EFFECT OF PIER SPACING ON SCOUR DEPTH

submitted in partial fulfillment of the degree

Bachelor in Technology

Under supervision of

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CERTIFICATE

This is to certify that the work titled “**EFFECT OF PIER SPACING ON SCOUR DEPTH** submitted by “**DEEPAK CHOUDHRY(101609) and ANURAG RAJPUT(101615)”** in partial fulfillment for the award of degree of B. Tech Computer Science Engineering of Jaypee University of Information Technology, Waknaghat has been carried out under my supervision. This work has not been submitted partially or wholly to any other University or Institute for the award of this or any other degree or diploma.

(Signature of Supervisor)

Name of Supervisor: DR. ASHISH KUMAR

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Date -

Abstract

One of the main cause of the bridge failure is scour around its piers and abutments. Requirement of new bridge in the close vicinity of existing one is increasing day by day due to rapid urbanization and increased traffic volume. The structure of the flow is significantly altered due to the presence of an obstruction, for example a pier in the flow. This situation becomes even more complex when a new bridge is constructed in the close vicinity of existing one. The proposed new bridge interfere the flow geometry and hence it alter the flow structure around the existing one and for itself also. This interference depends upon the stream wise spacing between the bridges. The main objective of the present work is to find the optimum distance between the two bridges so that new bridge constructed in the vicinity of old bridge or vice versa by studying the mechanism of scour and scour depth at bridge piers. Keeping the objective in mind, present work is carried out through the set of laboratory experiments conducted in the hydraulic laboratory of Civil Engineering Department JUIT Waknaghat. The present investigation will be an add to design the new bridge in the proximity of old one.

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Chapter 1
INTRODUCTION

1.1 GENERAL

Bridges constitute an important part of the transportation system in the sense that they are required wherever waterways are crossed by roads, railways etc. Piers on which the superstructure of these bridges rests, play an important role in their stability and safety. Failure of bridges due to scouring of piers at their support is not an uncommon occurrence. The scour is the local lowering of the stream bed elevation which takes place in the vicinity or around a structure constructed in the flowing water. The scour around the pier is a result of the development of high shear stress due to the three-dimensional separation of the boundary layer which results in a high level of turbulence and vorticity around the piers. The estimation of the correct depth of scour below the stream bed is very important since that determines the depth of foundation.

Most existing relationships for determination of local scour depth at bridge piers apply to piers with a constant cross-sectional dimension over the full length of the pier. Therefore, most existing scour-depth equations are expressed in terms of a single pier dimension, usually the projected pier width normal to the approach flow (for example the pier diameter, b, for cylindrical piers).

1.2 MECHANISM OF SCOUR

When a pier is placed in a stream with its axis normal to the bed, it creates an adverse pressure gradient in the longitudinal direction ahead of the pier and a favorable pressure gradient in the downward direction on its front face. This results in a complex three-dimensional flow system consisting of down flow and a horseshoe vortex in front of the pier and extending past it. Additionally, a wake-vortex system is formed by the rolling up of the shear layers generated at the surface of the pier. Furthermore, a surface roller also forms in front of the pier as shown in Fig. 1.1. These elements of the flow individually or in combination, result in local scour around the pier.

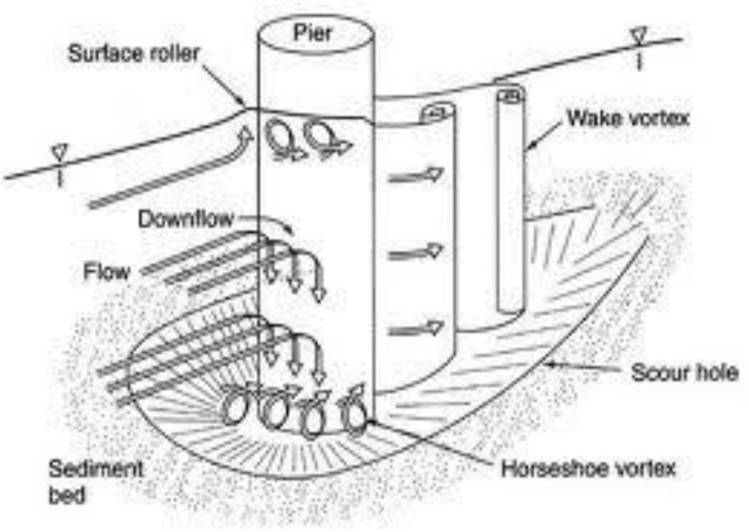


Fig. 1.1: Mechanism of scour

There are two schools of thought about the main cause of local scour around the pier. Shen et al. (1966), Baker (1980b), [as referred by Kumar (1996)] and Kothyari et al. (1992 a) consider the horseshoe vortex to be the main cause of local scour.

1.3 CLASSIFICATION OF SCOUR

The scour in the vicinity of a bridge piers and footings may be classified under the following categories.

1.3.1 Classification Based On Characteristics Of Flow

(a) General Scour occurs in a river or stream as a result of natural process irrespective of whether a structure is there or not.

(b) Constriction Scour occurs if a structure causes the narrowing of the river water course or the rechanneling of berm or flood plain flow. Accumulation of debris and ice-jamming can also add to constriction scour.

(c) Local Scour resulting directly from the impact of the structure on the flow. This scour which is a function of the type of structure is superimposed on the general and constriction scours.

1.3.2 Classification Based On Transport Of Sediment

(a) Clear-water scour

Clear-water scour occurs if the bed material in the natural flow upstream of structure is at rest and the stream is free of sediment. In other words, the shear stress on the bed upstream of the structure is less than the shear stress required for the initiation of particle movement. However, the bed shear stress increases as the flow approaches the structure, resulting in local scour. Final equilibrium is reached when the transport of sediment out of the scour hole is zero. It takes a long time for such a condition to be reached.

(b) Live-bed scour

Also referred to as scour with sediment transport, the term is used to designate scour in case of flow carrying sediment. Here the shear stress on the bed is greater than the critical shear stress. Compared to clear-water scour, this type of scour occurs more rapidly and oscillates non-periodically. Equilibrium is reached when the rate of sediment removed from the scour hole becomes equal to the rate of sediment supplied to the hole. In general, equilibrium scour depths in live-bed conditions are slightly smaller than those in clear-water conditions. It can be seen that, under identical conditions, scour depth in the latter case is about 10% more than the former (See Fig. 1.2).

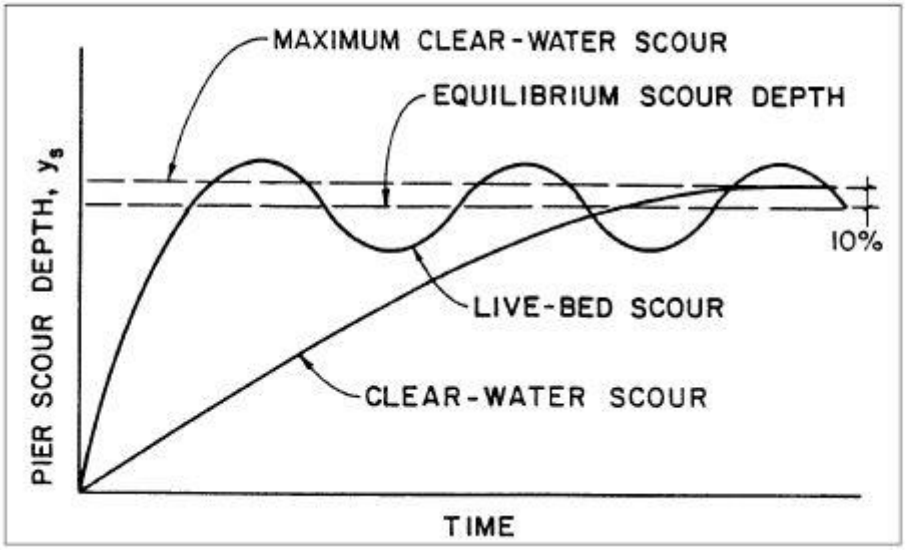


Fig.1.2: Typical variation of scour depth with time for the two cases.

1.4 BRIEF REVIEW

The phenomenon of scour around bridge piers has been studied extensively by a large number of investigators. We have done study related to following:

1. Study related to Local Scour around Circular Bridge Piers.
2. Study related to Effect of Stream-Wise Spacing of Bridge Piers on Local Scour.

3 Study related to Effect of Stream-Wise Spacing of Bridge Piers on Temporal variation of Scour Depth.

1.5 OBJECTIVES OF THE STUDY

The broad objective of the present work is to find the optimum distance between the two bridges so that new bridge constructed in the vicinity of old bridge or vice versa by studying the mechanism of scour and scour depth at bridge piers. his work will be implemented through a set of experiments in the laboratory by conducting detailed measurements on the flow structure around the piers. Additionally the information retrieved on the effect of pier spacing on scour depth around the piers will be useful to develop the mathematical model for determination of temporal variation of scour depth around circular piers.

The following main objectives are stipulated for the present study:

- ➢ To study the effect of stream-wise spacing of circular bridge piers on scour mechanism and scour depth.
- ➢ To study the temporal variation of scour depth around the circular bridge piers on the both bridges piers, by varying the stream wise spacing among the bridge piers.

Mainly we have worked like following:

- Thorough Literature survey related to the topic,
- Planning of Experimental work,
- Execution of experimental programme and collection of experimental data.
- Analysis and discussion of results

1.6 LIMITATIONS OF THE STUDY

The following are the main limitations of the present study:

1. Uniform cohesionless sediment of size 0.5 mm with relative density of 2.65 was used.
2. The experiments are restricted to the case of steady uniform flow.
3. Study is confined only to circular piers.

Chapter 2

REVIEW OF LITERATURE

2.1 GENERAL

Local scour around bridge piers is a complex problem that has been investigated extensively over the past 50 years. As a result, a large amount of literature is available on local scour around bridge piers and its control. Previous scour investigations mainly focused on local scour around piers of constant horizontal cross-section geometry and did not consider the effects of foundation geometry. Only a few investigators (Melville and Raudkivi, 1996) demonstrated that foundation geometry also affects the scour. Detailed review on the topic of scour around bridge piers is given by Kumar (1996) and Garde and Kothyari (1998). Only a brief mention is made below about the scour around uniform circular bridge piers.

