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Experimental investigation of grain size effect on the temporal variation of local scour around bridge piers

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Abstract

The soil grain size may affect the volume of scour-hole and maximum scour depth substantially. In this paper, the effect of soil grain sizes (d_{50} = 3, 0.1, 0.002 mm) on the temporal variation of local scour around bridge piers, circular in shape, is experimentally investigated. The experiments were performed under clear-water scour conditions in a rectangular flume at different Froude numbers, pier diameters and varying soil grain sizes. Sieve analysis was conducted to determine grain sizes distribution of the studied soils and find their d_{50} values. The scour test results showed that the grain size affects the volume of scour-hole and maximum scour depth and plays a critical function in the scour process. The results also illustrated that, in general, the equilibrium scour depths in the cohesive (or clayey) soils is less than that in the non-cohesive (or sandy) soils.

***Keywords**: Local scour; bridge pier; Froude number; scour-hole development; grain size effect.*

INTRODUCTION

Scour phenomena can be defined as the removal of soil from the stream bed and its banks by the erosive action of the stream flow. The major damage to the bridges at water stream crossings most probably occurs during the periods of floods or flash floods. There are various reasons for such damages; the prime reason being the scour of streambeds at the bridge piers and abutments widely known as local scour. Local scour around bridge piers is considered as one of the most frequent causes of bridge failures which may lead to tragic consequences. As the local scour gradually undermines the foundations, in the past, a large number of hydraulic structures collapsed due to local scour [1, 2]. It is due to this reason; an accurate estimation of the probable maximum scour depth and diameter of scour-hole was the subject of research for many decades. Padmini and Asis [3] reviewed some of the earlier studies related to scour.

Ansari et al. [4] carried out experimental investigations on temporal variation of scour around circular bridge piers in cohesionless and cohesive soils under the condition of the steady clear water flows considering the horse-shoe vortex to be the prime agent causing scour. They developed a method for determining the temporal variation of scour depth in cohesive soils. They also derived empirical relationships for the maximum scour depth prediction around bridge piers in cohesive soils. They found that the maximum equilibrium scour depth in cohesive soils could be smaller or more than that of non-cohesive soils for similar experimental conditions. Debnath and Choudhuri [5] investigated the effects of Froude number (F_r), bed shear strength, clay-content and water content on the development of the scour-hole. They proposed equations for estimating the maximum scour depth for cylinders embedded in clay–sand mixtures as functions of the above mentioned parameters. They also investigated the equilibrium scour-hole geometry and scouring process. They mentioned that the maximum equilibrium scour depth in clay beds is almost similar to that of sand. However, increase in the clay fraction in clay–sand mixed beds reduce the maximum equilibrium scour depth. Abou-Seida et al. [6] reported that the equilibrium scour depth is proportional to F_r and the liquidity index but inversely proportional to the clay content and compaction. It was noticed from their study that equilibrium scour width is approximately 1.8 times the equilibrium scour depth. They also developed formulas to predict the equilibrium scour pattern in terms of the approach flow F_r, the clay content, compaction, liquidity index, and abutment dimensions. They showed that the ratios of equilibrium scour depth for a sandy soil to that for a kaolin clay of low, medium, and high scour potential are 50, 6.5, and 1.5, respectively.

Deshmukh and Raikar [7] reported that scour depth increases with time up to a certain limit and then it attains a constant depth of scour which can be considered as equilibrium scour depth. Maximum depth of scour was observed on the upstream side of the pier. They concluded that the scour depth increases with an increase in the pier size/diameter when all the parameters related to flow and sediment characteristics are the same. Link [8] studied time variation of three-dimensional scour-hole geometry at a circular pier in a sandy soil through a number of experiments. His experimental results provided information for a quantitative definition of different scour phases. The data obtained from this study can be employed in bridge scour monitoring and validating results of numerical simulations. Lu et al. [9] proposed a semi-empirical model to estimate the variation of scour depth with time at cylindrical piers with unexposed foundations. His proposed model agrees well with the experimental data.

