Armouring and Its Effects on Local Scour around a Bridge Pier in Non-uniform Sediments

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***Abstract*—Bridges constitute an important part in the infrastructural development of any nation by connecting the regions and parts separated by water bodies and by providing access to inaccessible areas. Scour around bridge elements is one of the major causes of bridge failures and approximately 60 % of the bridge failures take place due to scour and other hydraulic related issues. Researchers have devoted significant time and attention towards this issue, but the research work is mainly concentrated towards uniform sized sediments. However, in nature no stream exists with truly uniform sized sediments. Therefore it is essential to carry out research work in non-uniform sediments. The main feature associated with non-uniform sediments is the formation of an armour coat which differentiates the non-uniform sediments from the uniform sized sediments. The armour coat by its presence prevents the scour up to certain velocity but once the armour layer is dislodged, the scour depth starts increasing again and becomes nearly equal to that of scour in uniformly sized sediments. As evident from the open literature, the correlation between the velocity of flow and stability of armour layer is yet to be established. Thus, an experimental investigation has been planned and experiments are being carried out in uniform flow, unsteady flow in discrete steps and some non-uniformity in the flow in the form of hydrographic run. The sediments used in the study were collected from River Yamuna and non-uniformity was generated by artificially mixing of sediments in different proportions. The results of the experimental investigation are being presented in this paper.**

***Index Terms*—Armour layer, hydrographic run, non-uniform sediment, unsteady flow.**

I. Introduction and Literature Review

Scouring refers to the erosion of sediments in a stream due to the action of flowing water [1]. When flow passes through a bridge, due to reduction in the cross sectional area of the stream, water level rises just upstream of the pier creating positive pressure difference as shown in Fig. 1. This positive pressure difference is referred to as adverse pressure gradient and is responsible for flow separation and descending flow. The combined action of descending flow and flow separation leads to the formation of horseshoe vortex and wake vortex. The horseshoe vortex carries the eroded bed material downstream essentially as bed load, and wake vortex picks up the sediment particles form the bottom and carries them downstream in the form of suspension [2].

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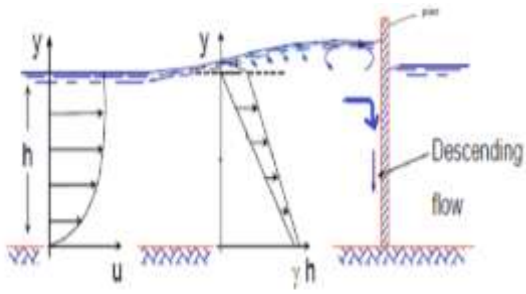

Fig. 1. Flow features around a bridge pier.

Fig. 2. Primary armour layer formed on mobile bed in the laboratory flume.

The main feature of non-uniform sediments is to form an armour coat, which protects the scouring of the underneath particles upto certain extent. The armour layer mainly consists of coarser sized particles which get deposited over finer particles, thus giving a protective cover to scour or erosion of the sediments. According to Baker (1986), around the threshold condition v/vc≈1, armouring occurs on the approach flow bed and at the base of the scour hole which helps in the reduction of scour depth around bridge pier. But at high values where the flow is capable of eroding all sized sediments, the non-uniformity of the sediments has only a minor effect on the scour depth [3]. The armour layer formed on the channel bed is referred to as primary armour layer (Fig. 2) and armouring on the base of scour hole is known as secondary armour layer [4] (Fig. 3). The scour depth in armored beds is less than that in unlayered beds, as the scour hole is shielded by the secondary armor layer formation, but once the secondary armor layer are scattered within the scour hole, the scour depth in armored beds is greater than that in unlayered beds (Dey and Raikar, 2007) [4]. The non-uniformity of the sediments is characterized by geometric standard deviation (σ_g), which is defined as the ratio of d_{84} size of particle to d_{50} size of particle (σ_g=d_{84}/d_{50}) [5]. At low velocities the armour layer forms a protective covering over the underlying sediments but at higher velocities armour layer is destroyed and scour depths starts increasing up to the equilibrium scour depth. The equilibrium scour depth in case of non-uniform sediments is found to be less than that in case of uniform sized sediments

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due to the formation of a protective covering known as armouring [3]-[5]. But at high velocities, the effect of armouring vanishes and the equilibrium scour depth for non-uniform sediments is found to be equal to that of uniform sediments (Melville and Chiew, 1989) [3]-[6].