2.2 Study related to Local Scour Circular Bridge Piers.

The phenomenon of scour around bridge piers has been studied extensively by a large number of investigators. Numerous studies have been conducted to develop the relationships for scour depth estimation at uniform shaped piers. In India the design depth of scour at bridge piers is estimated as per procedure given in IRC: 78, (2000) and IRC: 5, (1998). Other methods for estimation of scour depth include those by Breusers *et al*., (1977); Melville (1988); Kothyari *et al*., (1992 a, b); Melville, (Kothyari *et al*. (2007) *etc*. A few studies has been explained below.

Ettema *et al.* (1998) emphasized on the scale effects evidently overlooked in studies involving lab-flume experiments on bridge scour. The scale effect is attributable to a well-known hydraulic-modelling constraint imposed by the lower size limit to which cohesion-less alluvial sediment can be geometrically scaled. The constraint requires most lab-flume experiments to use coarser sediment relative to pier width than that typically prevails at bridge sites. It leads to a significant scale effect in simulating the local scour at a pier. Flume experiments, consequently, may produce larger values of maximum scour depth relative to pier width than that would likely occur at actual bridge piers. From the analysis they indicated that similitude of flow field at a circular cylinder requires constancy of U_∞/U_C, U_∞^2/gb, h/b and b/d.

Here b is diameter or width of bridge pier, d is the size of uniform sediment, h is the depth of flow, U_∞ is velocity of approach flow, U_c is velocity of approach flow corresponding to incipient motion of sediment particle in approach flow and g is the gravitational acceleration. They summarized that because of the typical dimensions of laboratory flume as well as the lower size limit of cohesion-less sediment size, it is difficult to satisfy the similitude requirements relating scour in the flume to scour in the river. This difficulty limits the use of laboratory flume data in developing accurate predictors of scour depth at full-scale piers.

Lee and Strum, (2009) conducted the pier scour experiments on rectangular and circular bridge pier models of three different prototype bridge piers with three different sediment sizes using flat-bed models of individual bridge pier, as well as full hydraulic river models of the river bathymetry, bridge piers, and abutments at different geometric scales. to investigate the effect of relative sediment size on pier scour depth. They used the experimental data of present study, three field site measurement monitored by the *USGS* and laboratory data from literature, to investigate the effect of sediment size on scour depth. From analysis of data they found that the relative scour depth is a unique function of the ratio of pier width to sediment size, b/d_{50}, if attention is restricted to data for which the approach flow Froude number is less than 0.4.

Based on regression analysis to all the laboratory data plus three field data points from this study, they developed two equations for pier scour depth

$$\frac{d_{se}}{b} = 5.0\log\left(\frac{b}{d_{50}}\right) - 4.0, \qquad 6 \le b/d_{50} \le 25 \qquad (1)$$

$$\frac{d_{se}}{b} = \frac{1.8}{\left(0.02\,b/d_{50} - 0.2\right)^2 + 1} + 1.3, \qquad 25 \le b/d_{50} \le 1X10^4 \qquad (2)$$

They narrated that the choice of sediment size in the laboratory model distorts the value of b/d_{50} in comparison with the prototype that causes larger values of scour depth in the laboratory than in the field. They explained this model distortion due to sediment size behavior by the scaling, or distortion, of the large-scale unsteadiness of the horseshoe vortex which is directly related to the distortion in b/d_{50}. It was suggested that the quasi periodic oscillation of the horseshoe vortex is related to transport of sediment particles during the scouring process. Two distinct types of sediment motion were observed for two different sediment sizes that ultimately affect the equilibrium scour depth in front of the pier. They further advised for research on the coherent structure of the horseshoe vortex at very large scales.

2.3 Study related to temporal variation of scour around isolated circular bridge piers.

The process of scour around bridge pier is time dependent. The study about temporal variation of bridge scour is important particularly when for predicting the scour depths in unsteady flows such as the flood flows. The temporal variation of scour depth around isolated bridge piers has been studied in the past. Such studies show that the live-bed scour depth under high shear stress could reach an equilibrium condition within a short period of time, *i.e.* a few hours, whereas clear-water scour increases slowly and take days to attain equilibrium or the maximum value. Some of the important contributions on temporal variation of scour are those from Chabert and Engeldinger, (1956); Hjorth, (1975); Ettema, (1980); Islam *et al.*, (1986); and Yanmaz and Altinbilek, (1991); Kothyari *et al.*, (1992 a, b); Melville and Chiew, (1999); Oliveto and Hagar, (2002, 2005); Mia and Nago, (2003); Chang *et al.*, (2004) *etc*. A few of these are explained below.

Melville and Chiew (1999) conducted several series of experiments in order to clarify the effect of time on the development of depth of scour at circular uniform bridge piers under clear-water conditions. A new definition for time to equilibrium was proposed by Melville and Chiew (1999). The equilibrium time t_e was defined as the time at which the scour hole develops to a depth that was considered as d_{se} such that at this condition the rate of increase of scour did not exceed 5% of the pier diameter in the succeeding 24 hours period *i.e.*

$$\frac{d(d_{se})}{dt} \leq \frac{0.05b}{24} \tag{3}$$

An equilibrium time scale ($t^{**} = t_e.U_\infty/b$) was defined. The equilibrium time scale for development of clear-water scour at a bridge pier is a function of flow intensity (U_∞/U_c), flow shallowness (h/b), and sediment coarseness (b/d_{50}). The influence of flow intensity, flow shallowness and sediment coarseness on time scale and equilibrium scour depth (d_{se}) was studied by using the laboratory data. A method was proposed for determination of temporal development of scour depth using pier, sediment and approach flow velocity in which firstly the equilibrium scour depth is computed using Melville, (1997) method. The second step is to determine the t_e from the following equations:

$$t_e(days) = 48.26\frac{b}{U_\infty}\left(\frac{U_\infty}{U_c} - 0.4\right) \qquad \frac{h}{b} > 6 \tag{4}$$

$$t_e(days) = 30.89\frac{b}{U_\infty}\left(\frac{U_\infty}{U_c} - 0.4\right)\left(\frac{h}{b}\right)^{0.25} \qquad \frac{h}{b} \leq 6 \tag{5}$$

Where,b and U_∞ must be expressed in a consistent units. Finally d_{st} can be determined using the following equation:

$$\frac{d_{st}}{d_{se}} = exp\left[-0.03\left\{\frac{U_c}{U_\infty} ln\left(\frac{t}{t_e}\right)\right\}^{1.6}\right] \tag{6}$$

Here, d_{st} is depth of scour below the initial bed level at time t. Thus combined use of the above equations gives the scour depth at any stage throughout the development of scour depth.

Mia and Nago (2003) developed a method for computing the temporal variation of scour depth around circular uniform pier on uniform sediment and steady clear-water flow condition. The experiments were conducted in 16 m long, 0.6 m wide and 0.4 m deep rectangular flume. The bed load sediment transport relation of Yalin, (1977) was modified to incorporate the temporal development of shear velocity at the pier nose. The relationship for the diameter of the primary vortex given by Kothyari *et al*., (1992 a) was used. The estimated equilibrium scour depth by Mia and Nago (2003) was compared with some commonly used empirical formulas for the same. It was indicated that *HEC*-18 method gives a comparatively good agreement with observations as compared to the other empirical equations. The method of Mia and Nago, (2003) was found to estimates equilibrium scour depth with a reasonable accuracy (maximum error of ± 25%) for most of the data of Chiew, (1995) and Melville and Chiew, (1999) *etc*.

Kothyari *et al*. (2007) developed a general approach to compute temporal evolution of scour depth around the bridge foundation elements under clear-water condition. They conducted additional experiments on the scour entrainment at piers, at rectangular and sloping abutments, as well as at singular and multiple spur dikes.

A general criterion was proposed to determine the densimetric particle Froude number for scour entrainment and general relationship was proposed for the entrainment densimetric particle.

Froude number $F_{d\beta}$ at a foundation element of given geometry.

$$F_{d\beta} = \left[F_{di} - 1.26.\Sigma.\Sigma_S.\Sigma_{ca}.\delta^{\Sigma/4}.\left(\frac{R}{d_{50}}\right)^{1/6} \right] \sigma_g{}^{1/3} \tag{7}$$

Here Σ represent the shape factor ; Σ_S is submergence and Σ_{ca} is cascade parameter. For circular pier, $\Sigma = \Sigma_S = \Sigma_{ca} = 1$, R is the hydraulic radius, F_{di} densimetric froude number for inception of sediment movement in approach flow and δ is *b/B* (element obstruction.

They related the scour depth to the difference between the actual and the entrainment densimetric particle Froude numbers and developed following relationship for the temporal scour evolution at bridge foundation elements along with a set of limitations as listed by Oliveto and Hagar (2002, 2005).

$$d_{st} = 0.272.L_R.\sigma_g^{-1/2}.\left(F_d - F_{d\beta}\right)^{2/3}\log(T) \tag{8}$$

This relationship was validated by the complete VAW scour data set, and verified by the available literature data.

2.4 Study related to Spacing of Bridge Piers on Scour Depth

A lot of investigations have been conducted around the circular bridge piers but only a few investigations are available on the effects of stream-wise spacing of group of bridge piers on scour depth (Hannah, 1978; Elliot and Baker, 1985; Breusers & Raudkivi, 1991; Sidek & Ismail, 2002 *etc*). However little or no information is available on the flow structure around the group of piers, when these piers are placed in a line parallel to the direction of flow.

Elliot and Baker (1985) conducted the experimental study on the effect of pier spacing on scour around bridge piers. They used the wooden pier models having rectangular shape with semi circular nose having width of pier 46 mm and length as 150 mm. They placed the pier models parallel to the direction of the flow and varied the spacing between the pier from 1.6 -3.2 times the pier diameter. They introduced multiplying factors in scour depth equation of Breusers et al., 1977 stating that these multiplying factors have been derived for clear-water scour, for one set of pier geometries, one value of water depth and one sediment type only and use in other condition should be done with caution.