Singh and Maiti [10] studied local scour around a circular pier in an erodible bed. They noticed that the highly unsteady complex flow field around a circular pier produces scour-hole mainly because of the vortices. They concluded that the prime mechanism which causes the formation and evolution of the scour-hole around the pier is horseshoe vortex motion. Muzzammil and Siddiqui [11-13] and Muzzammil et al. [14, 15] carried out the reliability analysis of bridge piers against scour considering various scour influencing parameters as random. They proposed probabilistic procedures for estimating failure probabilities of piers under given pier geometry, soil and flow conditions. Khassaf [16] investigated the effect of cohesive and non-cohesive soils on equilibrium scour depth. He concluded that the rate of scour in the clayey soils is less than that in the sandy soils. He also found that the time needed in reaching to maximum or equilibrium scour depth in the clayey soils is more than that in the sandy soils. The effects of the grain size and the density of the sediment material are often expressed as a function of the critical flow velocity for the initiation of sediment motion. Fouli and Elsebaie [17] experimentally studied the effect of an upstream subsidiary triangular pillar on the growth of local scour at a circular bridge pier. They showed that the maximum scour depth at the pier could be minimized using three different combinations of the apex angle and spacing. The maximum reduction in the maximum scour depth was observed for spacing and pier diameter ratio of 3 and apex angle of 90°. They also noticed that the performance of 90° angle pillar surpasses the other two angles.

The above review of literature shows that although a substantial work has been carried out on local scour around bridge piers, the effect of grain size on the local scour is not studied widely and more investigations are needed to understand the effect of grain size on the local scour in a better manner. The prime aim of the present investigation is to study the influence of different grain sizes of the soil on the variation of scour depth and scour-hole dimensions around bridge pier, circular in shape, under clear-water conditions.

Dimensional Analysis

For a specific discharge, scour depth due to a bridge pier develops with time. In general, scour depth is related to fluid flow, sediment properties, pier geometry, and time [1, 18]. The depth of scour d_s can be expressed as follows:

$$d_s = f(W, D, y, V, g, d_{50}, \rho, \mu, \psi, t_e, t) \quad (1)$$

in which W = flume width, D = diameter of the pier, y = flow depth, V = mean velocity of flow, g = gravitational acceleration, d_{50} = the median grain size, ρ and μ are density and dynamic viscosity of water, respectively, ψ indicates the scour type i.e. live bed scour or clear-water scour, t = time and t_e = time to equilibrium. Using dimensional analysis, eqn. 1 can be written in non-dimensional form as:

$$\frac{d_s}{D} = f\left(\frac{W}{D}, \frac{y}{D}, F_r, \frac{d_{50}}{D}, R_e, \psi, \frac{t}{t_e}\right) \quad (2)$$

in which F_r = Froude number of the incoming flow ($F_r = V/\sqrt{(gy)}$), and R_e = Reynolds' number = $\rho VR/\mu$; R = the hydraulic radius of the flume's cross section. After simplification of eqn. 2 and eliminating the variables that are not very influential to scour e.g. R_e and those with constant values in this study such as W, and y, one can obtain:

$$\frac{d_s}{D} = f\left(F_r, \frac{d_{50}}{D}, \psi, \frac{t}{te}\right) \quad (3)$$

The dependence of d_s on the grain size, as shown in eqn. 3, was investigated in the present study.

Experimental Setup

The experiments were conducted in a rectangular transparent flume. The total length of the fume was 10.55 m, including the inlet, the outlet and the working section. The flume has 0.50 m and 0.30 m depth and width respectively and was constructed on an adjustable steel frame, with its bed 1.60 m (approximately) above the floor. The flume is equipped with two controlling gates - vertical sluice gate at the upstream end and a tailgate at the downstream end. Water was delivered to the flume by a pump having a capacity range of 70 -180 m^3/hr. The discharge was measured by a V-notch installed at the downstream end in the outlet part (Figs.1 and 2). The discharge was increased gradually with the gate adjusted to maintain a constant flow depth (y) of 0.20 m in all the experiments. After reaching to the required discharge the downstream gate was adjusted to reach the desired flow depth. The discharge and the flow depth were held constant during the entire experiment time. Two values of discharges were used corresponding to two Froude numbers (F_r) 0.2 and 0.1. A point-gauge mounted on a sliding aluminum frame was used to measure surface elevations. The test setup is shown in Figs.1, 2 and 3.