Fig. 3. Secondary armour layer formed around a pier in the laboratory flume.

A lot of work has been done in the recent past on this topic covering various aspects of scour. The prediction part has been extensively investigated, and part dealing with mechanism and protection against scour needs further exploration. Researchers have devoted a lot of time and attention towards this issue, but the studies are mainly concentrated in uniformly sized sediments. Therefore, scour related phenomenon needs to be explored in the non-uniformly sized sediments. Garde (1998) emphasized that a lot of work had been done on the uniformly sized sediments, and the researchers were required to devote some time towards non- uniformly or well graded sediments [7].

The current method of estimation of scour depth (Lacey-Inglis method) used in the design of bridge piers sometimes gives excessive scour depth, which occurs after a very long time of design flow leading to uneconomical design of bridges. Some others researchers had also given equations to estimate the equilibrium scour depth but mainly the researchers have considered the median sediment size without giving much importance to the non-uniformity of the sediments in terms of geometric standard deviation (σ_g).

But it has not been well established about the velocity upto which armour layer becomes stable and act as a protective covering for the underneath particles. The temporal variation of the stability of the armour layer has also not been well established in the literature. Baker (1986), Melville and Chiew (1989), Kothyari (2008) have significantly contributed in the research in non-uniform sediments.

Upon a review of the literature, it may be inferred that there is a gap in the stability of the armour layer:

- It was found that the corelation of the velocity and the stability of the armour layer were not well established.
- The influence of non-uniformity of sediments on formation and stability of armour layer has also not been depicted in the literature.
- The effect of unsteadiness of flow on scour depth was also not found in the open literature.
- The effect of non-uniformity of sediments (in terms of standard deviation) is to be related with the scour depth to estimate the correct scour depth by considering the variation of the sediments.
- The temporal variation of scour depth around bridge piers in non-uniform sediments ware not well established [8], [9].
- In the past, the studies were mainly carried out in clear water conditions. However, live bed conditions exist in prototype particularly during floods. Therefore the different aspects of bridge scour needs to be explored in live bed conditions [10].

Thus, to bridge this gap in information, there is a need to develop an equation relating the scour depth with the non-uniformity of the sediments in terms of standard deviation. Therefore, it is essential to carry out research work in non-uniform sediments with special reference to the armour layer. In order to achieve these objectives, an experimental study was planned and conducted.

II. Experimental Work and Procedure

The experimental work and the results reported herein is a part of a bigger experimental programme to study the effect of non-uniformity of sand on scour depth and scour related phenomena. The study was carried out in the Fluid Mechanics laboratory of Department of Civil Engineering, National Institute of Technology, Kurukshetra. The experiments were carried out in a recirculating flume of length(L), width(B) and height(H) 15m, 0.4m, and 0.5m respectively with circular piers of diameter 25mm, 30mm, 40mm, 50mm, 65mm, 75 mm and 100 mm. The experimental work was divided into 3 phases and in each phase the non-uniformity of sediments was increased. The effect of diameter of piers on scour depth was also studied by keeping the depth of flow and velocity as constant for one set of piers. The duration of the experiment was kept as 5 hours to study the time scale variation of the scour depth. The scour depth readings were taken after the duration of 5, 10, 20, 30 minutes, and then at 1 hour interval up to 5 hours with the help of a point gauge. The experiments were also carried out in discrete steps unsteady flow and non-uniform flow in the form of hydrographic run. A typical definition sketch indicating the schematic and symbols used in the experimental investigation and study are as shown in Fig. 4.

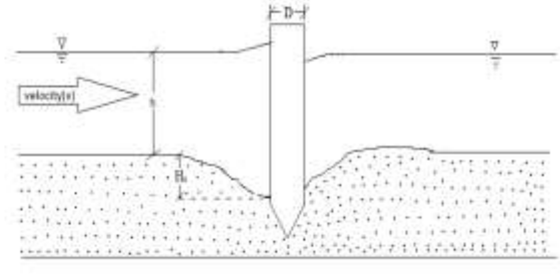


Fig. 4. Definition sketch of symbols.

The scheme of experiments is given in Table I.