Breusers and Raudkivi (1991) have summed up that in general the scour hole for a group of two piers could be considered as the coincidental positioning of separate scour holes of the individual piers. They proposed the correction factors for computation of equilibrium scour depth for a group of two piers when piers are placed in tandem, two piers side by side and two piers at a variable angle. According to them when two piers are in a line parallel to the flow direction; the maximum scour depth around the front pier will increase by a maximum of 15% if the pier spacing is 2 to 3 times the pier diameter. The influence of the second pier on the front pier disappear as pier spacing is greater than 15 times the pier diameter. The maximum scour depth of the rear pier is reduced by 10-20%. This reduction is almost independent of pier spacing.

Mandal (2003) performed experiments on effect of stream-wise spacing of cylindrical piers on equilibrium scour depth. Three different iron pipes having diameter as 27mm, 33.5 mm and 42 mm were used as uniform cylindrical piers. Piers were arranged for two types of arrangements, viz., in-line and staggered. In the first case, the pipes were placed one behind other to represent piers of two bridges in a line. In the second case piers were placed with a staggered arrangement. On the basis of experimental study **Mandal (2003)** concluded that

(a) The equilibrium scour depth for the upstream piers is more than that of the downstream pier in case of in-line arrangement of piers.

(b) The equilibrium scour depth for the downstream piers is more than that of the upstream piers in case of staggered arrangement.

(c) As the diameter of the cylindrical piers increases the stream-wise spacing for the non-interference effect also increases. The non-interference effect of downstream piers have been noticed for pier diameter 27 mm, 33.5 mm and 42 mm as at stream-wise distance 30 *b*, 38 *b*and 44 *b* respectively.

Chapter 3

EXPERIMENTAL SET UP AND PROCEDURE

3.1 GENERAL

Extensive data are available in literature on scour around uniform bridge piers. Keeping this in view experiments were planned and conducted in the Hydraulics Laboratory. The present chapter contains the description of the experimental set-up and procedure.

3.2 DETAILS OF EXPERIMENTAL SET-UP

3.2.1 Flume

A fixed bed masonry flume of 12 m length, 60 cm depth was used in the experiments. The flume receives its water supply from a tank. The water supply in the flume was regulated with the help of a valve provided at the inlet of the flume.

Masonry grid built and loaded with small sized bricks and pebbles too was provided at the upstream end of the flume to minimize the disturbance in the flow entering the flume.

An adjustable iron gate was provided at the downstream end of the flume to enable adjustment of the depth of the flow in the flume. Adjustable rails and a trolley were mounted on the two walls of the flume to carry the pointer gauge for water surface and bed level measurements. A working section 3.0 m long, 0.75 m wide and 0.6 m deep was located 5.0 m downstream of the flume entrance. The working section was filled with the desired sediment to the level of the flume bed. The piers were placed at the center of the working section of the flume. Figure 3.1 shows the photographic view of the experimental set-up flume used in experimentation. The working section was filled with the desired sediment to the level of the flume bed. The pier was placed at the center of the working section of the flume.

Fig.3.1: Photographic view of the experimental set-up flume

3.2.2 Sediment Used

Non-cohesive river bed sediment was used in all the experiments as the sediment. The sand used had a d_{50} size of 0.5 mm and a standard deviation (σ_g) of 1.33 .The size distribution curves for the sediment used are shown in Fig. 3.2. Calculation of the sieve analysis in shown in Appendix A.

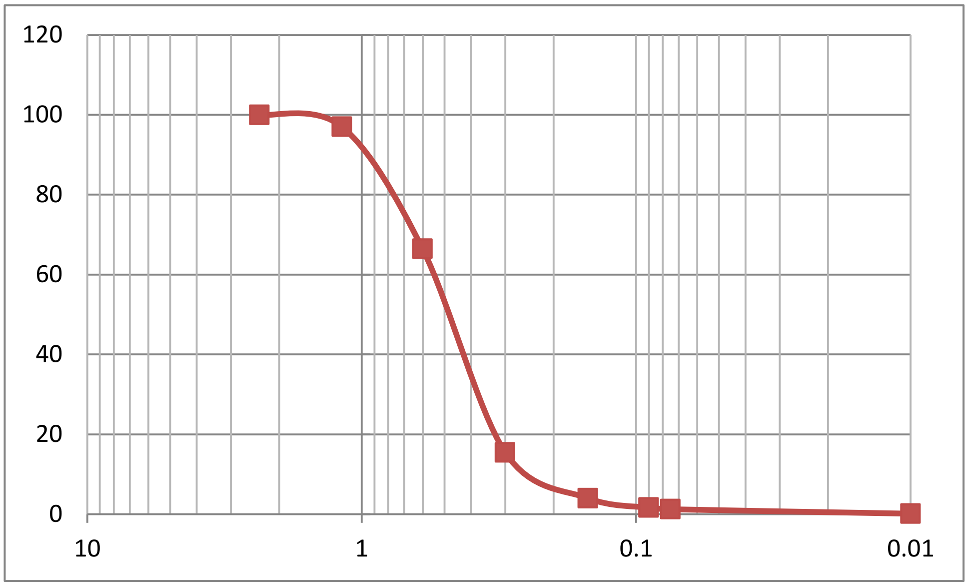


Fig. 3.2: Size distribution curves for the sediment used in the experiment.
Where,
x-axis denotes equivalent spherical diameter (µm),
y-axis denotes percentage mass finer than(%).

3.2.3 Pier

A circular pier have diameter = 8.12 cm was used as bridge pier model. The pier model used was made of concrete.

3.3 MEASURING INSTRUEMENTS

3.3.1 Discharge Measurement

The discharge in the flume was measured with the help of Orifice fitted in the inlet pipe of the flume only one values of flow discharge (*Q*) was used herein.

3.3.2 Scour Depth Measurement

The temporal variation of scour depth at the nose of the pier was measured using an pointer gauge with least count of 0.1 mm. A digital watch was used to measure the time elapsed since the beginning of scour. The initial and final bed levels were also measured with the help of a pointer gauge.

3.4 EXPERIMENTAL PROCEDURE

(a) Experimental details

The study of the temporal variation of scour depth around circular pier alone and when two piers was placed at specified spacing was conducted. As previously mentioned, one circular cylinders having diameters 81.2 mm was used as pier model. The sediment having particle size d_{50}=0.5 mm (σ_g = 1.2) and specific gravity 2.65 were used as sediment in this series of runs. Clear - water scour conditions prevailed during the experiments. Each pier model was founded in sediment bed having d_{50} = 0.5 mm and flow depth 8.7 cm. One experiment was conducted at the circular pier alone. Then two piers were placed in the working section and pier spacing between them (x/b) were varied from 2, 3, 4, 6, 8, 10, 12 and 16. In each experiment time variation of scour depth and scour pattern after the scour process at the centerline of the flume was monitored. Calculation of flow depth , discharge and velocity is shown in Appendix B

(b) Measurement of scour depth

Before the start of each run for the temporal variation of scour, the working section was filled with desired sediment and the pier or footing was inserted in it vertically and centrally.

The predetermined discharge was allowed into the flume and when the desired flow conditions were established using tailgate and the inlet valve. The bed level at the nose of the upstream pier and downstream pier were measured at intervals varying from one minute in the beginning of the run to half an hour at the end of the run.

Theoretically, scour depth develops asymptotically with time. However it was difficult to run the experiments for very long time. It is well known that scour development is rapid initially and becomes slow after a few hours. All experiments were therefore, conducted for a duration of four hours. The bed profile of scour hole in the test section was also measured at the end of each run.

Chapter 4

Results and discussions

Analysis of the data collected on temporal variation of scour depth around the circular uniform pier alone and on the piers (upstream pier and down stream pier) when spacing between them was varied is presented in this chapter.

Scour around isolated bridge pier

In order to check the effect of stream wise spacing on the scour depth at upstream pier and down stream pier one experiment was performed on a single bridge pier. The pier of size 8.12 cm was place on the text section and predetermined flow condition was established as explained in the previous chapter. The time variation of scour depth was monitored at the nose of the pier at regular time interval. The experiment was run for a period of 4 hrs. Fig 4.1 shows the geometry of the scour hole for single pier. While Fig. 4.2 shows the bed Profile of Scour pattern along the centerline of flow for single pier. It has been observed during the past as well as in the present study that, for the case of circular pier, the deepest scour hole occurred in the pier front and side while wake scour was much smaller in depth. The deepest scour depth was measure at the nose of pier and it was equal to 6cm

Fig. 4.1: Geometry of the scour hole for single pier

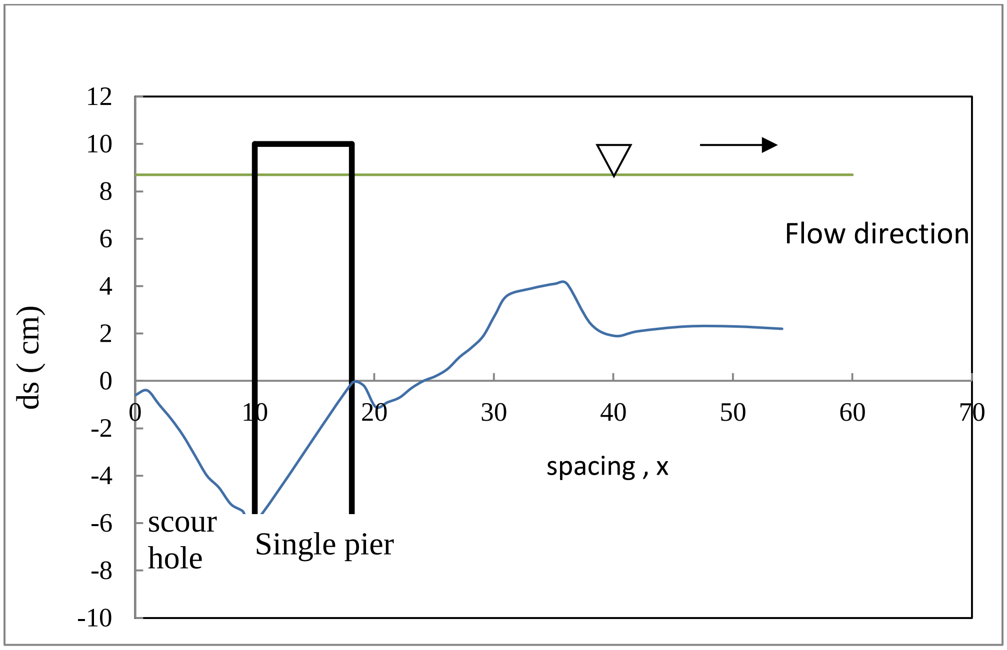


Fig. 4.2: Bed Profile of Scour pattern along the centerline of flow for single pier

Effect of stream wise spacing on scour depth

The main objective of the present work to study the effect of stream wise spacing of the bridge piers on scour depth so In order to determine the effect the pier spacing between the two piers were changed systematically in the direction of the flow. Stream wise spacing between piers was varied as 2, 3, 4, 6, 8, 10, 12 and 16 times the pier diameter. The temporal variation of the scour depth was studied around the bridge pier models. Table 4.1 shows the relation between pier spacing and scour depth.