The following well-known formula was used to calculate the flow rate or discharge [19]:

$$Q = \frac{8}{15} C_d \tan\frac{\phi}{2} \sqrt{2g} (H - H_0)^{5/2} \quad (4)$$

Where, Q = Flow rate; C_d = Discharge coefficient; H = Final head; H_0 = Initial head

Description of the Experiments

The reinforced plastic circular piers of 1 and 6 cm diameters were used. The bed was levelled with the soil and initial level of bed was measured with the sliding point gauge before the start of flow in the flume. All the levels of bed with different experiment were observed with the same moving gauge installed at upstream and downstream separately. For every experiment, the discharge was kept the same and the water was allowed to flow for the duration of 6 hours. After each defined interval, the elevation of the sand bed was gauged with the same moving gauge. Scour depth measurements were recorded along three directions which were longitudinal (x), transverse (y) and vertical (z) directions.

A total of 14 experiments were done for different flow conditions as listed in Table 1. The experiments were conducted to investigate the effect of the soil grain sizes on the scour-hole dimensions and to observe the variation of the scour-hole under the condition of clear-water scour. Sieve analysis was used to determine grain sizes distribution of the soil and to find grain size d_{50} of the three types of soil used in this study.

Results and Discussion

In the clear-water scour experiments, the scour depth continuously increased with time. About 93% of d_s occurred in the first 360 minutes (6 hours). This time (360 minutes) was therefore considered as time to equilibrium (t_o) [18] and the maximum scour depths (d_{sm}) in the following experiments were measured at this time and presented in Table 1.

The spatial pattern of the scour-hole was examined at different grain sizes of the clay and sand soils and at different Froude numbers at the equilibrium time (t_o). Figs.4 (a) and 4 (b) show the dimensions and shape of the scour-hole in the stream (i.e. longitudinal, x), and across (i.e. transverse, y) directions of the channel, respectively for Froude number = 0.2. From Fig.4 (a), it is evident that there is a quasi-linear rate decrease of d_s with the distance away from the pier. The maximum scour depth in the clayey soil varies from 0.5 to 0.9 times the maximum scour depth observed in the sandy soil. As shown in Fig. 4 (b), the profiles reflect similarity of the flow field in the transverse direction (y) of the channel at either side of the pier.

It was noticed that all the profiles upstream of the pier maintain steep slope closer to the pier up to certain location, after that the slope became milder. The scour-hole profiles were still within the flume's boundaries and did not reach the sides, as shown in Fig. 5. On the downstream side of the pier, the profiles showed approximately flat bed very close to the pier, then steep slope followed by mild slope.