TABLE I: SCHEME OF EXPERIMENTS

Type of flow	Velocity (m/sec)	Diameters (mm)	Sediment type
Uniform flow	3 variations (0.21,0.25,0.29)	7 variations (25,30,40,50,65,75,100)	Sediment A $d_{1,50}$=0.22mm, σ_g =1.86 Sediment B- $d_{2,50}$=0.30mm, σ =3.0
Unsteady flow (Rising Trend)	10 variations (0.12-0.56)	on 40 mm pier	Sediment A $d_{1,50}$=0.22mm, σ_g =1.86 Sediment B- $d_{2,50}$=0.30mm, σ =3.0
Unsteady flow (Rising and Falling Trend) (Hydrographic run)	10 variations (0.13-0.43-0.16)	on 40 mm pier	Sediment A $d_{1,50}$=0.22mm, σ_g =1.86 Sediment B- $d_{2,50}$=0.30mm, σ =3.0

III. RESULTS AND DISCUSSIONS

The experiments were conducted on two types of sediments based on the median sediment size (d_{50}) and standard deviation (σ_g) and under three types of flow conditions as given in Table I.

A. *Uniform Flow*

The experiments were conducted for three different velocities on seven sets of piers. Temporal variation of scour depth for all piers for the 5 hour duration is presented in Fig. 6 and 7 for sediment A and sediment B respectively. Further the figures have nomenclature as subscript a, b, c, d, e, and f. Subscript a, c, and e represents the temporal variation of scour depth, while subscript b, d, and f represents the variation of non-dimensional values of scour depth with the diameter of pier and time.

The results of the 5 hour test run representing temporal variation of scour depth are being presented in this paper. The first reconnaissance of the results shows the strong dependence of scour depth on the diameter or size of cylindrical pier. The smallest of the diameters has the least scour depth and the biggest, the highest. From the graphs shown below, it can be concluded that for smaller diameter piers scour occurs at a progressive rate in the beginning of the experiment; but with the passage of time rate of scour decreases and becomes nearly constant. For larger diameter piers, rate of scour also decreases with time, but this rate of decrease of scour is less as compared to smaller diameter piers. The scour depth seems to be increasing even after the 5 hours run. The notations used to indicate the different diameter of piers is as shown in Fig, 5.

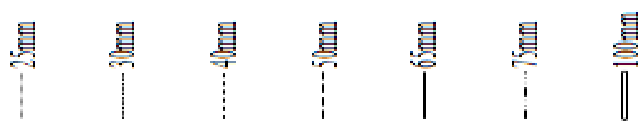


Fig. 5. Symbols representing piers of different diameters

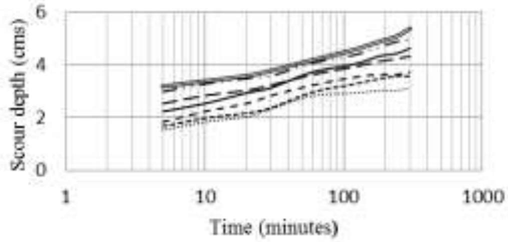


Fig. 6(a). Temporal variation of Scour depth on seven pier sizes (v=0.21m/sec, h=0.078m, d_{50}=0.22mm σ_g =1.86).

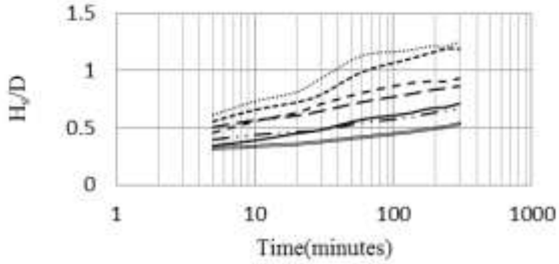
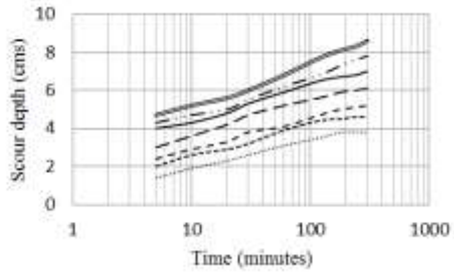
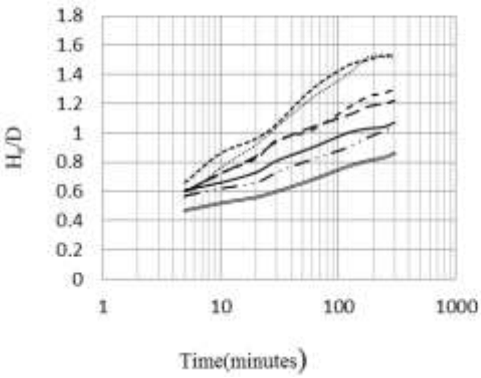


Fig. 6(b). Variation of non-dimensionalised scour depth with time on seven pier sizes (v=0.21m/sec, h=0.078m, d_{50}=0.22mm σ_g =1.86).