Table 4.1: Scour depth as a function of pier spacing

Ex. No.	Spacing(x/b)	Scouring front pier(cm)	Scouring rear pier(cm)	scour depth at front pier/scour depth at single pier	scour depth at rear pier/scour depth at single pier
1	0	6		-	-
2	2	6.8	4.2	1.13	0.70
3	3	6.8	4.4	1.13	0.73
4	4	6.7	4.2	1.12	0.70
5	6	6.8	4.1	1.13	0.68
6	8	6.3	2.5	1.05	0.42
7	10	6.2	2.3	1.03	0.38
8	12	6.1	2	1.02	0.33
9	16	6.1	1.2	1.02	0.20

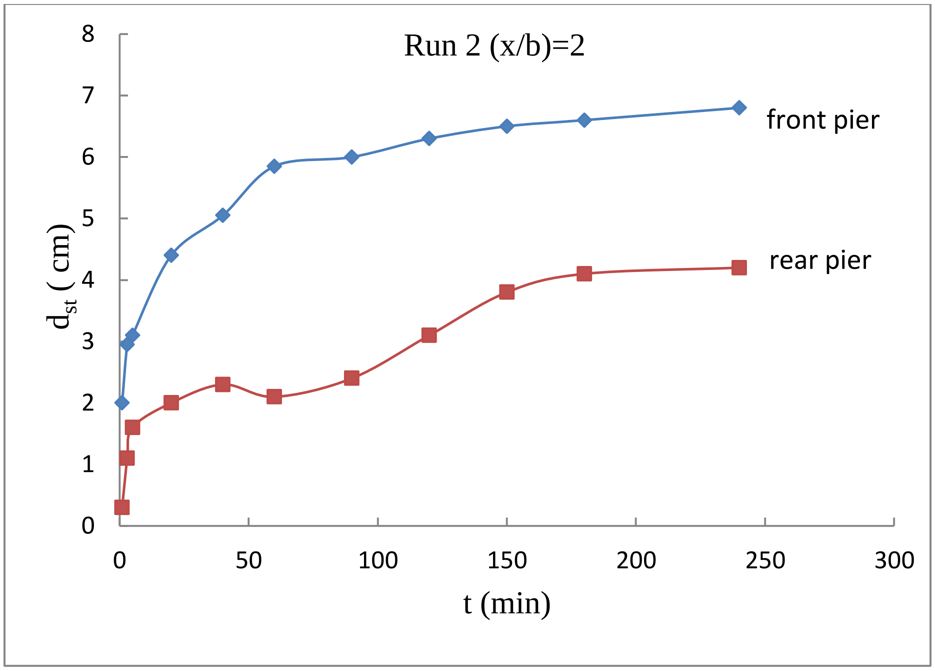
From the experiments it was observed that while value of $X/b \leq 6$, the influence of the rear pier on the front pier was observed. It is noticed that the scour depth at the front pier increased by 13% than that is was noticed at isolated bridge pier. Fig 4.3 depicts the geometry of scour hole for both the piers at pier spacing 2. From this figure it is clear that both piers have same scour hole. This effect of rear pier diminishes as pier spacing between the pier increase above 6. It is also evident from the Fig. 4.4. Figures 4.4 and 4.5 show the geometry of scour hole for both the piers at x/b = 8 and 16 respectively. From this figure it is clear the both the piers have independent scour hole and thus there is no mutual interference of among the piers.

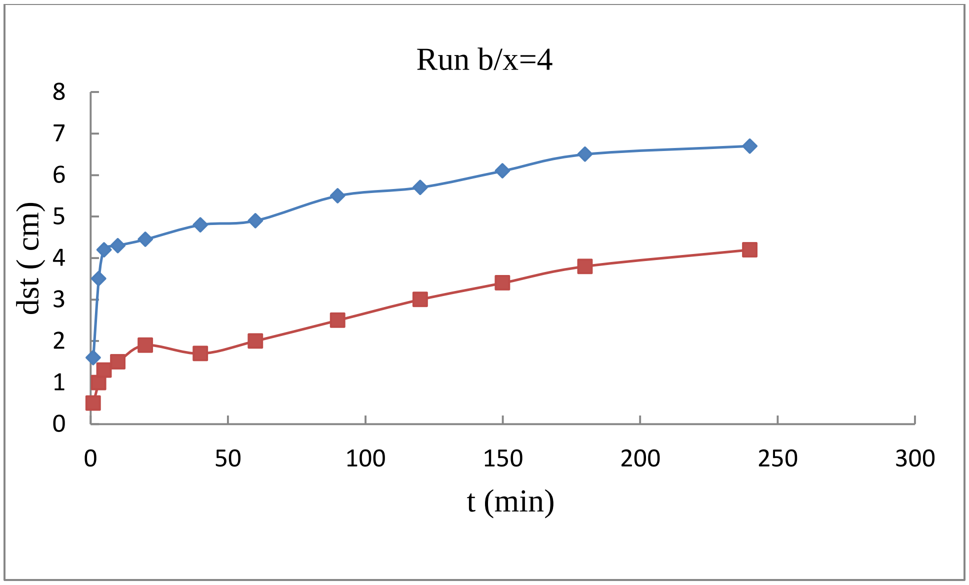
Fig. 4.3 Geometry of the scour hole for both the piers at x/b=2

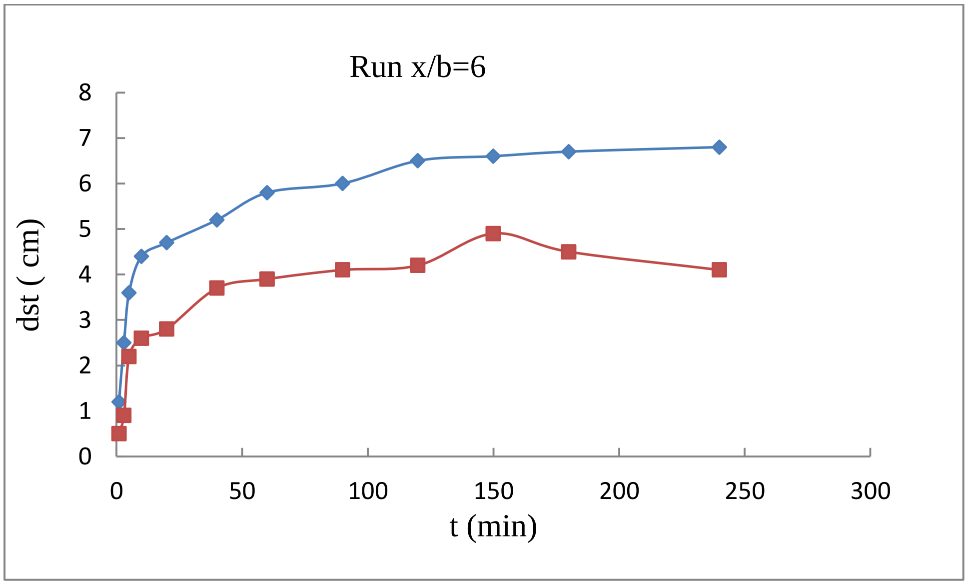
Fig 4.4: Geometry of the scour hole for both the piers at x/b=8

Fig 4.5 Geometry of the scour hole for both the piers at x/b=16

Figure 4.6 shows the temporal variation of scour depth at both the piers for x/b = 2, 4 6 and 12. In all the experimental run the scour depth at the rear pier was observed less than that is was observed at front pier. More over scour depth observed at rear pier was less that that obsereved at isolated single pier. From the Fig 4.6 it is observed that for x/b ≤ 12, the scour depth was intial observed to me more but as the time elapsed and scour at the front pier increase a decrease in the scour depth at rear pier was observed. It is attributed to the fact that as time elapse scour hole at the front pier increases and as a consequence of that material eroded from the front pier gets deposited in the scour hole of the rear pier thus reducing the scour depth at the rear pier. This phenomenon is applicable when pier spacing is less than 8, as pier spacing increase beyond that there is very less probability of disposition of material in the rear pier. But in that cases also scour depth at rear pier is observed less. The probable reason behind it that scour experiments has been conducted for short period of time and thus only transient scour depth were obtained.




