THE INTERFERENCE EFFECTSOFANUPSTREAM LARGE PIERONADOWNSTREAM SMALL BRIDGEPIER

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***Abstract*:** Safetyofabridgedependsonthedepthandvolumeoflocalscouraroundits piers.The existence of parallel railway-bridge and road-bridge or a newly constructed bridge by the side of an old bridge gives rise to a situation, where the interference of the presence of an upstream pier and a downstream pier is prevalent. The upstream pier could primarily influence the scour at a downstream pier in two ways: (1) upstream pier modifies the flow field in the wake flow region that acts as an approaching flow for the downstream pier to scour and (2) the sediment that is scoured from the upstream pier is being fed to the scour hole at the downstream pier. Thepresentstudyattemptstoquantifythe effectofthe mutualinterferenceof upstreamand downstream piersonlocalscourat both thepiers.Themutualinterferenceofthepiersonlocalscourdependsontheshapeofthepiers,flowvelocity,flowdepth, sediment size, andoblique distance between the piers andflow oblique angle Thestudydeals with an experimental study of local scour around two in-line piers accomplished bymeasuring the equilibriumscourdepthsinclearwaterscourincarefullydesignedandcontrolledexperimentsin thelaboratory. These studies were accomplished by measuring equilibriumscourdepthsinclear waters courin carefully designed andcontrolled experiments in the laboratory.The results reveal that the equilibriumscourdepthatrearpier increasesas the distance betweenrearandupstreampiers increases. The scour depth at the rear pier is approximately 70-80% of the scour depth at the front pier. However, the equilibrium scourdepthatupstreampierisindependentofstreamwise spacingbetweenthepiers. Similarly,for spacing between front and rear piers is more than7 times the rear pier diameter, the equilibriumscourdepthatupstreampierisindependentofspacingbetween them.

Keyword: Local scour, Two piers in series, Mutual interference, Horse shoe vortex, Equilibrium scour depth

1. INTRODUCTION

Bridge scour was the removal of sediments such as sand and rocks from around bridge abutments or piers. Swiftly moving water can scoop out scour holes and compromising the integrity of a structure. Bridge scour was one of the three main causes of bridge failure (the others being collision and overloading). It has been estimated that 60% of all bridge failures were result of scour and other hydraulic related causes. At the bridge sites, localized scour in the vicinity of piers poses a challenging problem to the hydraulic engineers. Failure of bridges due to scour at pier foundations was a common occurrence. The obstruction to the flowing stream by a bridge pier causes a 3-dimensional separation of flow which in turn forms a vortex flow field around the pier (Dey, Bose, & Sastry (1995)). The flow separates at the upstream face of the pier as it travels by the side of the pier, creating a vortex trail, termed as horseshoe vortex, which moves downstream. As a result of which, local scour takes place around the pier due to the removal of bed sediments.

The safe and economical design of bridge piers requires an accurate prediction of equilibrium scour depth around them. Since circular piers are the most commonly used, many investigators have studied the problem of scour in its various aspects. For geotechnical and economic reasons, pier groups have become more and more popular in bridge design. In case of scour around a group of piers, the presence of the piers can generate a complex interaction in the hydrodynamic characteristics of the flow field near the piers themselves and therefore, lead to the occurrence and development of a scour process that was quite different from one which occurs around a single pier.

Scouring at a single pier has been more extensively investigated than at pier groups. When the scour proceeds due to the presence of a group of piers, some mechanisms occur that make the phenomenon more complex. Four of these mechanisms which affect scour at pier groups and are not present in scouring at single pier are: 1) reinforcing, that leads to increased scour depth at the upstream pier and overlaps with that of the rear piers; 2) sheltering by the upstream pier can reduce the effective approach velocity for the downstream pier and reduce the scour depth; 3) vortices shed from the upstream pier are convected downstream (if the downstream pier is close to the path of vortices, that will assist scouring by lifting material from the scour hole); and 4) compressed horseshoe vortex. The interaction between piers in a group intensifies the reinforcing and compressed horseshoe vortex effects.