Table 1 also illustrates the influence of pier diameter on the maximum scour depth, measured right upstream of the pier. The results of experiments 1 to 8 (with two different sizes of diameters) showed that the maximum scour depth increases with the increase in the pier diameter. In case of using pier size = 6 cm, the maximum scour depth reaches almost 3 times the maximum scour depth when using pier size =1 cm. Also, the scour-hole volume, in case of 6 cm pier diameter, increased between 2.2 to 3.6 times more than the volume of scour-hole in case of using 1 cm pier diameter. An example of these results is also graphically shown in Figs. 4 and 6. Table 1 also shows the effect of Froude number on the depth of scour. For sandy soil (d_{50}= 0.1 mm), depth of scour slightly increases with increase in the Froude number. The scour-hole volume also increases slightly (from 6% to 10%) when Froude number of the flow changes from 0.1 to 0.2. For the pier size of 1 cm, the maximum scour depths in the clayey soil were 0.38 and 0.73 times the maximum scour depth occurred in the sandy soils for the two Froude numbers 0.1 and 0.2 respectively. The volume of scour-hole in the clayey soil, however, was about 0.7 times the scour volume in the sandy soils. For the pier size of 6 cm and at the same Froude numbers, the maximum scour depths in the clayey soil were 0.49 and 0.90 times the maximum scour depth observed in the sandy soils. The volumes of scour-hole in this case were 0.35 and 0.38 times the scour volume in the sandy soils. It was observed that in case of the two soils with d_{50} sizes as 3 and 0.1 mm the smaller pier size (pier diameter = 1 cm) has no much effect on the scour development. There were significant differences in the volume of the scour-hole for the three grain sizes (d_{50} = 3, 0.1, 0.002 mm) when using the bigger pier sizes and the higher Froude numbers. The maximum scour depth increases as the pier diameter increases. In case of using 6 cm piers, the maximum scour depths reach almost 3 times the maximum scour depths when using 1 cm piers. Also, there were substantial increase in the scour-hole volume in case of 6 cm piers compared to 1 cm piers.

CONCLUSIONS

In the present study, local scour around a circular bridge pier was experimentally studied under different sizes of the soils (d_{50} = 3, 0.1, 0.002 mm) for clear-water conditions. Based on the obtained results, it can be concluded that the grain size affects the volume of scour-hole and maximum scour depth and plays a critical function in the scour process. The results showed that, in general, the scour depth in the clayey soil is less than that in the sandy soils. It was observed that in the case of the two soils with d_{50} sizes as 3 and 0.1 mm the smaller pier size (pier diameter = 1 cm) has no much effect on the scour development. There were significant differences in the volume of the scour-hole for the three grain sizes (d_{50} = 3, 0.1, 0.002 mm) when using the bigger pier sizes and the higher Froude numbers. For sandy soil (d_{50} = 0.1 mm), depth of scour slightly increases with increase in the Froude number. For the pier size of 1 cm, the maximum scours depths in the clayey soil were 0.38 and 0.73 times the maximum scour depth occurred in the sandy soils for the two Froude numbers 0.1 and 0.2 respectively. However, for the pier size of 6 cm (at the same Froude numbers), the maximum scour depths in the clayey soil increases to 0.49 and 0.90 times the maximum scour depth observed in the sandy soils.

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***Table 1**. Summary of the experiments.*

Exp. No.	d_{50} (mm)	D (m)	F_r	d_s (m)	d_s/D	Vol.(cm^3)
1	3	0.01	0.2	0.015	1.5	375.7
2	3	0.01	0.1	0.015	1.5	354.8
3	3	0.06	0.1	0.048	0.8	768.9
4	3	0.06	0.2	0.046	0.77	835.9
5	0.1	0.06	0.1	0.052	0.87	1266.2
6	0.1	0.06	0.2	0.047	0.78	1328.4
7	0.1	0.01	0.2	0.015	1.5	371.4
8	0.1	0.01	0.1	0.013	1.3	338.8
9	0.002	0.01	0.2	0.011	1.1	311
10	0.002	0.06	0.2	0.042	0.7	682
11	0.002	0.06	0.1	0.025	0.42	275
12	0.002	0.01	0.1	0.005	0.5	7.1
13	0.002	0.03	0.2	0.032	1.07	430
14	0.002	0.03	0.1	0.018	0.6	76.4