Fig, 6(c). Temporal variation of Scour depth on seven pier sizes (v=0.25m/sec, h=0.098m, d_{50}=0.22 mm, σ_g =1.86).



Fig, 6(d). Variation of Non-dimensionalised scour depth with time on seven pier sizes (v=0.25m/sec, h=0.098m, d_{50}=0.22 mm σ_g =1.86).

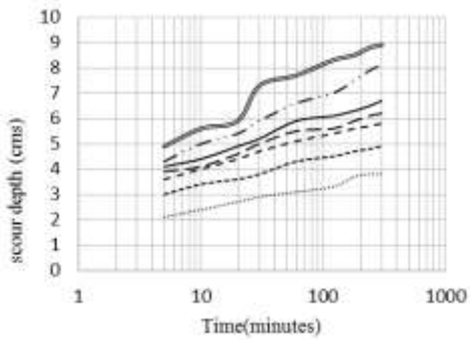


Fig. 6(e). Temporal variation of Scour depth on seven pier sizes (v=0.29m/sec, h=0.103m, d_{50}=0.22 mm σ_g =1.86)

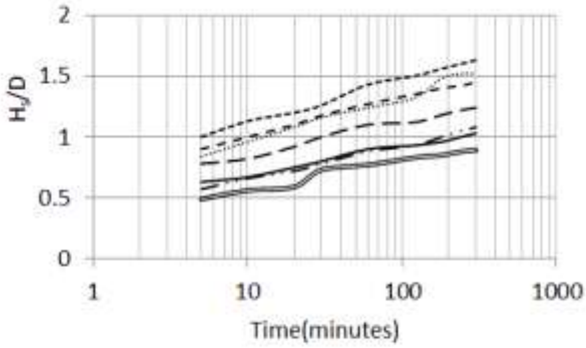


Fig. 6(f). Variation of Non-dimensionalised scour depth with time on seven pier sizes (v=0.29m/sec, h=0.103m, d_{50}=0.22mm σ_g =1.86).

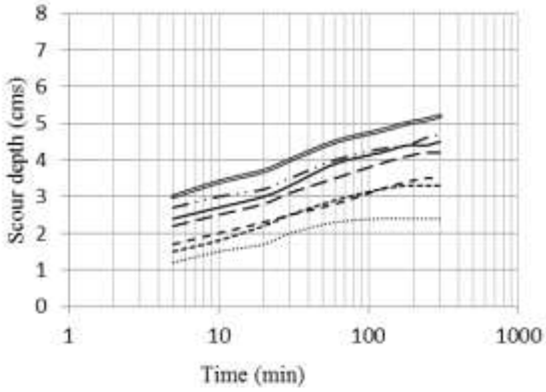


Fig. 7(a). Temporal variation of Scour depth on seven pier sizes (v=0.21m/sec, h=0.078m, d_{50}=0.30mm σ_g =3.0).

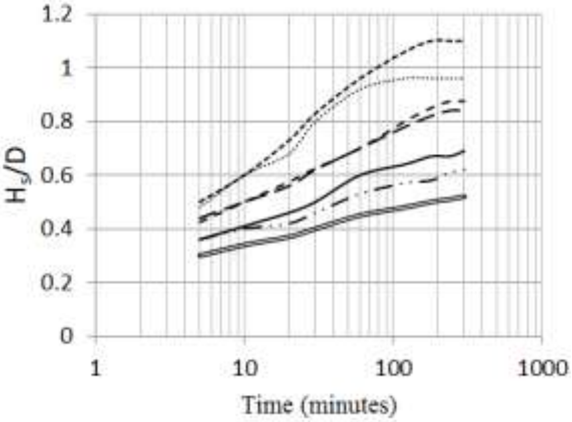


Fig. 7(b). Variation of Non-dimensionalised scour depth with time on seven pier sizes (v=0.21m/sec, h=0.078m, d_{50}=0.30mm σ_g =3.0).