Run b/x=4
8
7
6
5
4
3
2
1
0
dst (cm)
0
50
100
150
200
250
300
t (min)


Run x/b=6
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7
6
5
4
3
2
1
0
dst (cm)
0
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100
150
200
250
300
t (min)

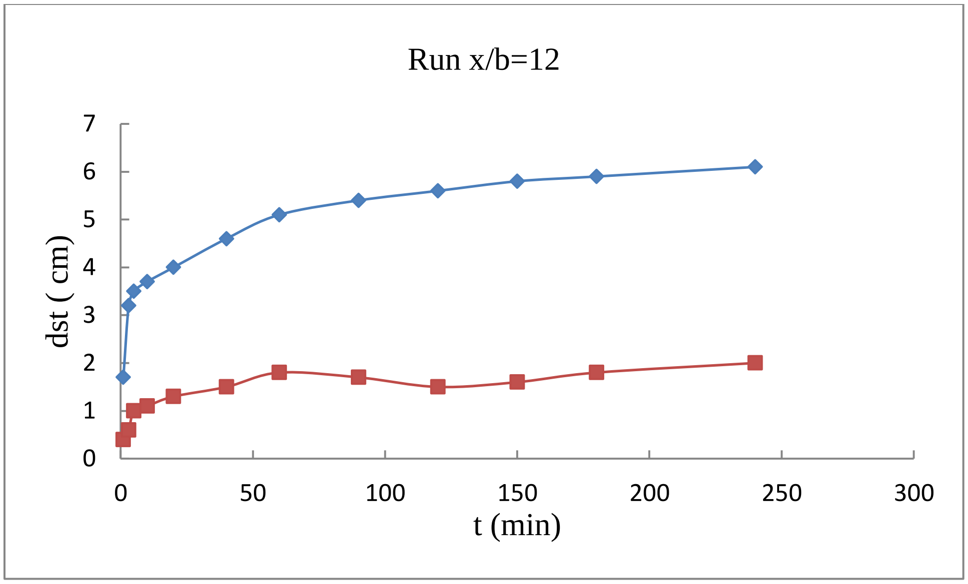
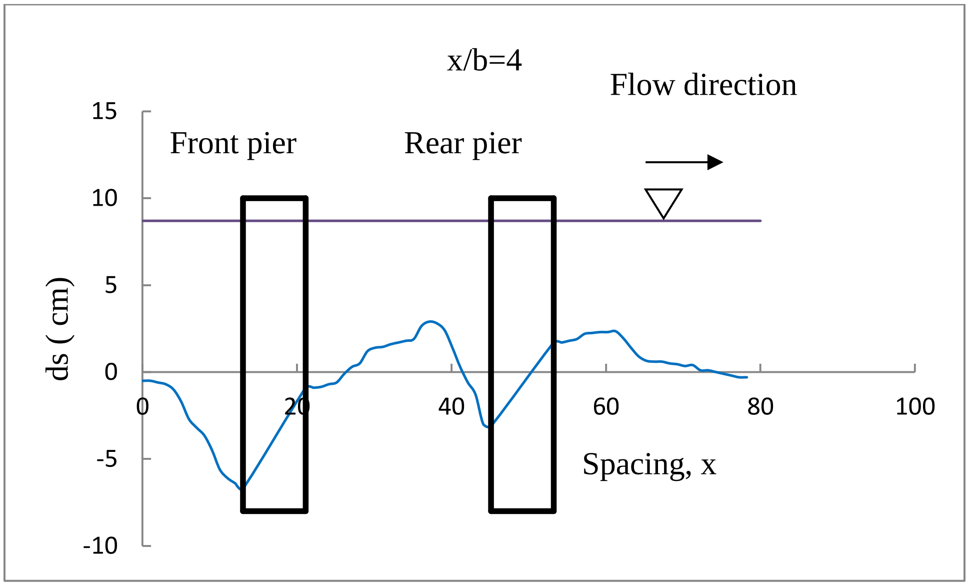
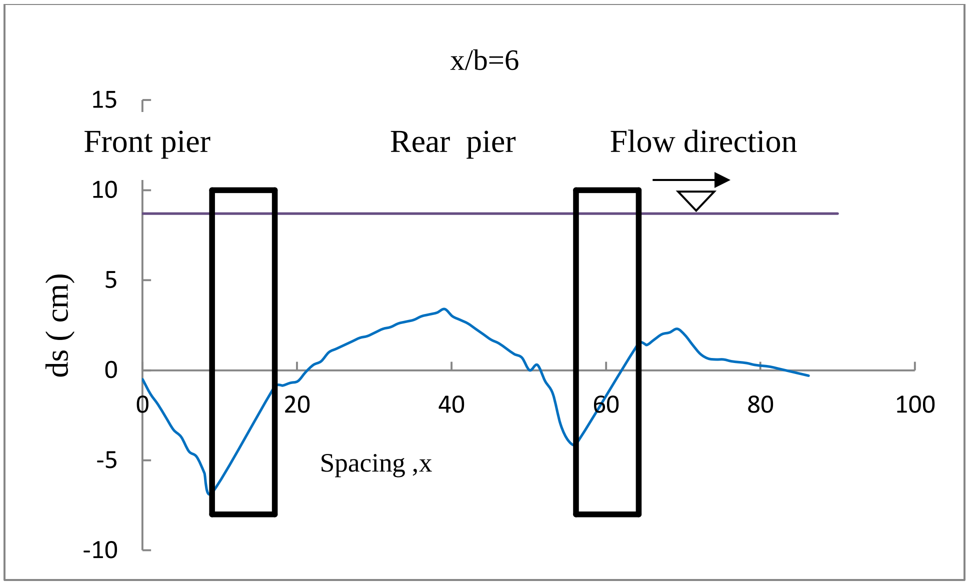
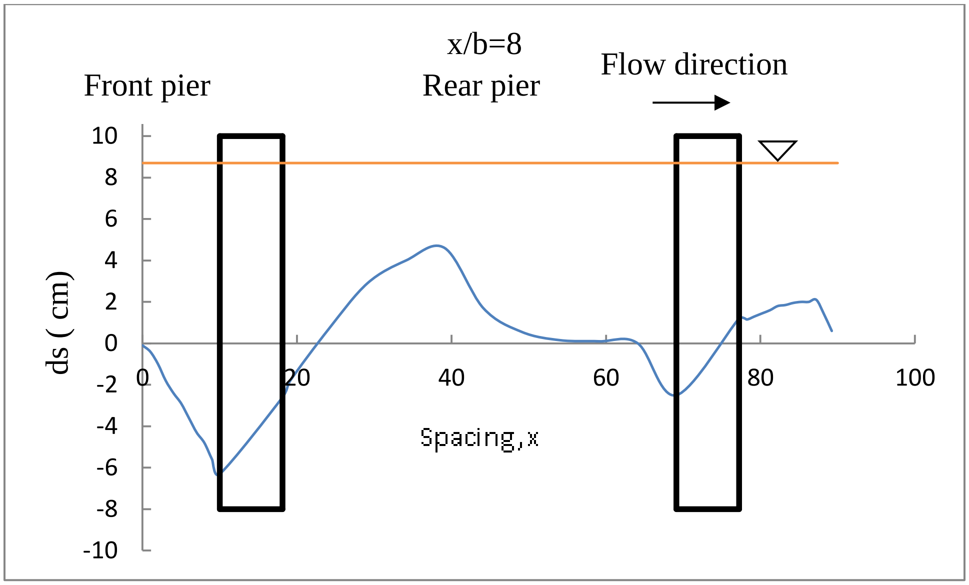


Fig. 4.6: Temporal variation of scour depth at different pier spacing

Fig4.7 shows the bed profile of Scour pattern along the centerline of the flume in the direction of flow for some experimental runs. From these figures it is also clear that as pier spacing increases , the scour hole around the each pier develop independently without mutual interference between the piers.




x/b=6
Front pier
Rear pier
Flow direction
ds (cm)
15
10
5
0
-5
-10
0
20
40
60
80
100
Spacing ,x


x/b=8
Front pier
Rear pier
Flow direction
ds (cm)
10
8
6
4
2
0
-2
-4
-6
-8
-10
0
20
40
60
80
100
Spacing,x

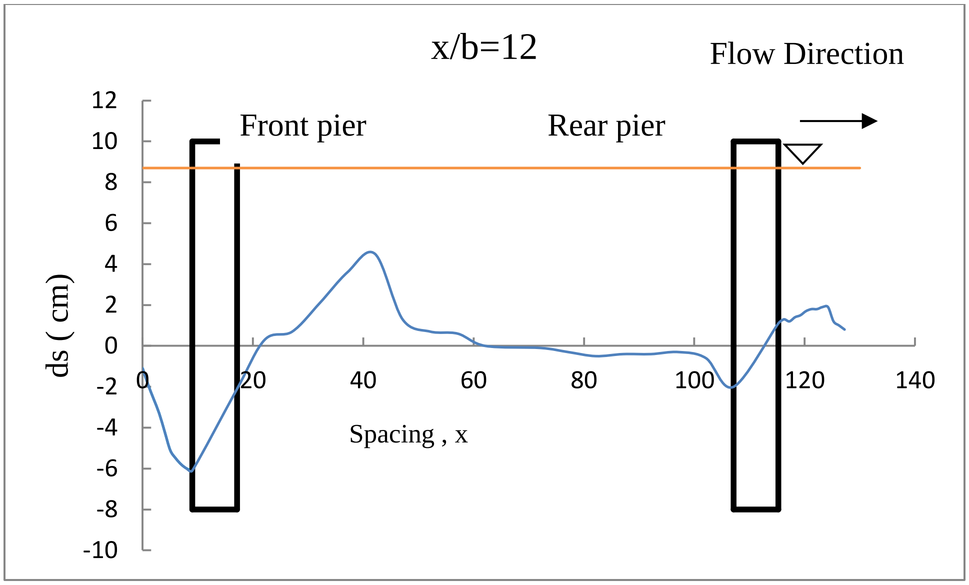


Fig 4.7: Bed Profile of Scour pattern along the centerline of for different pier spacing

Figure 4.8 shows the varition of scour depth for front pier and rear pier with pier spacing. From this figure it is obvious that as pier spacing increase to x/b =16, the scour depth at front pier approaches to scour depth at isolated single pier. Where as scour depth at rear pier is obsereved to be less than that obsered at osolated single pier for spacing up to x/b =16. Similar observation was also noticed by Breusers and Raudkivi (1991). As explained earlier it is attributed to the ineterference to the flow due to the front pier. Figure 4.8 b shows the varaiation of scour depth normalized with scour depth at single pier with ratio of pier spacing and pier diameter. From this figure it ics clear that maximum scour depth at front pier was incresed by 13% if pier spacing is 2-4 times the pier diamter. Similar observation were noticed by Breusers and Raudkivi (1991) who noticed the maximum scour depth around the front pier will increase by a maximum of 15% if the pier spacing is 2 to 3 times the pier diameter. The maximum scour depth of the rear pier is reduced to 20%. However Breusers and Raudkivi (1991) noticed the reduction in maximum scour depth around the rear pier only 80%. The probable reason behind it that scour experiments has been conducted for short period of time and thus only transient scour depth were obtained.