Only a small number of publications addressed the local scouring at submerged and partly submerged pile groups. They include Elliott & Baker (1985), Smith (1999), Sumer & Fredsoe (2002), Ataie & Beheshti (2006), and Amini & Ghazali (2012) have added parameters such as spacing between piles in pile groups, pile group skew angle, shape factor of individual piles, arrangement of piles which affect local scour at the pile groups, to the already existing parameters of local scour at isolated pier. Lanca, Fael, Maia, Pego, & Cardoso (2013) carried out long duration scour experiments at pile groups and developed equations for ratio of the equilibrium scour at a pile group and the equilibrium scour depth at an isolated cylindrical pier under the same hydrodynamic conditions. Lanca, Fael, Maia, Pego, & Cardoso (2013) reported that sheltering effect was not observed in their experiments on pile groups and they have found that equilibrium scour depth occurs for pile group skew angle of 30 degrees.

Single or multiple piles embedded in front of a pier modify and divert the approach flow away from it. The piles, which may experience substantial scour, protect the pier from scouring by deflecting the high velocity flow and creating a lower velocity wake region of less erosive potential (Melville & Hadfield (1999), Chiew & Lim (2003), Haque, Rahman, Islam, & Hussain (2007)). The effectiveness of this countermeasure depends on the pile characteristics (e.g. number, size relative to pier dimension, partial or full submergence and geometric arrangement in relation to each other and to the pier, and the flow characteristics including intensity and angle of attack or flow obliqueness (Melville & Hadfield (1999)).

Mutual interference of two different diametercircular piers in series on equilibrium scour depths with varied spacing between them wasexperimentally studied. The objective of the present study is to experimentally study the non-dimensional spacing vs non-dimensional scour depth at the different diameter circular piers placed in line with the flow.

2 EXPERIMENTS

2.1 Experimentalsetup

The experiments were conducted in a parallel sided recirculating flume of overall length 1550 cm and a clear width of 91 cm. The depth of the flume was 70 cm. A part of the flume was filled with river sand. The sand was confined between two walls 20 cm high and 15 cm thick built 250 cm apart. The sand was a pure river sand which was sieved in laboratory to pass through a sieve of 1 mm mesh and utilized for the experiments. The weighted mean diameter of the particles, d_{50} = 0.95 mm was obtained from the grain size distribution curve. Sand trap was built adjacent to one of the dwarf wall on the downstream side, with a clear length of 150 cm, to arrest the suspended bed load during the flow of the water. The schematic of the experimental setup was presented in Figure 1.

The water supply system comprised of a constant head reservoir at an elevation of about 4 m above a large underground reservoir. Pumps were used to lift water from the underground reservoir to the constant head reservoir. A valve fitted at the junction of constant head reservoir and the inlet tank was used to regulate the water supply level in the inlet tank. Water flows from the inlet tank into the flume via a stilling basin through a calibrated right angled V-notch weir. A point gauge was set up in an adjacent chamber which was directly connected with the chamber to which the right angled V-notch was fixed. The necessity of fixing the point gauge was to maintain the calculated total head of the flow through the V-notch.

To facilitate the measurement of water surface elevation, scour-depth and pattern etc., guide rails were provided along the sides of the flume for movable carriage. A point gauge mounted over the moveable carriage was utilized to measure the water surface elevation and the scour-depth readings. The accuracy of the point gauge was ± 0.1 mm.