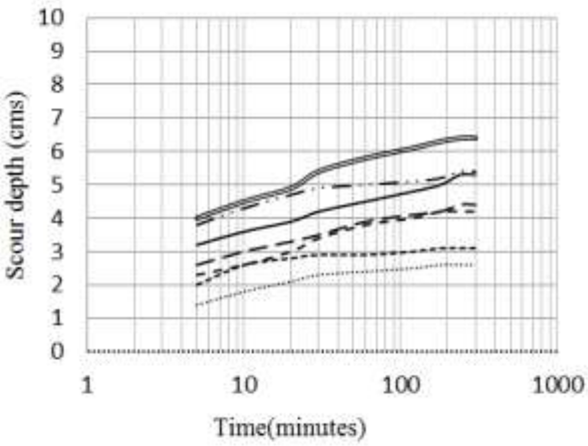


Fig. 7(c). Temporal variation of Scour depth on seven pier sizes (v=0.25 m/sec, h=0.097m, d_{50}=0.30mm σ_g =3.0).

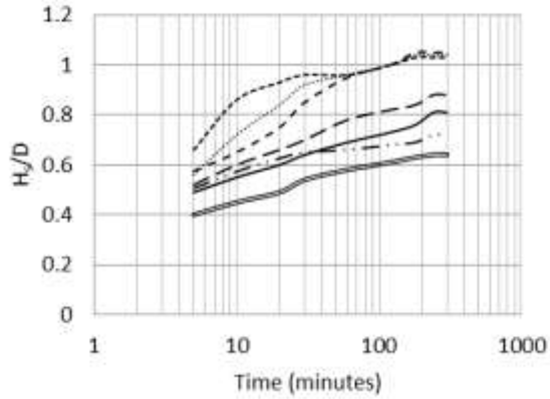


Fig. 7(d). Variation of Non-dimensionalised scour depth with time on seven pier sizes (v=0.25m/sec, h=0.097m, d_{50}=0.30mm σ_g =3.0).

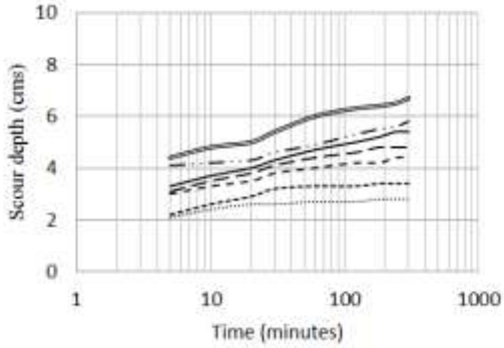


Fig. 7(e). Temporal variation of Scour depth on seven pier sizes (v=0.29m/sec, h=0.103m, d_{50}=0.30mm σ_g =3.0).

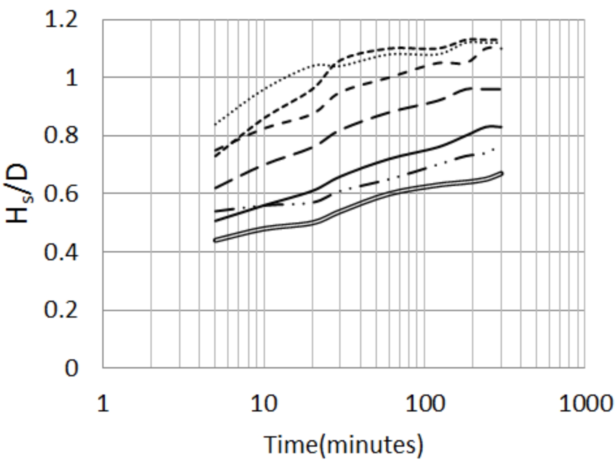


Fig. 7(f). Variation of Non-dimensionalised scour depth with time on seven pier sizes (v=0.29m/sec, h=0.103, d_{50}=0.30mm σ_g =3.0).

The second observation from the above graphs shows that with increase in the non-uniformity of the sediments the scour depth is reduced due to the formation of the secondary armour layer on the base of the scour hole. Initially, the scour occurs at a rapid rate, but after the formation of secondary armour layer on the base of the scour hole, the rate of scour almost ceases or increases at a very slow rate. Due to the action of upstream descending flow, the underneath finer particles gets eroded and transported through the voids of the secondary armour layer when the scour hole is partially covered by secondary armour layer leading to the continuous increase in the scour depth. This increase in scour depth is very less till the secondary armour is stable and acts as a protective layer. The scour hole at a pier develops through the armour layer, and the equilibrium of scour hole reaches when it is fully covered with secondary armour layer. When the scour hole is shielded by secondary armour layer, the scour depth in non-uniform sediments is found to be less than that of the uniform sized sediments. But once the armour layer gets scattered within the scour hole, the scour depth in non-uniform sized sediments is greater than that in uniform sized sediments.