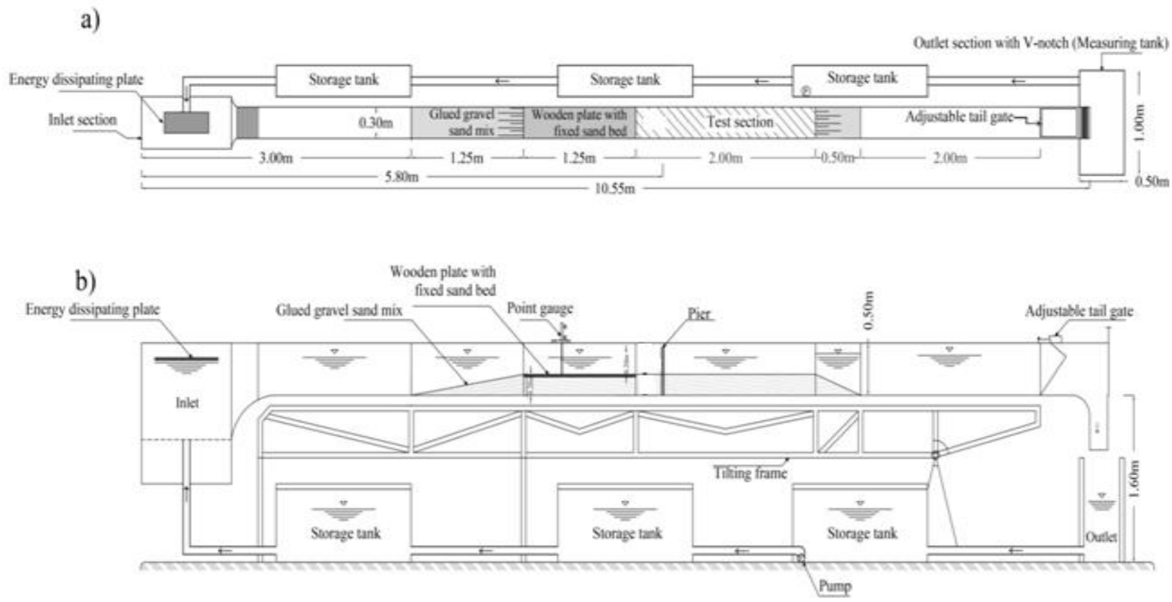

Fig.1. *Schematic view of the experimental setup: a) plan view and b) side view.*