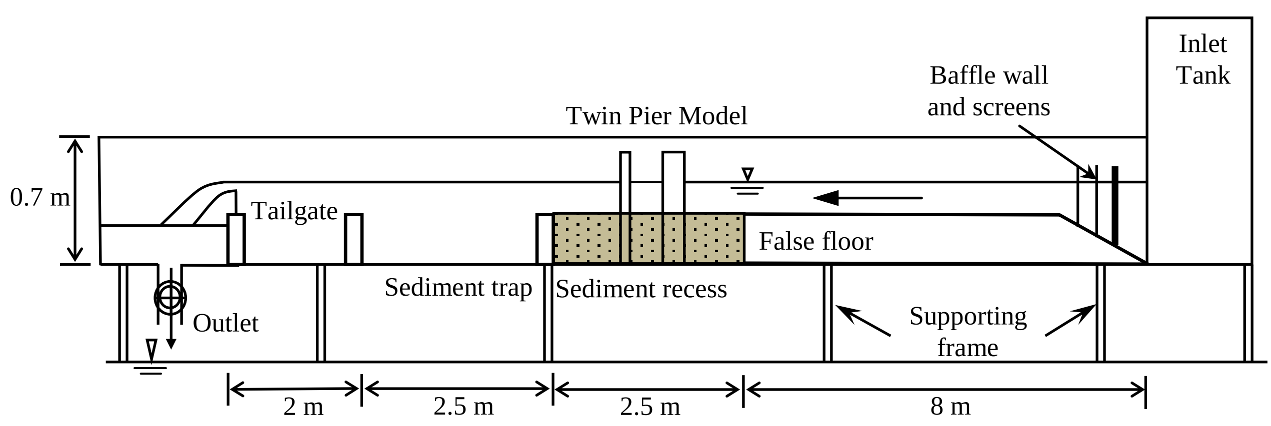


Figure1:Schematicoftheexperimentalsetup

2.2 Typesofexperiments

In these experiments front pier diameter was fixed and rear pier diameter was changed in each experiment. The pier diameters 40 mm, 50 mm, 60 mm, 77 mm, 80 mm and 100 mm were used in the study. Front pier diameters used were 40 mm, 77 mm and 100 mm and rear pier diameter was changed in each experiment such that no identical piers were used as front and rear piers in an experiment. In total, 13 different experiments were carried out andin which 4, 5, 4 number of experiments were carried where front pier diameters were 40 mm, 77 mm and 100 mm respectively. Diameters of front and rear piers were denoted as D_1 and D_2 respectively.

The front pier (from upstream to downstream direction) was fixed at a distance of 85 cm from the starting of the sand bed and the location of the rear pier was varied. Center to center spacing between the two piers (S) = $7D_2$was used and equilibrium local scour at both piers was measured. Before the start of each experiment, the twin piers were inserted centrally and vertically in the flume and the sediment bed was leveled perfectly using a steel float. The bases of the piers were bolted to the floor of the flume. Utmost care was taken in aligning the two piers parallel to the flow.

2.3 Flumesetup

Three separate holes of 3 cm diameter each were provided along the two dwarf walls on the downstream side. This arrangement facilitated the draining of water from sand bed after completion of experiment. The holes were sealed by jute balls during the experimental run to prevent sand escaping through them. A layer of medium sized stones was placed as an armoring on the upstream just where the sand bed starts, to facilitate smooth flow of water above the sand bed, without any extra turbulence due to change in type of bed surface on the upstream.

Non-uniform flow conditions in the form of swirls and waves were created in the flow through the flume as it entered from the inlet tank containing V-notch. Since uniform flow conditions were a necessary pre-requisite for the experiment. An 800 cm stilling bed upstream of the sand bed was used to eliminate the turbulence caused by the inlet condition, such that the water can become wave free before it reaches the sand bed for avoiding unnecessary ripples on the sand surface.

2.4Experimentalprocedure

The experiments were started with a perfectly leveled smooth bed which was checked by the point gauge mounted on the movable carriage. The piers were fixed on the base of the flume at desired locations. The initial bed level was measured using the point gauge. The sand trap on the downstream of the sand bed was started filling with water before opening the main water supply on the upstream. This was done so that the sand bed becomes fully saturated and ripples plus general scour do not take place. The water in the chamber flowed through the V-notch, till it reaches the desired head. The inlet valve was opened gradually and care was taken to keep enough depth of stagnant water before the flow was started, to avoid the initial formation of bed ripples and scour. First the discharge was regulated to the required quantity which could be found by the point gauge reading. Tailgate was used to control the flow depth in the flume. Point gauge was used to maintain the desired water depth in the flume. Formation of Karman vortices on either side of the front pier diverging and converging on the rear pier as they passed downstream was noticed in each experiment.

