flow increases. Many bridges have collapsed during the flood season. Because of this, piers should be designed for maximum predicted discharge.

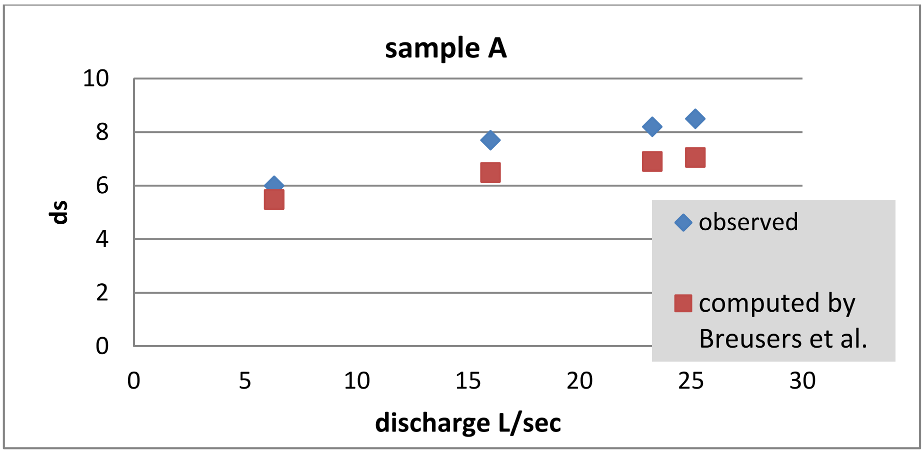

Figure (6): Comparison between observed and computed results of scour depth for sample A

Variation of discharge with local scour depth of the present experimental results is shown in Figure 6 and compared with the results of Breusers et al. (1977) equation with a pier diameter of 5 cm. There is some discrepancy between our results and Equation 1. The reason may be the experimental conditions of Breusers et al. (1977). The limitations of Equation 1 are not clear in their study.

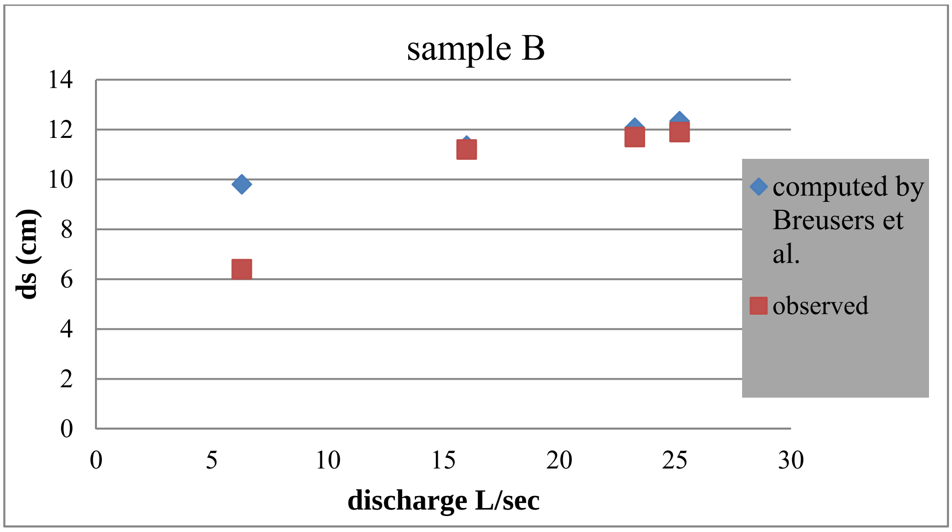

Figure (7): Comparison between observed and computed results of scour depth for sample B

Figure 7 shows the variation of present experimental results of local scour with discharge. In contrast to Figure 6, there is no discrepancy between our experimental results and Breusers et al. (1977) except for one point where the discharge is less than 10 l/s. Figure 7 is in good agreement with Equation 1.