Fig. 2. *Rectangular transparent glass flume.*

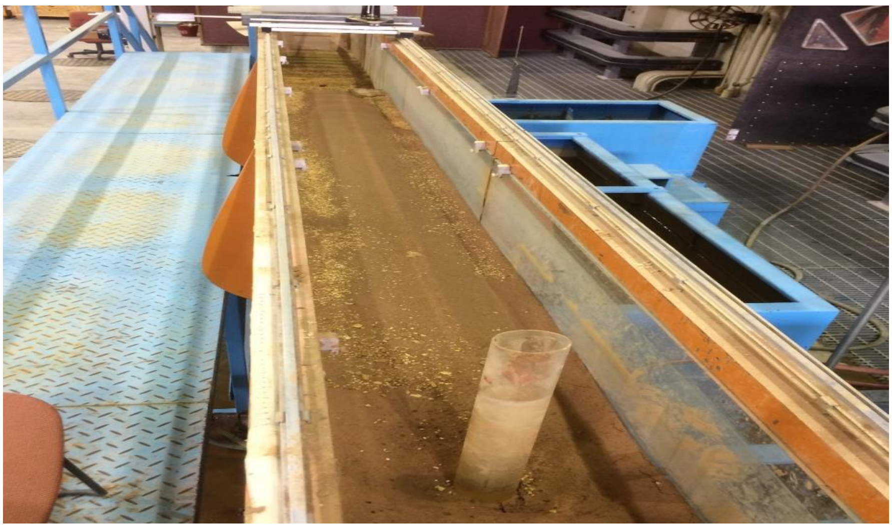

Fig. 3. *Top view of the flume with the pier setup.*

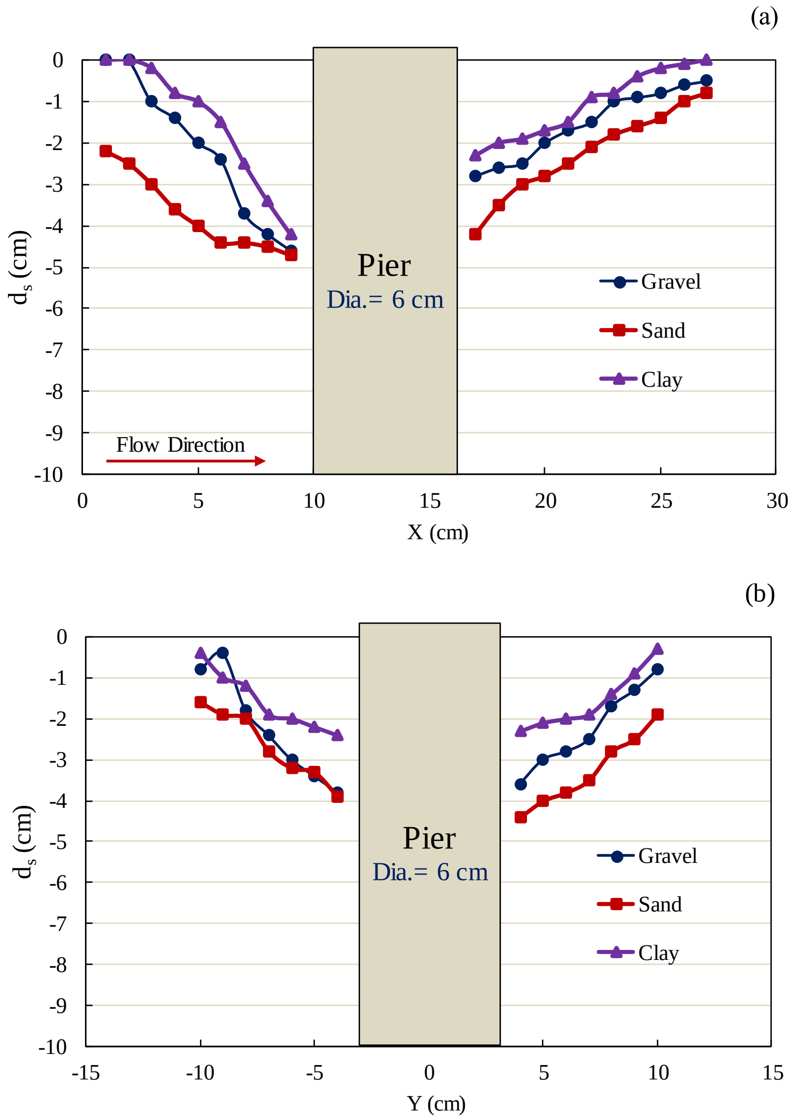

***Fig. 4**. The profiles of the scour-hole (a) in the flow direction (b) across the channel.*

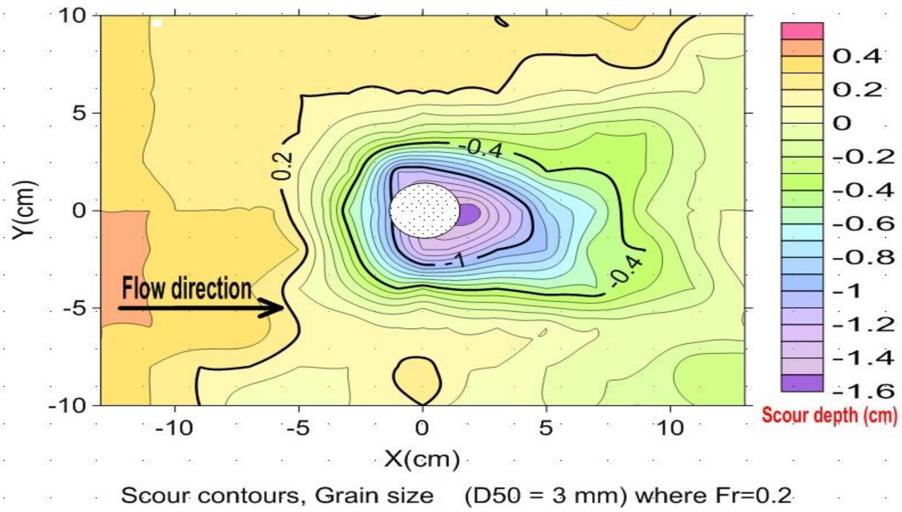