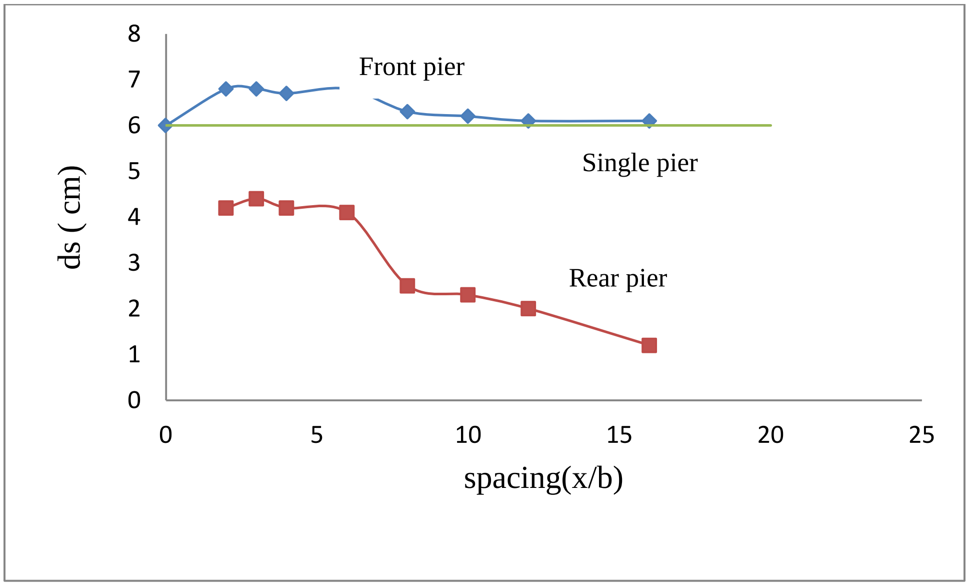


Fig 4.8 a: Scour depths for two piles in line as a function of pile spacing

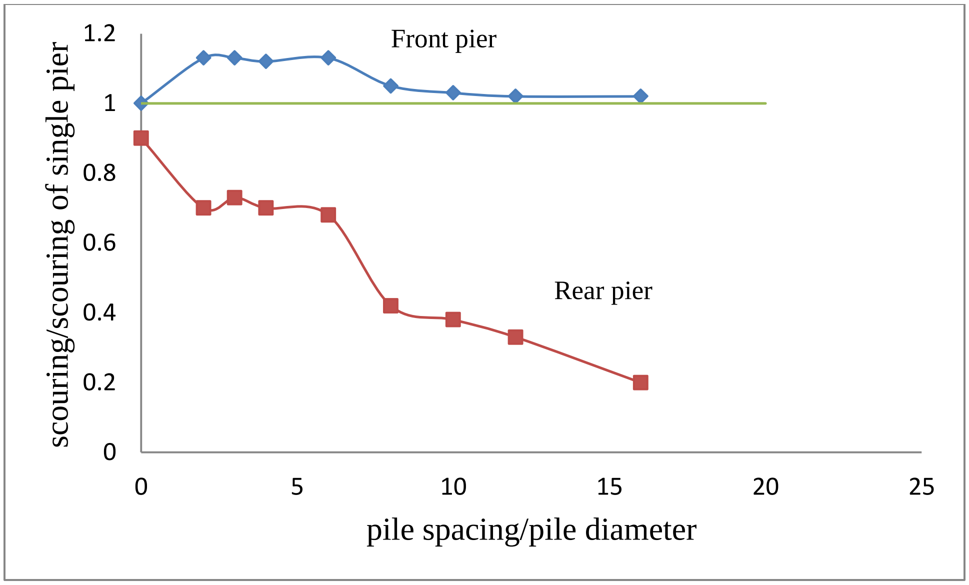


Fig 4.8 b: Scour depths for two piles in line as a function of pile spacing

Conclusions:

Scour around bridge pier is one of the main cause of the bridge failure. In the present work effect of stream-wise spacing of circular bridge piers on scour mechanism and scour depth has been studied through laboratory experiments.

The temporal variation of scour depth around the circular bridge piers on the both bridges piers, were noticed by varying the stream wise spacing among the bridge piers from 2, 3, 4, 6, 8, 10, 12 and 16 times the pier diameter.

It is observed that while value of X/b≤ 6, the influence of the rear pier on the front pier was observed. It is noticed that the scour depth at the front pier is increased by 13% than that is was noticed at isolated bridge pier. The effect of rear pier diminishes as pier spacing between the pier increases above 6.

The geometry of scour hole for both the piers at x/b = 8 and 16 reveals that both the piers have independent scour hole and thus there is no mutual interference of among the piers beyond the pier spacing of 8.

Maximum scour depth at front pier was incresed by 13% if pier spacing is 2-4 times the pier diamter. Similar observation were noticed by Breusers and Raudkivi (1991) who noticed the maximum scour depth around the front pier which will increase by a maximum of 15% if the pier spacing is 2 to 3 times the pier diameter. The maximum scour depth of the rear pier is reduced to 20%. The probable reason behind it is that scour experiments have been conducted for short period of time and thus only transient scour depth were obtained.

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Appendix A

Sieve analysis

Sieve no.	mass of soil retained (gram)	cumulative mass of soil retained (gram)	cumulative % of soil retained	% finer
2.36	0.3	0.3	0.03	99.97
1.18	29.8	30.1	3.01	96.99
0.6	305.8	335.9	33.59	66.41
0.3	509.6	845.5	84.55	15.45

0.15	114.3	959.8	95.98	4.02
0.09	23.7	983.5	98.35	1.65
0.075	4	987.5	98.75	1.25
0.01	11.1	998.6	99.86	0.14
	998.6			

Appendix B

To find velocity, flow depth and discharge in flume:

d_{50}=median grain size

ν=kinematic viscosity

s=relative density

d_x=dimensionless grainsize

τ_0=bed shear stress

ϒ=unit weight

R=hydraulic mean radius

s=slope of river bed

d_{50}=0.5mm

τ_c=bed shear stress at initiation of bed sediment

τ^*_c=from graph of modified form of yalin-karahan curve

U_{*c}=shear velocity at initiation of sediment motion

A=cross sectional area of flow

Q=discharge

V=velocity

h=flow depth

n=manning’s constant

Calculation:

$\nu=10^{-6}$

$d_x=[(s-1)g(d_{50})^3/\nu^2]^{-0.3}$

$=0.1019$

$\tau_{*c}=0.22d_x +0.06(10)^{-7.7d}x$

$=0.03108$

$\tau_c=0.03108*9810*1.65*0.5*10^{-3}$

$=0.2516N/mm^2$

$U_{*c}= (\tau_c /\varrho)^{1/2}$

$=0.01586m/s$

water flow depth,

h=8.7cm

cross section area of flow (A) $=0.087*0.75=0.06525\ m^2$

Now discharge measurement by orifice meter:

$Q=1212.7*(h^{`})^{1/2}$

$h'=x(12.6)$

$=(24-14.5)*12.6$

$=119.7cm$

$Q=0.0132m^3/s$

So velocity of flow $V=0.20\ m/s$

Use eq: $V=(1/n)*R^{2/3}*S^{1/2}$

And get the value of $S = 1.43*10^{-4}$

Now

$\tau_0=\Upsilon RS$

$=9810*.0789*1.43*10^{-4}$

$=0.110N/m^2$

$\tau_0/ \tau_c=0.43$

Appendix C-1

Bed profile reading For Experiment No. 1 (Single pier)

Y (cm)	Bed level(cm)	reading(cm)	Actual bed level (cm)
0	21	21.4	-0.6
1	21	21.6	-0.4
2	21	22	-1
3	21	22.6	-1.6
4	21	23.3	-2.3
5	21	24.15	-3.15
6	21	25	-4
7	21	25.5	-4.5
8	21	26.2	-5.2
9	21	26.7	-5.5
10	21	27	-6
18.12	21	21.1	-0.1
19.12	21	21.2	-0.2
20.12	21	22.1	-1.1
21.12	21	21.9	-0.9
22.12	21	21.7	-0.7
23.12	21	21.3	-0.3
24.12	21	21	0
25.12	21	20.8	0.2
26.12	21	20.5	0.5
27.12	21	20	1
28.12	21	19.6	1.4
29.12	21	19.1	1.9
30.12	21	18.2	2.8
31.12	21	17.4	3.6
33.12	21	17.1	3.9
35.12	21	16.9	4.1
36.12	21	16.9	4.1
38.12	21	18.6	2.4
40.12	21	19.1	1.9
42.12	21	18.9	2.1
46.12	21	18.7	2.3
50.12	21	18.7	2.3
54.12	21	18.8	2.2

Where,

‘Y’ is the distance measured in the direction of flow where, y=0 denotes point on the periphery of scour hole.

“-ve” sign indicates scouring and “+ve” sign indicates hump formed.

Appendix C-2

Temporal variation for experiment 2 (x/b =2)

Time (min)	Bed level(cm)	Reading front pier(cm)	scouring(cm)	Reading rear pier(cm)	scouring(cm)
1	21	23	2	21.3	0.3
3	21	23.95	2.95	22.1	1.1
5	21	24.1	3.1	22.6	1.6
20	21	24.4	4.4	23	2
40	21	25.05	5.05	23.3	2.3
60	21	25.85	5.85	23.1	2.1
90	21	27	6	23.4	2.4
120	21	27.3	6.3	24.1	3.1
150	21	27.5	6.5	24.8	3.8
180	21	27.6	6.6	25.1	4.1
240	21	27.8	6.8	25.2	4.2

Bed profile reading For Experiment No. 2 (x/b=2)

y(cm)	bed level(cm)	reading(cm)	actual level(cm)
0	21	22	-1
1	21	21.9	-0.9
2	21	22.35	-1.35
3	21	22.4	-1.4
4	21	22.65	-1.65
5	21	23.2	-2.2
6	21	23.75	-2.75
7	21	24.5	-3.5
8	21	25.3	-4.3
9	21	25.85	-4.85
10	21	26.6	-5.6
11	21	27.45	-6.45
12	21	27.7	-6.7
13	21	27.8	-6.8