However the non-dimensionalized values of the scour depth with the diameter of the pier shows reverse trend with smallest diameter having highest value and largest diameter having the least. The reverse nature of non-dimensionalized scour depth with time shows that scour depth strongly depends on the diameter of the pier; however it depends on some other parameters as well [11].

The armour layer acts as a protective layer at a velocity much greater than the armour layer. In the present study, the primary armour layer and secondary armour layer both were stable at velocity about 1.2 times the incipient velocity of flow. Once the velocity exceeds 1.2 times the incipient velocity, the primary armour layer gets scattered at different locations, but secondary armour layer still acts as a protective covering in the scour hole. Further increase in the velocity leads to the dislodging of secondary armour layer too, leading to the rapid increase in the scour depth. It was observed that the formation of various bed forms and features (ripples and dunes) also ceases with increase in the non-uniformity of the sediments.

The 5-hour maximum scour depth can be related with the diameter of the pier, velocity of flow, median sediment size, and standard deviation of the sediments using non-linear regression in XLSTAT by the Equation 1 given below:-

$$H_s = \frac{0.45V^{0.88}D^{0.54}}{{\sigma_g}^{0.39}d^{0.11}} \qquad (1)$$

where,

H_s= scour depth measured from the average bed level (m)

V=velocity of flow (m/sec)

D=diameter of the pier (m)

σ_g =geometric standard deviation ($\sigma = d_{84}/d_{50}$)

d= median sediment size (d_{50}) (m)

A plot between observed and predicted values of the scour depth is as shown in Figure 8. However, the all values lie within the 15 % variation line justifying the goodness of the equation.

B. Unsteady Flow (Rising Trend)

In the second phase, experiments were conducted under unsteady flow conditions in discrete steps of varying velocity for the 5 hours duration. Velocity of flow was varied form a small value equal to 0.12 m/sec to 0.56 m/sec. Enroute the conditions of scour changed from clear water scour to live bed scour. In order to avoid the side wall effects [11], a pier diameter of 40 mm was identified for the flume of width 400 mm, thus giving an aspect ratio (B/D) of 10. The results of the 5 hour test run are as shown in Fig. 9(a) to 9(d).

From the above graphs, it can be observed that an increase in the discharge results in the corresponding increase in velocity of flow, depth of flow, and scour depth. The scour depth continued to increase as the velocity was increased continuously and sediments in suspension remained in suspension and no deposition in scour hole took place.

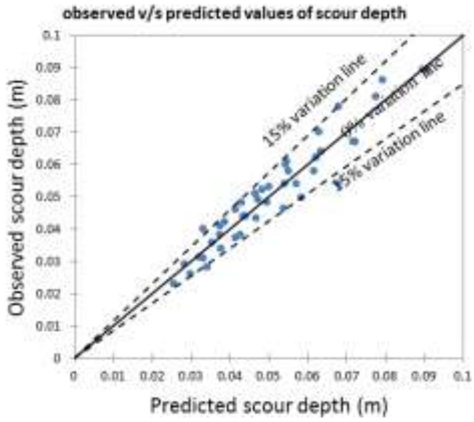
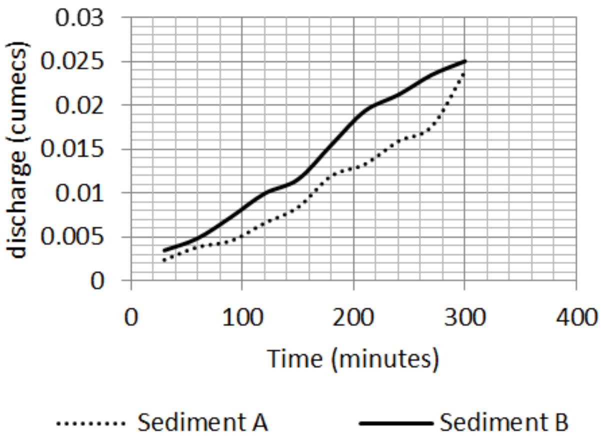
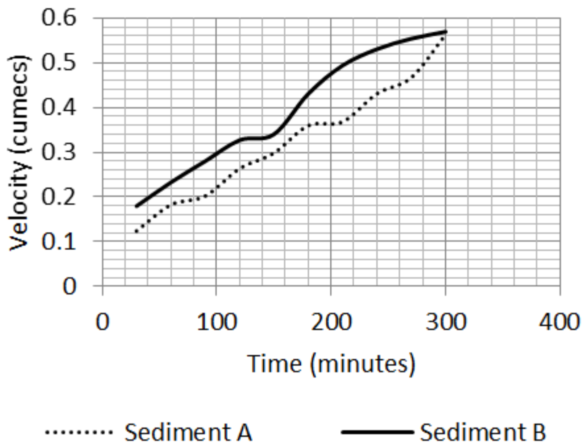


Figure 8. Observed v/s predicted values of 5-hour scour depth.