***Fig. 5**. The size of scour-hole.*

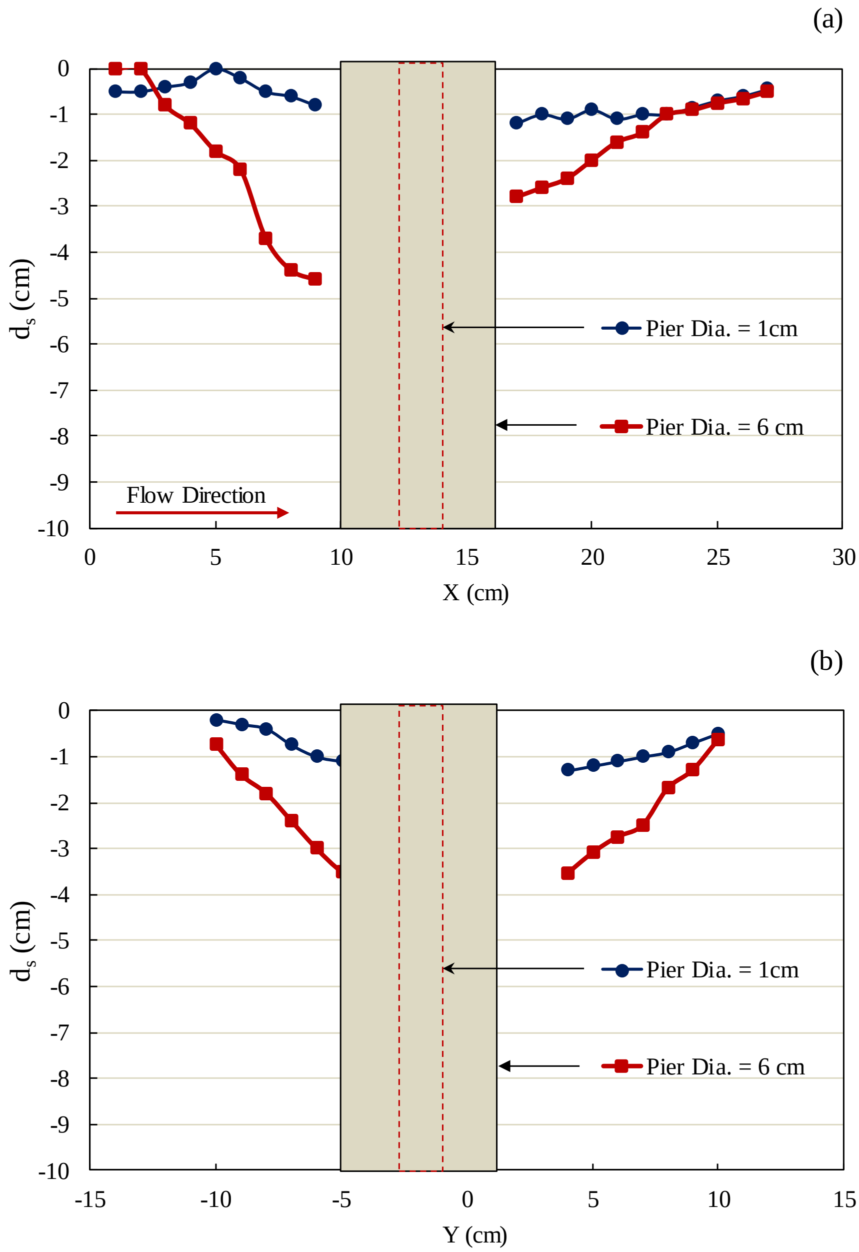

***Fig. 6**. Effect of pier diameter on the profile of scour-hole (a) in the flow direction (b) across the channel (soil d_{50} = 3 mm and F_r = 0.2).*

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