Duration of each experimental run was a minimum period of 10 hours to ensure that maximum equilibrium scour depth has been reached and there could be no more scouring. After stopping the flow, the water in the saturated sand was allowed to drain completely before taking the point gauge readings of the equilibrium scour hole depths at both the piers.

2.5 Flowconditions

Duringtheexperiments, theaverageapproachflow velocity $\overline{U}$ wassetatanapproximately0.9timesthe criticalvelocity(U_C)oftheuniformsedimentbedto satisfythenearlylimitingclear-water condition.The corresponding criticalvelocity,whichwasapproach flowdepth(h)dependent,wascalculatedusingfollowingsemialogarithmic equation.

$$\frac{\overline{U}}{U_c} = 5.75 ln\left(\frac{h}{2d_{50}}\right) + 6.0 \tag{1}$$

$$\overline{U} = 0.9U_c \tag{2}$$

Where(U_C)=approach flow velocity for the threshold of sediment entrainment from the Shields diagram by using Van Rijn (1984) empirical equation of the shields curve; d_{50} = median size of the sediment.

Average approach flow velocity was obtained using (1) and (2), and discharge was calculated from velocity. Experimental flow conditions were given in Table 1. The discharge was measured using a calibrated V- notch installed at the inlet tank in the reservoir. The discharge Q was expressed as a function of the head of water (H) above the sill level of the calibrated V-notch by following equation.

$$Q = 1.139H^{2.346} \tag{3}$$

3. RESULTS AND DISCUSSION

Local scour around a single bridge pier was affected by a large number of interdependent parameters. The flow properties, sediment properties, pier characteristics and time were the main variables affecting this phenomenon. As a consequence of extensive research by several investigators on the phenomenon of local scour around a single bridge pier, a large number of design relationships have been developed and made available to the bridge designer. Notwithstanding this, many bridges still suffer damage by local scour. This was due to more intense complexities due to the mutual interaction of group of piers, which was negotiated by many engineers. In addition to the above mentioned variables affecting local scour around a single pier, Shivakumar et al. (2014) found that streamwise and transverse spacing between piers wasa most important factor influencing the local scour depth at the two piers placed in streamwise direction. Shivakumar et al. (2014) study on mutual interference of pierswas limited to only identical piers. In this paper, scope of the research extended to mutual interference of different diameter piers placed in series arrangement. Figure 2 shows the schematic of different diameter piers in series.

Table1:Experimentalconditions

B(m)	D_1(m)	d_{50}(mm)	h(m)	U(m/s)	U/U_{*c}	D_1/d_{50}	B/D_1	Re	Fr
0.91	0.077	0.95	0.2	0.358	0.90	81.05	11.81	27566	0.25
0.91	0.10	0.95	0.2	0.358	0.90	105.26	9.10	35800	0.25
0.91	0.04	0.95	0.2	0.358	0.90	42.10	22.75	14320	0.25