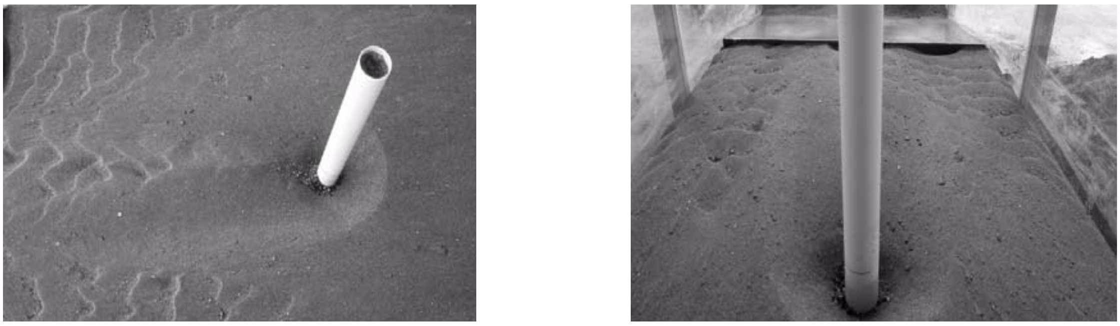

Figure (8): Experimental work showing the pier bridge sample A

Figure (9): Experimental work showing the pier bridge sample B

Figure 8 shows the bathymetry of our experimental work of 5 cm pier diameter. It is seen that there is an accumulation of sediments in the downstream of the pier and that there is scour around the pier. This picture also shows that the present local scour is a live-bed scour, because erosion happens at the upstream side of the pier.

Figure 9 shows the bathymetry of our experimental work of 11.1 cm pier diameter. Deposition and scour are clearly seen.

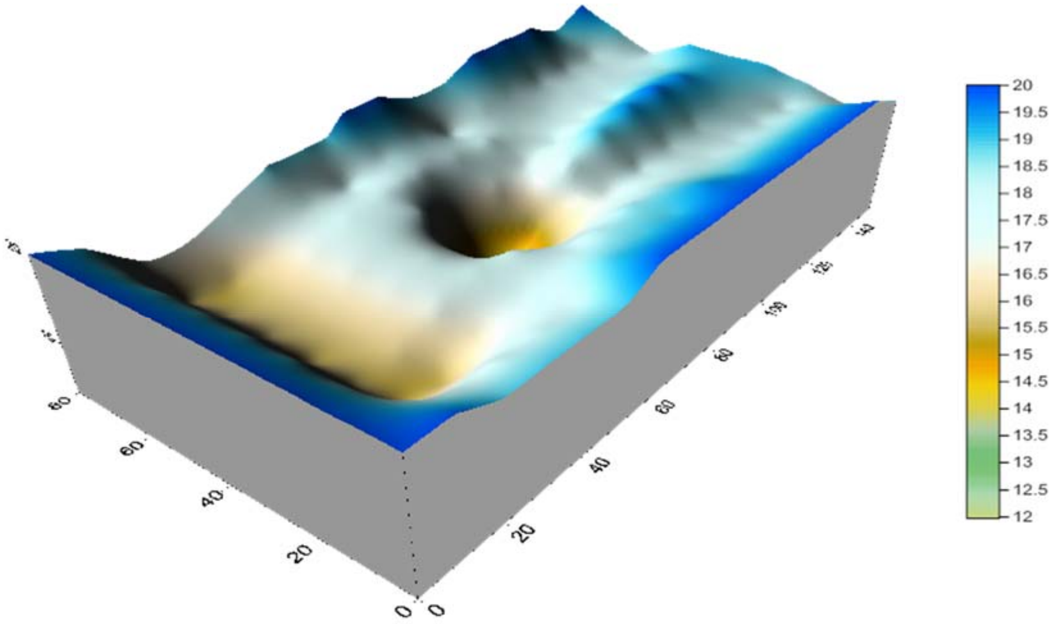

Figure (10): Bed bathymetry for experimental run A4 (scale in cm)