21.12	21	24	-3
22.12	21	24.2	-3.2
23.12	21	24.3	-3.3
24.12	21	24.4	-3.4
25.12	21	24.5	-3.5
26.12	21	24.5	-3.5
27.12	21	24.55	-3.55
28.12	21	25	-4
29.12	21	25.2	-4.2
37.24	21	19.4	1.6
38.24	21	19.55	1.45
39.24	21	19.4	1.6
40.24	21	19.1	1.9
41.24	21	18.8	2.2
42.24	21	18.55	2.45
43.24	21	18.3	2.7
44.24	21	18	3
45.24	21	17.8	3.2
46.24	21	17.7	3.3
47.24	21	17.5	3.5
48.24	21	17.4	3.6
49.24	21	17.2	3.8
50.24	21	17.05	3.95
51.24	21	16.9	4.1
52.24	21	16.8	4.2
53.24	21	16.6	4.4
54.24	21	16.5	4.5
55.24	21	16.4	4.6
56.24	21	16.4	4.6
57.24	21	16.5	4.5
58.24	21	17.1	3.9
59.24	21	17.8	3.2
60.24	21	18.6	2.4
61.24	21	19.6	1.4
62.24	21	19.9	1.1
64.24	21	20	1
66.24	21	20	1
68.24	21	20	1

Appendix C-3

Temporal variation for experiment 3 (x/b =3)

Time(min)	Bed level(cm)	Reading front pier(cm)	Reading rear pier(cm)	Scouring front pier(cm)	Scouring rear pier(cm)
1	20	21.2	20.4	1.2	0.4
3	20	21.7	20.7	1.7	0.7
5	20	22	21	2	1
20	20	22.6	21.7	2.6	1.7
40	20	23.1	22.5	3.1	2.5
60	20	23.4	22.6	3.4	2.6
90	20	24.6	22.9	4.6	2.9
120	20	25.2	23.2	5.2	3.2
150	20	26	23.5	6	3.5
180	20	26.4	24.1	6.4	4.1
240	20	26.8	24.4	6.8	4.4

Bed profile reading For Experiment No. 3 (x/b=3)

y(cm)	bed level(cm)	reading(cm)	actual level(cm)
0	20	20	0
1	20	20.5	-0.5
2	20	21.45	-1.45
3	20	21.85	-1.85
4	20	22.35	-2.35
5	20	22.9	-2.9
6	20	23.6	-3.6
7	20	24.2	-4.2
8	20	25	-5
9	20	25.7	-5.7
10	20	26.1	-6.1
11	20	26.2	-6.2
19.12	20	22.7	-2.7
20.12	20	22.8	-2.8
21.12	20	21.5	-1.5
22.12	20	21.1	-1.1
23.12	20	20.9	-0.9

24.12	20	20.6	-0.6
25.12	20	20.1	-0.1
26.12	20	20.2	-0.2
27.12	20	19.95	0.05
28.12	20	19.65	0.35
29.12	20	19.85	0.15
30.12	20	20.5	-0.5
31.12	20	21.2	-1.2
32.12	20	22	-2
33.12	20	22.4	-2.4
34.12	20	22.4	-2.4
42.24	20	17.3	2.7
43.24	20	17.3	2.7
44.24	20	17	3
45.24	20	16.7	3.3
46.24	20	16.35	3.65
47.24	20	16.3	3.7
48.24	20	16.3	3.7
49.24	20	16.45	3.55
50.24	20	16.4	3.6
51.24	20	16.55	3.45
52.24	20	16.6	3.4
53.24	20	17.3	2.7
54.24	20	17.6	2.4
55.24	20	18.8	1.2
56.24	20	19.4	0.6
57.24	20	19.9	0.1
58.24	20	19.95	0.05
59.24	20	19.8	0.2
60.24	20	19.8	0.2
61.24	20	19.5	0.5
62.24	20	19.4	0.6
63.24	20	19.5	0.5
64.24	20	19.4	0.6
65.24	20	19.3	0.7
67.24	20	19.5	0.5
69.24	20	19.55	0.45

Appendix C-4

Temporal variation for experiment 4 (x/b =4)

Time(min)	Bed level(cm)	Reading front pier(cm)	Reading rear pier(cm)	Scouring front pier(cm)	Scouring rear pier(cm)
1	20	21.6	20.5	1.6	0.5
3	20	23.5	21	3.5	1
5	20	24.2	21.3	4.2	1.3
10	20	24.3	21.5	4.3	1.5
20	20	24.45	21.9	4.45	1.9
40	20	24.8	21.7	4.8	1.7
60	20	24.9	22	4.9	2
90	20	25.5	22.5	5.5	2.5
120	20	25.7	23	5.7	3
150	20	26.1	23.4	6.1	3.4
180	20	26.5	23.8	6.5	3.8
240	20	26.7	24.2	6.7	4.2

Bed profile reading For Experiment No. 4 (x/b=4)

x(cm)	bed level(cm)	reading(cm)	actual level(cm)
0	20	20.5	-0.5
1	20	20.5	-0.5
2	20	20.6	-0.6
3	20	20.7	-0.7
4	20	21	-1
5	20	21.7	-1.7
6	20	22.7	-2.7
7	20	23.2	-3.2
8	20	23.65	-3.65
9	20	24.5	-4.5
10	20	25.6	-5.6
11	20	26.1	-6.1
12	20	26.4	-6.4
13	20	26.7	-6.7
21.12	20	20.9	-0.9
22.12	20	20.9	-0.9
23.12	20	20.85	-0.85
24.12	20	20.7	-0.7
25.12	20	20.6	-0.6

26.12	20	20.1	-0.1
27.12	20	19.7	0.3
28.12	20	19.5	0.5
29.12	20	18.8	1.2
30.12	20	18.6	1.4
31.12	20	18.55	1.45
32.12	20	18.4	1.6
33.12	20	18.3	1.7
34.12	20	18.2	1.8
35.12	20	18.1	1.9
36.12	20	17.35	2.65
37.12	20	17.1	2.9
38.12	20	17.2	2.8
39.12	20	17.6	2.4
40.12	20	18.6	1.4
41.12	20	19.7	0.3
42.12	20	20.6	-0.6
43.12	20	21.3	-1.3
44.12	20	23	-3
45.12	20	23.1	-3.1
53.24	20	18.3	1.7
54.24	20	18.3	1.7
55.24	20	18.2	1.8
56.24	20	18.1	1.9
57.24	20	17.8	2.2
58.24	20	17.75	2.25
59.24	20	17.7	2.3
60.24	20	17.7	2.3
61.24	20	17.65	2.35
62.24	20	18.05	1.95
63.24	20	18.6	1.4
64.24	20	19.1	0.9
65.24	20	19.35	0.65
66.24	20	19.4	0.6
67.24	20	19.4	0.6
68.24	20	19.5	0.5
69.24	20	19.55	0.45
70.24	20	19.65	0.35
71.24	20	19.6	0.4
72.24	20	19.9	0.1
73.24	20	19.9	0.1

74.24	20	20	0
75.24	20	20.1	-0.1
76.24	20	20.2	-0.2
77.24	20	20.3	-0.3
78.24	20	20.3	-0.3

Appendix C-5

Temporal variation for experiment 5 (x/b =6)

Time(min)	Bed level(cm)	Reading front pier(cm)	Reading rear pier(cm)	Scouring front pier(cm)	Scouring rear pier(cm)
1	20	21.2	20.5	1.2	0.5
3	20	22.5	20.9	2.5	0.9
5	20	23.6	22.2	3.6	2.2
10	20	24.4	22.6	4.4	2.6
20	20	24.7	22.8	4.7	2.8
40	20	25.2	23.7	5.2	3.7
60	20	25.8	23.9	5.8	3.9
90	20	26	24.1	6	4.1
120	20	26.5	24.2	6.5	4.2
150	20	26.6	24.9	6.6	4.9
180	20	26.7	24.5	6.7	4.5
240	20	26.8	24.1	6.8	4.1

Bed profile reading For Experiment No. 5 (x/b=6)

y(cm)	bed level(cm)	reading(cm)	actual level(cm)
0	20	20.5	-0.5
1	20	21.3	-1.3
2	20	21.9	-1.9
3	20	22.6	-2.6
4	20	23.3	-3.3

5	20	23.7	-3.7
6	20	24.5	-4.5
7	20	24.8	-4.8
8	20	25.7	-5.7
9	20	26.8	-6.8
17.12	20	20.9	-0.9
18.12	20	20.85	-0.85
19.12	20	20.7	-0.7
20.12	20	20.6	-0.6
21.12	20	20.1	-0.1
22.12	20	19.7	0.3
23.12	20	19.5	0.5
24.12	20	19	1
25.12	20	18.8	1.2
26.12	20	18.6	1.4
27.12	20	18.4	1.6
28.12	20	18.2	1.8
29.12	20	18.1	1.9
30.12	20	17.9	2.1
31.12	20	17.7	2.3
32.12	20	17.6	2.4
33.12	20	17.4	2.6
34.12	20	17.3	2.7
35.12	20	17.2	2.8
36.12	20	17	3
37.12	20	16.9	3.1
38.12	20	16.8	3.2
39.12	20	16.6	3.4
40.12	20	17	3
41.12	20	17.2	2.8
42.12	20	17.4	2.6
43.12	20	17.7	2.3
44.12	20	18	2
45.12	20	18.3	1.7
46.12	20	18.5	1.5
47.12	20	18.8	1.2
48.12	20	19.1	0.9
49.12	20	19.3	0.7
50.12	20	20	0
51.12	20	19.7	0.3
52.12	20	20.6	-0.6

53.12	20	21.3	-1.3
54.12	20	23	-3
55.12	20	23.9	-3.9
56.12	20	24.1	-4.1
64.24	20	18.5	1.5
65.24	20	18.6	1.4
66.24	20	18.3	1.7
67.24	20	18	2
68.24	20	17.9	2.1
69.24	20	17.7	2.3
70.24	20	18.05	1.95
71.24	20	18.6	1.4
72.24	20	19.1	0.9
73.24	20	19.35	0.65
74.24	20	19.4	0.6
75.24	20	19.4	0.6
76.24	20	19.5	0.5
77.24	20	19.55	0.45
78.24	20	19.6	0.4
79.24	20	19.7	0.3
80.24	20	19.75	0.25
81.24	20	19.8	0.2
82.24	20	19.9	0.1
83.24	20	20	0
84.24	20	20.1	-0.1
85.24	20	20.2	-0.2
86.24	20	20.3	-0.3

Appendix C-6

Temporal variation for experiment 6 (x/b =8)