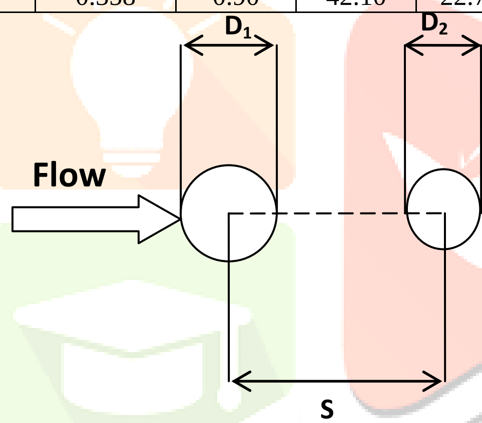
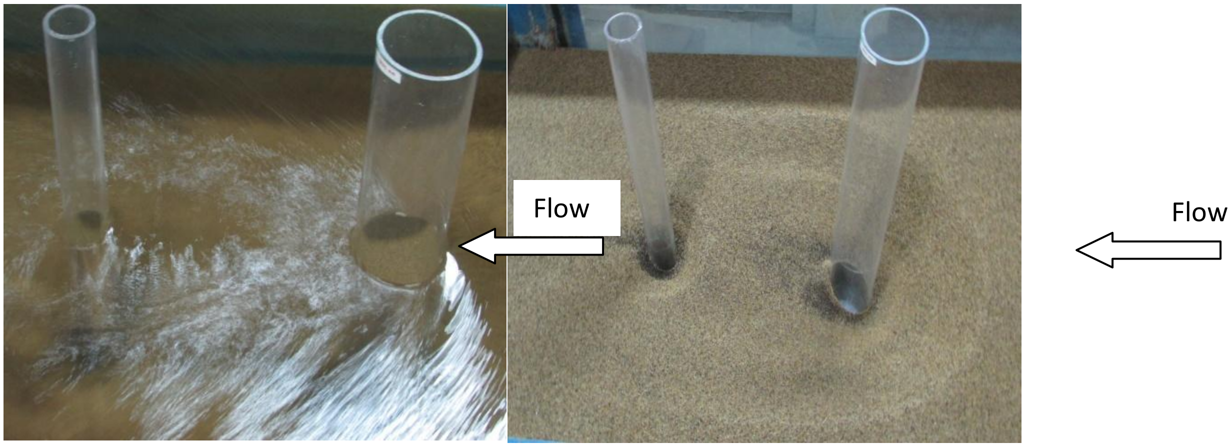


Figure 2: Piers in series arrangement

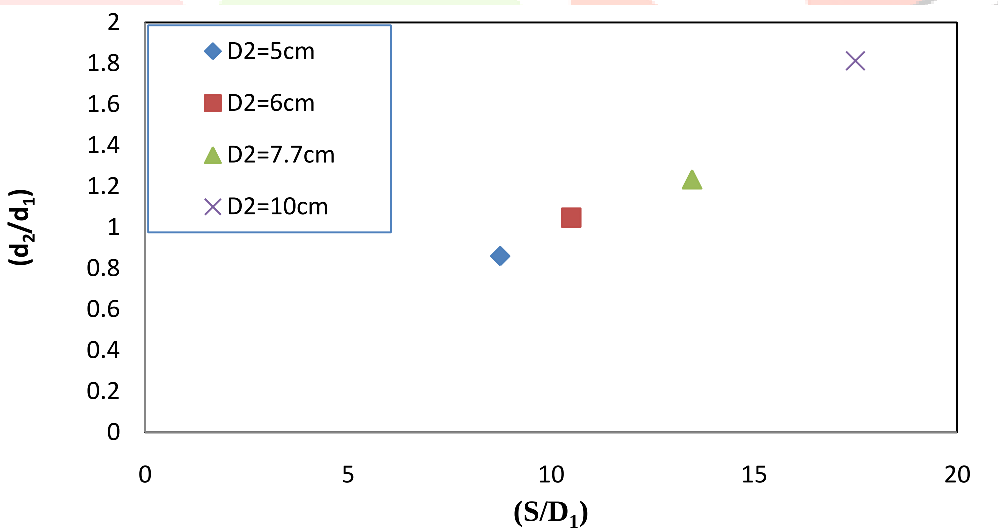
Different diameter piers 40 mm, 50 mm, 60 mm, 77 mm, 80 mm and 100 mm were considered in this set of experiments. In each experiment, two different diameter piers in series were fixed vertically in the sediment bed at a constant streamwise distance of $7D_2$, i.e. $S = 7D_2$.The equilibrium scour depths at front and rear piers were denoted by d_1 and d_2 respectively. These experiments were again subdivided into three sets of experiments depending on the diameter of front pier. First set of experiments consisted diameter of front pier = 40 mm as a constant and rear pier diameter was selected as 50 mm, 60 mm , 77 mm and 100 mm in each experiment respectively. In the second set of experiments diameter of front pier = 77 mm was chosen as a constant and rear pier diameter was used as 40 mm, 50 mm, 60 mm, 80 mm and 100 mm diameter in each experiment respectively. In third set of experiments, diameter of front pier = 100 mm was used as a constant and rear pier diameter was selected as 40 mm, 50 mm, 60 mm and 77 mm in each experiment respectively. The spacing between the piers in the second set of experiments is fixed as 7 times the diameter of rear pier following Shivakumar et al. (2014) recommendation of minimum spacing between the identical piers to have least equilibrium scour depth at the rear pier. Non-dimensional equilibrium scour depth measured at rear pier in each experiment were plotted in Figure 4. The equilibrium scour depths measured at front pier were64 mm, 106.5 mm and 134 mmfor constant front pier diameters 40 mm, 77 mm and 100 mm respectively. The spacing of $7D_2$between the piers was chosen because equilibrium scour depth at rear pier was found to be minimum at $7D$spacing in experiments with identical piers in series (Shivakumar et al., 2014).Photographs (Fig. 3) of typical different diameter piers in series arrangement shows the scour and deposition patterns developed on the bed around the piers at the end of the experiment. In addition, Figure 3(a) shows the wake region around the rear pier.