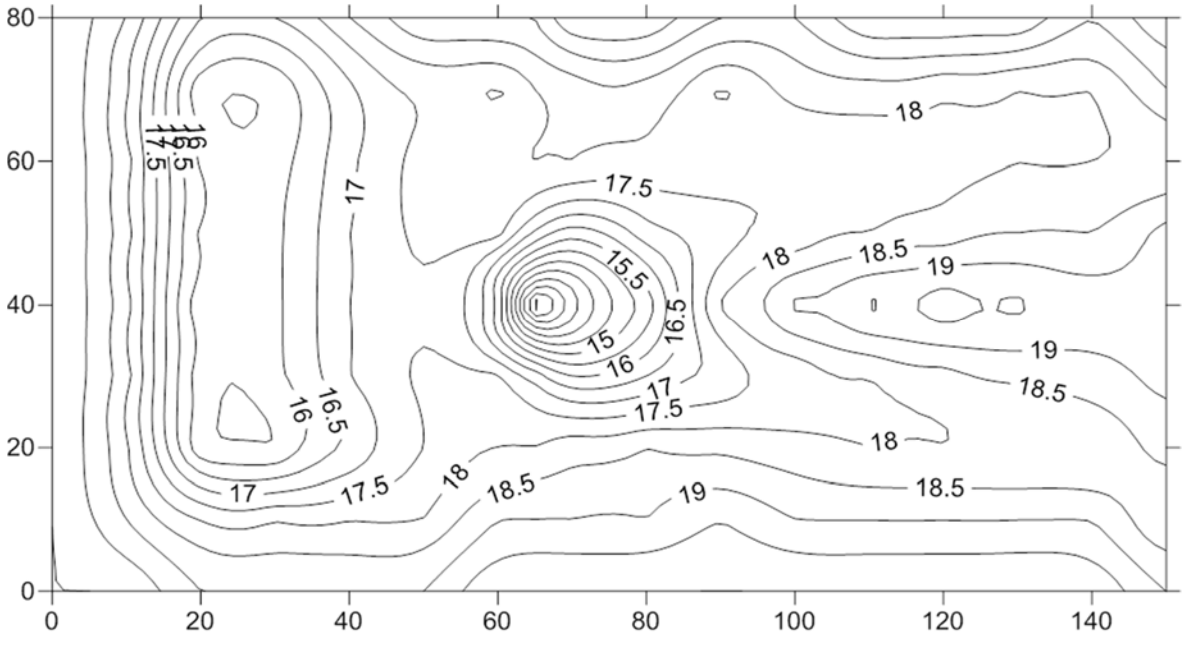

Figure (11): Graph of topographic bed for experimental run A4 (scale in cm)

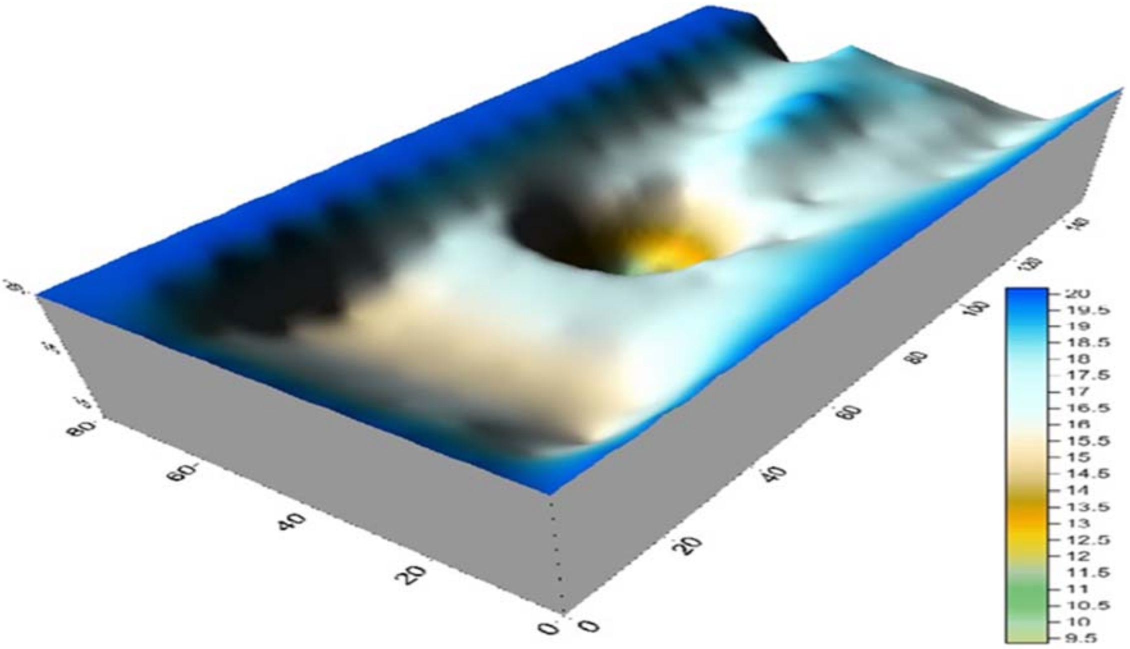

Figure (12): Bed bathymetry for experimental run B4 (scale in cm)