(a).



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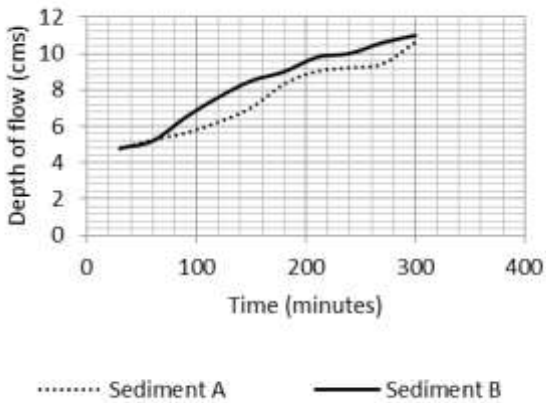
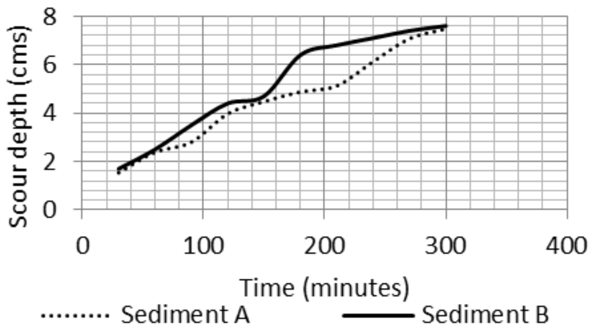


(c).



(d)

Fig. 9. Temporal variation of various flow parameters for two types of non-uniform sediments.

The scour depth v/s velocity graph (Fig. 10) clearly shows that scour depth in sediment B (d_{50}=0.30mm and σ_g =3), is less than scour depth in Sediment A (d_{50}=0.22mm and σ_g =1.86) due to the formation of armour layer. But after the scattering of the armour layer, the scour depth increases rapidly and the maximum scour depth (H_{sm}=7.6 cm) after 5 hours was found to be greater than that of the previous case (H_{sm}=7.475 cm). Thus, it can be concluded that the scour depth in case of non-uniform sediments is found to be less than that of uniform sized sediments till the armour layer acts as a protective layer, but once the armour layer is dislodged the scour depth in case of non-uniform sediments is found to greater than the uniform sized sediments.

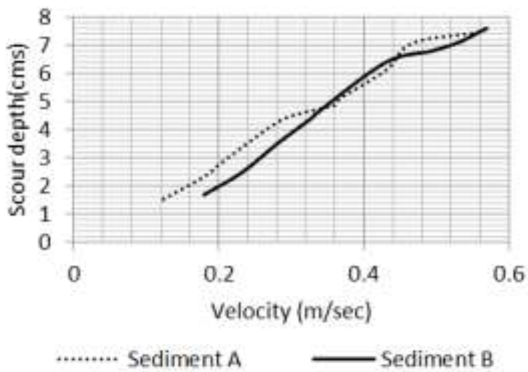
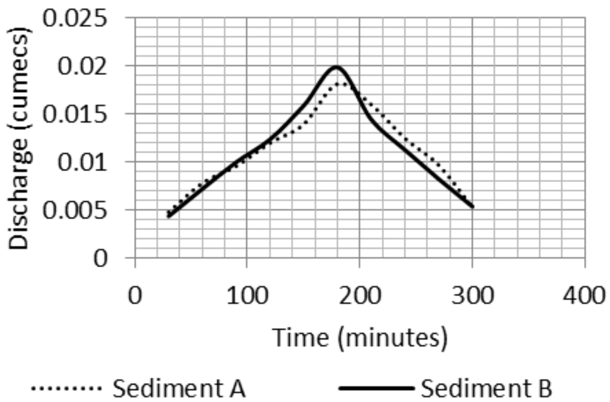
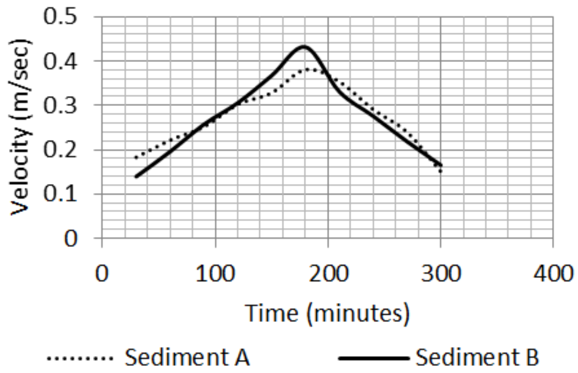