Time(min)	Bed level(cm)	Reading front pier(cm)	Reading rear pier(cm)	Scouring front pier(cm)	Scouring rear pier(cm)
1	20.5	22	21.4	1.5	0.9
3	20.5	22.4	21.45	1.9	0.95
5	20.5	22.6	21.5	2.1	1
10	20.5	23.4	21.7	2.9	1.2
20	20.5	23.8	21.8	3.3	1.3
40	20.5	24.4	20.9	3.9	0.4
60	20.5	25.2	21.4	4.7	0.9

90	20.5	25.6	22.7	5.1	2.2
120	20.5	25.9	22.5	5.4	2
150	20.5	26.1	22.7	5.6	2.2
180	20.5	26.6	22.9	6.1	2.4
240	20.5	26.8	23	6.3	2.5

Bed profile reading For Experiment No. 6 (x/b=8)

y(cm)	bed level(cm)	reading(cm)	actual level(cm)
0	20.5	20.6	-0.1
1	20.5	20.9	-0.4
2	20.5	21.5	-1
3	20.5	22.3	-1.8
4	20.5	22.9	-2.4
5	20.5	23.4	-2.9
6	20.5	24.1	-3.6
7	20.5	24.8	-4.3
8	20.5	25.3	-4.8
9	20.5	26.1	-5.6
10	20.5	26.8	-6.3
18.12	20.5	23.1	-2.6
19.12	20.5	22.3	-1.8
24.12	20.5	19.8	0.7
29.12	20.5	17.6	2.9
34.12	20.5	16.5	4
39.12	20.5	15.9	4.6
44.12	20.5	18.8	1.7
49.12	20.5	19.95	0.55
54.12	20.5	20.35	0.15
59.12	20.5	20.4	0.1
64.12	20.5	20.5	0
69.12	20.5	23	-2.5
77.24	20.5	19.3	1.2
78.24	20.5	19.35	1.15
79.24	20.5	19.2	1.3
80.24	20.5	19.05	1.45
81.24	20.5	18.9	1.6
82.24	20.5	18.7	1.8

83.24	20.5	18.65	1.85
84.24	20.5	18.55	1.95
85.24	20.5	18.5	2
86.24	20.5	18.5	2
87.24	20.5	18.4	2.1
88.24	20.5	19.1	1.4
89.24	20.5	19.9	0.6

Appendix C-7

Temporal variation for experiment 7 (x/b =10)

Time(min)	Bed level(cm)	Reading front pier(cm)	Reading rear pier(cm)	Scouring front pier(cm)	Scouring rear pier(cm)
1	21	23.2	21.7	2.2	0.7
3	21	23.8	21.9	2.8	0.9
5	21	24.6	22.05	3.6	1.05
10	21	24.8	22.1	3.8	1.1
20	21	25.1	22.2	4.1	1.2
40	21	25.2	22.5	4.2	1.5
60	21	25.5	22.6	4.5	1.6
90	21	25.9	22.7	4.9	1.7
120	21	26.4	23.3	5.4	2.3
150	21	26.6	23.5	5.6	2.5
180	21	27	23.5	6	2.5
240	21	27.2	23.3	6.2	2.3

Bed profile reading For Experiment No. 7 (x/b=10)

y(cm)	bed level(cm)	reading(cm)	actual level(cm)
0	21	21.2	-0.2
1	21	22.2	-1.2
2	21	22.9	-1.9
3	21	23.6	-2.6
4	21	23.9	-2.9
5	21	24.65	-3.65
6	21	25.5	-4.5
7	21	26	-5

8	21	26.7	-5.7
9	21	26.9	-5.9
10	21	27.2	-6.2
18.12	21	22.6	-1.6
19.12	21	22.9	-1.9
20.12	21	22.9	-1.9
21.12	21	23.1	-2.1
26.12	21	20.6	0.4
31.12	21	19.6	1.4
36.12	21	18.5	2.5
41.12	21	18.1	2.9
46.12	21	18.1	2.9
51.12	21	20.3	0.7
56.12	21	19.9	1.1
61.12	21	19.3	1.7
66.12	21	20.7	0.3
71.12	21	20.6	0.4
76.12	21	20.7	0.3
81.12	21	20.9	0.1
86.12	21	20.9	0.1
88.12	21	22.5	-1.5
91.12	21	23.3	-2.3
99.24	21	19.9	1.1
100.12	21	19.9	1.1
101.24	21	19.7	1.3
102.24	21	19.5	1.5
103.24	21	19.3	1.7
104.24	21	19.1	1.9
105.24	21	19	2
106.24	21	19	2
107.24	21	19	2
108.24	21	18.9	2.1
109.24	21	19.4	1.6
110.24	21	20.3	0.7
111.24	21	20.5	0.5
112.24	21	20.5	0.5
113.24	21	20.4	0.6
114.24	21	20.4	0.6
115.24	21	20.2	0.8

Temporal variation for experiment 8 (x/b =12)

Time(min)	Bed level(cm)	Reading front pier(cm)	Reading rear pier(cm)	Scouring front pier(cm)	Scouring rear pier(cm)
1	20.2	21.9	20.6	1.7	0.4
3	20.2	23.4	20.8	3.2	0.6
5	20.2	23.7	21.2	3.5	1
10	20.2	23.9	21.3	3.7	1.1
20	20.2	24.2	21.5	4	1.3
40	20.2	24.8	21.7	4.6	1.5
60	20.2	25.3	22	5.1	1.8
90	20.2	25.6	21.9	5.4	1.7
120	20.2	25.8	21.7	5.6	1.5
150	20.2	26	21.8	5.8	1.6
180	20.2	26.1	22	5.9	1.8
240	20.2	26.3	22.2	6.1	2

Bed profile reading For Experiment No. 8 (x/b=12)

y(cm)	bed level(cm)	reading(cm)	actual level(cm)
0	20.2	21.3	-1.1
1	20.2	22.1	-1.9
2	20.2	22.8	-2.6
3	20.2	23.5	-3.3
4	20.2	24.4	-4.2
5	20.2	25.3	-5.1
6	20.2	25.7	-5.5
7	20.2	26	-5.8
8	20.2	26.2	-6
9	20.2	26.3	-6.1
17.12	20.2	22.3	-2.1
22.12	20.2	19.9	0.3
27.12	20.2	19.5	0.7
32.12	20.2	18.1	2.1
37.12	20.2	16.6	3.6
42.12	20.2	15.7	4.5
47.12	20.2	18.9	1.3
52.12	20.2	19.5	0.7

57.12	20.2	19.6	0.6
62.12	20.2	20.2	0
72.12	20.2	20.3	-0.1
77.12	20.2	20.5	-0.3
82.12	20.2	20.7	-0.5
87.12	20.2	20.6	-0.4
92.12	20.2	20.6	-0.4
97.12	20.2	20.5	-0.3
102.12	20.2	20.8	-0.6
107.12	20.2	22.2	-2
115.24	20.2	19.1	1.1
116.24	20.2	18.9	1.3
117.24	20.2	19	1.2
118.24	20.2	18.8	1.4
119.24	20.2	18.7	1.5
120.24	20.2	18.5	1.7
121.24	20.2	18.4	1.8
122.24	20.2	18.4	1.8
123.24	20.2	18.3	1.9
124.24	20.2	18.3	1.9
125.24	20.2	19	1.2
126.24	20.2	19.2	1
127.24	20.2	19.4	0.8

Appendix C-9

Temporal variation for experiment 9 (x/b =16)

Time(min)	Bed level(cm)	Reading front pier(cm)	Reading rear pier(cm)	Scouring front pier(cm)	Scouring rear pier(cm)
1	20.5	21.2	20.6	0.7	0.1
3	20.5	21.6	20.8	1.1	0.3
5	20.5	22.1	20.9	1.6	0.4
10	20.5	22.7	20.8	2.2	0.3
20	20.5	23.5	20.7	3	0.2
40	20.5	24.6	20.5	4.1	0
60	20.5	25.4	21.5	4.9	1
90	20.5	25.8	21.4	5.3	0.9
120	20.5	26.1	21.3	5.6	0.8

150	20.5	26.3	21.4	5.8	0.9
180	20.5	26.4	21.5	5.9	1
240	20.5	26.6	21.7	6.1	1.2

Bed profile reading For Experiment No. 9 (x/b=16)

y(cm)	bed level(cm)	reading(cm)	actual level(cm)
0	20.5	20.5	0
1	20.5	20.4	0.1
2	20.5	20.9	-0.4
3	20.5	21.5	-1
4	20.5	22.2	-1.7
5	20.5	23	-2.5
6	20.5	23.4	-2.9
7	20.5	24.4	-3.9
8	20.5	25	-4.5
9	20.5	25.6	-5.1
10	20.5	26.1	-5.6
11	20.5	26.2	-5.7
12	20.5	26.6	-6.1
20.12	20.5	22.5	-2
25.12	20.5	21.8	-1.3
30.12	20.5	19.6	0.9
35.12	20.5	17.6	2.9
40.12	20.5	16.4	4.1
45.12	20.5	15.6	4.9
50.12	20.5	17	3.5
55.12	20.5	18.6	1.9
60.12	20.5	18.6	1.9
65.12	20.5	19.3	1.2
70.12	20.5	19.4	1.1
75.12	20.5	19.4	1.1
80.12	20.5	19.6	0.9
85.12	20.5	19.8	0.7
90.12	20.5	19.8	0.7
95.12	20.5	19.8	0.7
100.12	20.5	19.7	0.8
105.12	20.5	20	0.5
110.12	20.5	20.3	0.2

115.12	20.5	20.3	0.2
120.15	20.5	20.1	0.4
125.12	20.5	20.2	0.3
130.12	20.5	20.15	0.35
135.12	20.5	21.7	-1.2
143.24	20.5	19.4	1.1
144.24	20.5	19.45	1.05
145.24	20.5	19.3	1.2
146.24	20.5	18.9	1.6
147.24	20.5	18.7	1.8
148.24	20.5	18.3	2.2
149.24	20.5	18.1	2.4
150.24	20.5	18.1	2.4
151.24	20.5	18	2.5
152.24	20.5	18.2	2.3
153.24	20.5	18.6	1.9
154.24	20.5	19.2	1.3