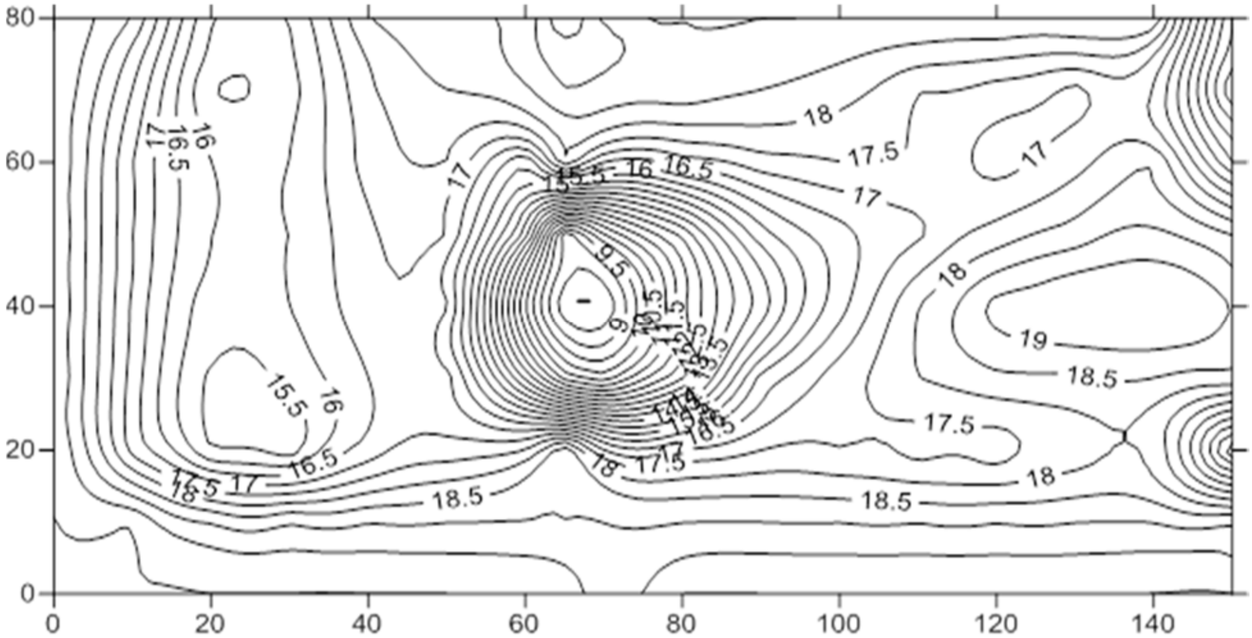

Figure (13): Graph of topographic bed for experimental run B4 (scale in cm)

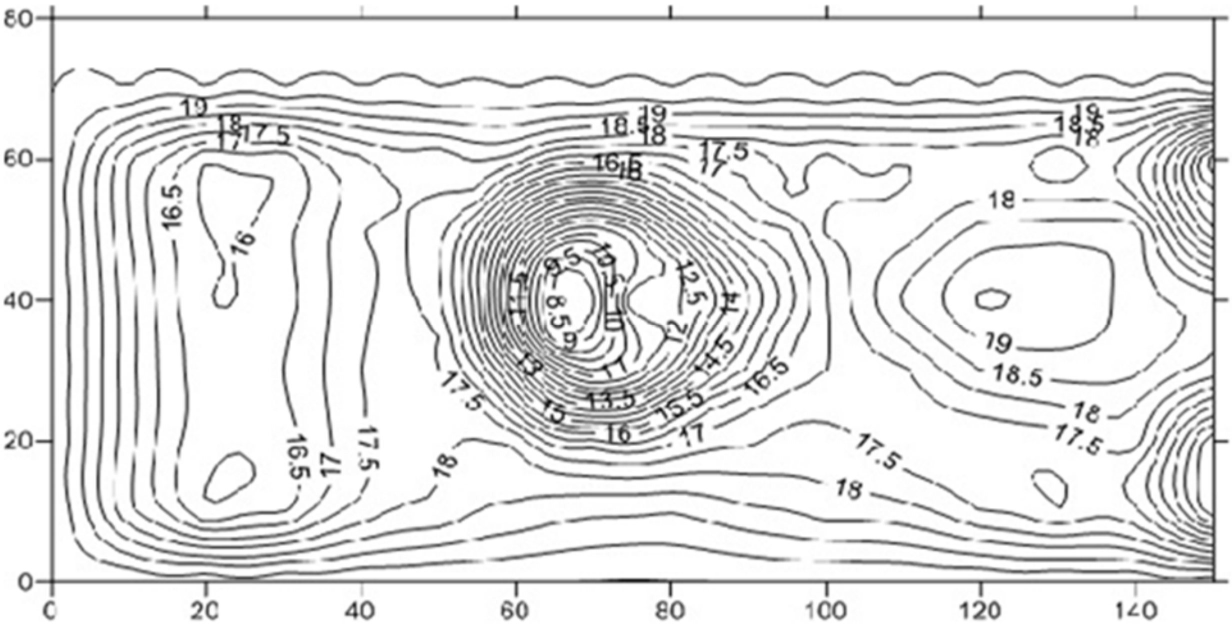

Figure (14): Graph of topographic bed for experimental run C4 (scale in cm)