Fig. 10. Comparison of scour depth at varying velocity for sediment A and sediment B.

C. *Unsteady Flow (Rising and Falling) (Hydrographic Run)*



(a).



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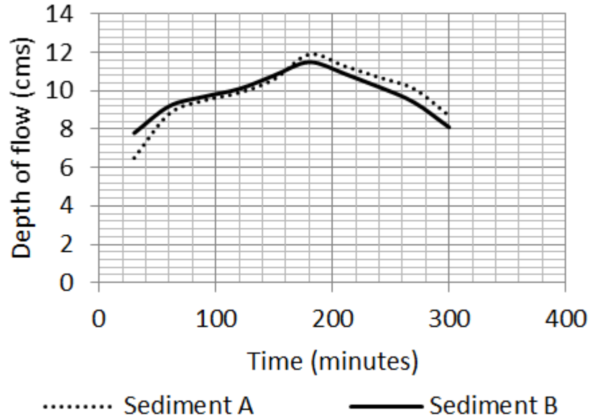

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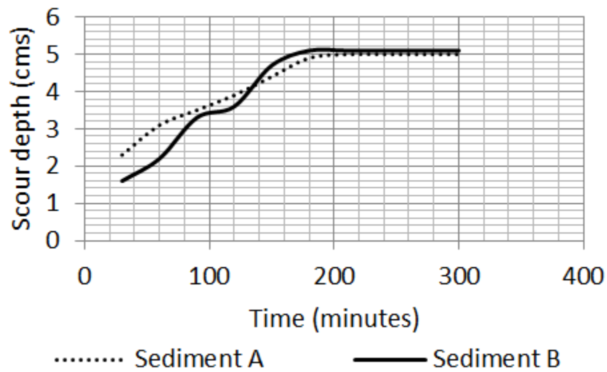

(d).

Fig. 11. Temporal variation of flow parameters in hydrographic run for two types of sediments

To simulate the natural flow conditions in the laboratory, some non-uniformity is introduced in the flow in the form of hydrographic run. Discharge in the flume was increased in steps to reach a peak and thereafter it was decreased to come back to the initial value of first step. Velocity, depth of flow, and scour depth being the dependent parameters responded accordingly. The test run was made for 5 hours on 40 mm and the results of the hydrographic run are as shown in Fig. 11(a) to 11(d).

With an increase in the velocity of flow, scour depth also increased and correspondingly reached its maximum value. After reaching the peak value, the velocity is decreased gradually. With a decrease in the velocity of flow, the scour depth remained constant as no deposition of sediments took place in the scour hole for the period of experimental run. Based on the sieve analysis, a comparison of sediment properties within and outside the scour hole was made. The properties of the sediments in scour hole were found to be different from that of the rest of the sediments. It was found that sediments in scour hole were composed of coarser sized particles with an increase in the median size of the sediments. The non-uniformity of the sediments in the scour hole was also observed to decrease and uniform coarser sized particles were found to be deposited in the scour hole.

IV. Conclusions

An experimental study was conducted on scouring around circular piers introducing non-uniformity in flow conditions and sediments. The salient conclusions of the study are:

- Researchers in the past have conducted studies on uniform sized sediment and under uniform flow conditions. There is a wide scope to extend the work with non-uniformity of sediment.
- For non-uniform sediment, the scour depth increases with an increase in velocity, but after the formation of armour layer the rate of scour decreases. Further increase in the velocity scatters the armour layer leading to increase in scour depth at a higher rate.
- Most researchers have not considered change in temperature of the stream which can have some effect on the scour depth and scouring pattern.
- The water qualities like salinity of water becomes important in case of offshore bridge piers, the effect of which on scour phenomenon is yet to be explored in detail.
- A very few studies have been carried out for scour in gravel, boulders, clay, and rocky bed rivers. The investigations in these topics can be extended further.

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