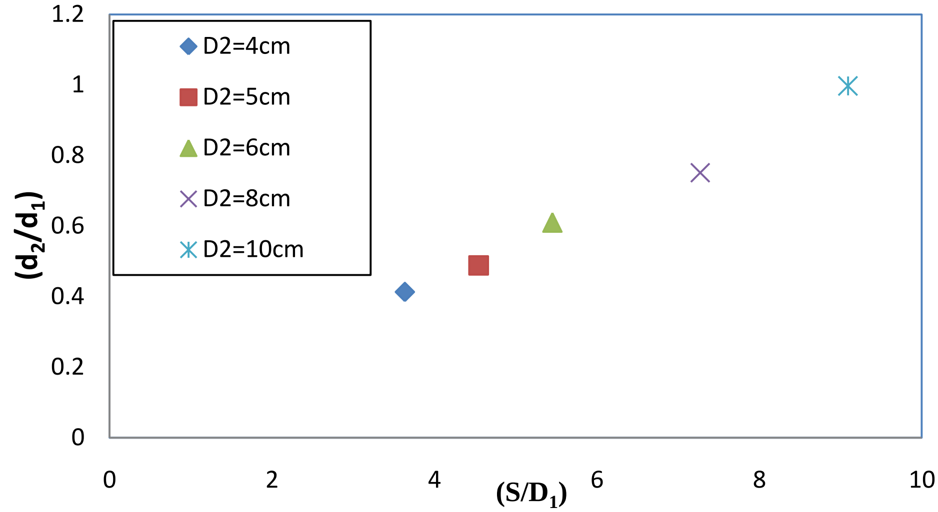
(a) (b)

Figure 3: Two piers of different diameters in series (a) during Experiment (b) after Experiment

It was observed that the equilibrium scour depth measured at the front pier was independent of the rear pier if spacing is seven times the diameter of the rear pier. However equilibrium scour depth measured at the rear pier decreases with increase in distance between the piers. It was noted that equilibrium scour depth at the rear pier increases as the non-dimensional spacing (S/D_1) which is shown in Figure4. However if the spacing between them is very small (<4*D* in case of identical piers) then reinforcement effect may increase the scour depth at the front and rear piers. The equilibrium scour depth at the rear pier is small compared to the front pier for the non-dimensional spacing (S/D_1) ≤ 10 because of sheltering effect of front pier due to which the approach flow velocity at rear pier is small. The deflected approach flow velocity at the rear pier decreases the strength of horse shoe vortex and which in turn decreases the equilibrium scour depth at the rear pier. In addition, the scoured bed material at the front pier carried and deposited at the rear pier due to reduced approach velocity. As the pier spacing increases, the scour depth at rear pier increases. The increase in scour depth is attributed to the effect of shed vortices approaching from front pier and which strikes the rear pier. The striking action of shed vortices from front pier reinforces the strength of horse shoe vortex at rear pier and results in increased scour depth.