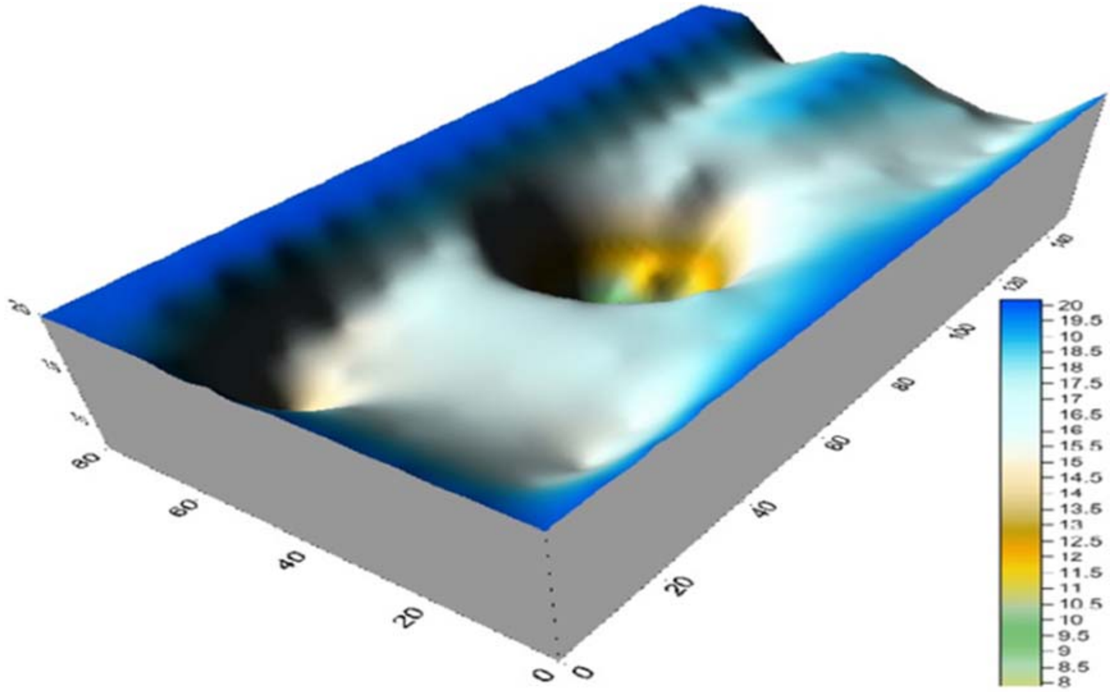

Figure (15): Bed bathymetry for experimental run C4 (scale in cm)

Figures 10 and 11 show the bathymetry of the scoured bed for 5 cm pier diameter. Scour depth is 8.5cm at the upstream of the pier from the top of the undisturbed sediment bed which is 20 cm. There is erosion at the downstream and at the upstream, but erosion at the upstream is higher than that at the downstream.

Figures 12 and 13 show the bathymetry of the scoured bed for 7.5 cm pier diameter. Scour depth is 10.5cm at the upstream of the pier from the top of the undisturbed sediment bed which is 20 cm. There is erosion at the downstream and at the upstream. The erosion at the upstream of the pier is higher than that at the downstream of the pier.

Figures 14 and 15 show the bathymetry of the scoured bed for 11.5 cm pier diameter. Scour depth is 11.9 cm at the upstream of the pier from the top of the undisturbed sediment bed which is 20 cm. There is erosion at the downstream and at the upstream. The erosion at the downstream of the pier is higher than that at the upstream of the pier.

CONCLUSIONS

1. The present experimental results show that there is a relation between depth of scour and pier diameter, where the depth of scour increases with the increase of pier diameter for the same sediment size and discharge.
2. Our experimental study shows that there is a relation between the size of the sediments and the maximum scour depth. With the increase of the mean size of the sediments, the maximum scour depth increases.
3. Our experimental results show that deposition does not occur at high discharges. Scour is occurring as live-bed scour.

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