(a)



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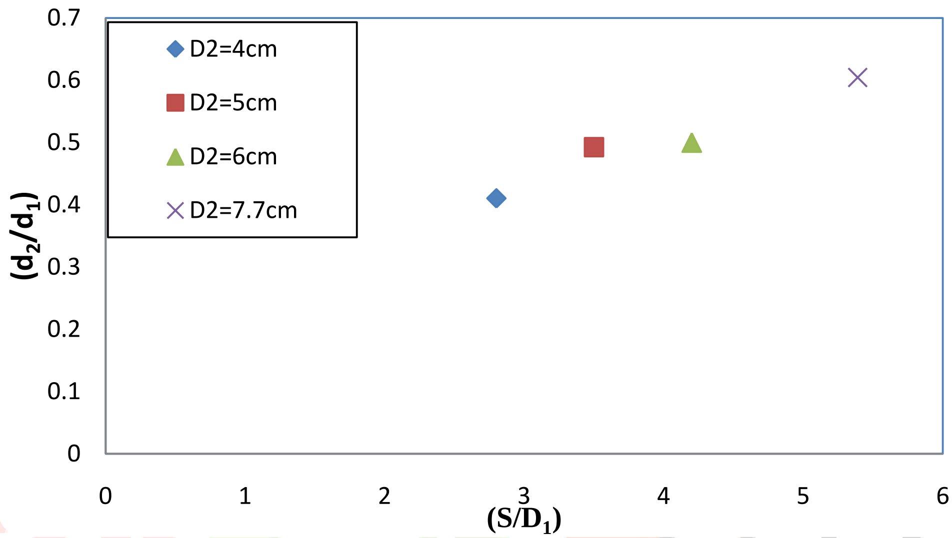

(c)

Figure 4:Local scour at rear pier for front pier fixed as (a) D_1 = 40 mm(b) D_1 = 77 mm and (c) D_1 = 100 mm

4. CONCLUSIONS

Experiments to studymutual interference of upstream (front)and downstream (rear) piers placed in series were performed by varying the center to center stream wise spacing between the non-identical piers. In these experiments, 40mm, 50mm, 60 mm, 77mm, 80 mm and 100 mm were used as pier diameters, in which, front pier diameter was fixed as constant and rear pier diameter was changed in each experiment and the spacing between the piers is fixed as 7 times the diameter of rear pier. In this study, all experiments were carried out in steady uniform flow conditions. Finally, following conclusions were obtained on the basis of the experimental results.

1. The equilibrium scour depth around the front pier was independent of the spacing between piers for streamwise distance of$7D_2$for different diameterpiers in series arrangement.
2. If the front and rear piers are of different diameters and arranged in series, the equilibrium scour depth at rear pier attains that of front pier for pier spacing of $9D_1$ to $10D_1$.
3. If the front and rear piers are of different diameters and arranged in series, the equilibrium scour depth at the rear pier is half of the equilibrium scour depth at front pier for the spacing of $3.5D_1$ to $4.5D_1$.
4. The non-dimensional equilibrium scour depth at the rear pier (d_2/d_1) is linearly proportional to non-dimensional spacing (S/D_1) between the piers.
5. The equilibrium scour depth at rear pier is more than the equilibrium scour depth at front pier for a non-dimensional spacing (S/D_1) > 10 for D_2>D_1

6. If the spacing (S/D_1) >5 then the non-equilibrium scour depth (d_2/d_1) at the rear pier is approximately (K)*(S/D_1) *(D_2/D_1) whereKis a constant and its value varies between 0.05 and 0.15.

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