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Characteristics of Developing Scour Holes around Two Piers Placed in Transverse Arrangement

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ABSTRACT

Local scour at single pier has been extensively studied by several investigators, but scanty work is available on scour around bridge piers founded in close proximity. The work reported herein is concerned with a carefully controlled extensive experimental study of local scour around a group of two bridge piers placed in transverse direction to the flow at varied pier spacing under steady uniform flow clear water scour conditions at flow intensity equal to 0.95. The objective of present study is to investigate the effect of mutual interference of bridge piers on local scour. The data on temporal scour depth, areal extent of scour and sediment deposition around the piers and scour hole characteristics are collected which may provide very useful information to the bridge engineers. Present study reveals that the piers founded in transverse direction to the flow at close proximity may lead to bridge failure, if pier group effect is ignored and bridge piers are designed merely as an isolated pier.

INTRODUCTION

Local scour at group of bridge piers

In case of scour around group of piers, the presence of 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 is quite different from one which occurs around a single pier.

Local scour around a single bridge pier is affected by a large number of inter-dependant variables. The flow, sediment, pier characteristics and time are 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 bequeathed to the bridge designer. Not withstanding this, many bridges still suffer damage by local scour. This is due to more intense complexities due to the mutual interaction of piers group. It indicates that in addition to the variables affecting local scour around a single pier, spacing of piers and pattern of piers' placement in the riverbed also affect the scour depth around group of piers.

Hannah (1978), Elliot, K.R. and Baker, C.J. (1985), El-Taher, R.M. (1984, 85). Breusers and Raudkivi (1991), Vittal et. al. (1994), Babaeyan-Koopaei and Valentine (1999) and Mubeen Beg (2008) have made some studies on scour around group of piers.

Mechanism of scour around piers placed in transverse arrangement
The presence of group of piers in the river-bed 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 is quite different from one which occurs around a single pier.

Tison (1940) carried out a model study to investigate the effect on scour depths caused by variation of spacing of piers placed in side-by-side arrangement. He found a mutual interference on maximum scour depth for $Z_c/b \geq 4.3$, where Z_c/b is the lateral spacing of piers measured from center to center. Dietz (1973) made a study of the angle of attack (θ) on maximum scour depth around laterally separated circular piers. He concluded that scour depth is not influenced by (θ) for $Z_c/b \geq 3$.

(Hannah, 1978) has recognized compressed horseshoe vortices responsible to enhance scour at piers placed at close spacing in lateral arrangement. He observed that when piers were placed transverse to the flow, each was having, except at very close spacing, its own horseshoe vortex. As pile spacing was decreased, the inner arms of the horseshoe vortices were observed to be compressed. This caused velocities within the arms of horseshoe vortices to increase with a consequent increase in scour depths.

It can be concluded that it is well established that mostly, the bridge piers are designed as a single pier. However, in the field a bridge is usually supported on a number of piers. Therefore, if a bridge pier is merely designed as a single pier, it may lead to the bridge failure. In these perspectives, to ensure the stability of the bridge piers, the need of a study on the effect of mutual interference of bridge piers on local scour assumes significance. This experimental study investigates the effect of mutual interference on the characteristics of developing scour holes around two piers placed in transverse arrangement.

EXPERIMENTAL PROGRAMME
A series of experiments was conducted to investigate the effect of mutual interference of bridge piers on local scour for the piers located in a direction transverse to the flow at varying lateral pier spacing.
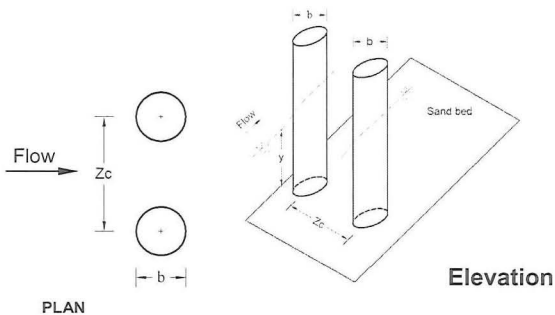

Figure 1. Piers in transverse arrangement

As shown in Figure 1, two circular pier models of 33 mm diameter were set vertically in the sediment bed in the flume at varying lateral spacing, $\dfrac{Z_c}{b}$ = 1, 2, 3, 4, 5, 6, 7, 8 and 9 where Z_c is the center to center lateral spacing between the piers and b is the pier diameter.

The approach flow was steady uniform for all experiments with average flow depth 140 mm. The stage of particle motion expressed in terms of the shear velocity parameter U_* / U_{*_c}, was set so that all the experiments were performed at the clear-water local scour condition $U_* / U_{*_c} < 1.0$. The threshold of bed material motion was found by experiment when the pier was not installed. The sediment used in present investigation was cohesionless coarse sand (Median diameter d_{50}=0.95 mm and Geometric standard deviation σ_g=1.187).

Each experiment commenced from a condition of still water at the predetermined flow depth over a leveled bed surface. The time of start of initial movement, and of water surface establishment were recorded. On the completion of the experimental run, the water supply to the flume was gradually stopped and the water from the flume was drained off carefully so that the scour holes and the scour patterns around the piers developed by the flow were not disturbed.

COLLECTION OF DATA AND ANALYSIS OF RESULTS

During the experimental runs, the scour depths were measured at the nose of the two piers at regular interval of time. On the completion of the experimental run, detailed measurements of the scoured area around the piers were made and thereafter the photographs of the scour patterns were taken. The results are analyzed under the following heads:

Variation of scour depth at front faces of piers

During experiments it was observed that both piers scoured to the same depth (± 3mm). Therefore, the maximum scour depths observed at two piers are averaged and plotted against lateral pier spacing 'Z_c/b' as shown in Figure 2.
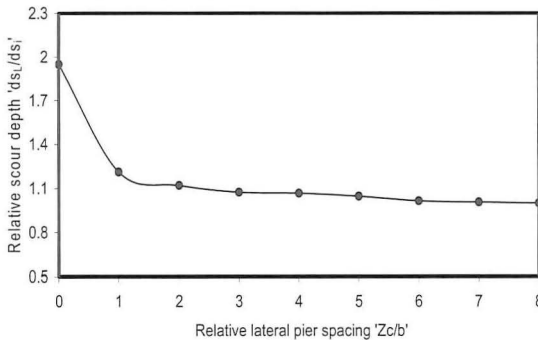

Figure 2. Variation of relative scour depth 'ds_L/ds_i' with pier spacing Z_c/b (where ds_L = scour depth at lateral piers, ds_i= scour depth at an isolated pier).

It is worth mentioning that when the two piers are placed at lateral pier spacing $Z_c/b=0$, the scour depth ds_L is about 1.95 time's ds_i. This is in accordance with the concept of scour depth being proportional to the frontal width of the pier. The scour depth reduces rapidly with piers separation and reaches to about 1.21 (*i.e.*, 'ds_L' about 21% more than 'ds_i') at lateral pier spacing $Z_c/b=1$. The reason for this scour depth being more at $Z_c/b=1$ is the increase in the strength of horseshoe vortex caused by the compression of inner limbs of horseshoe vortices between the two piers. As the pier spacing Z_c/b increases, the effect of compression of horseshoe vortices reduces. Thereafter, the scour depth reduces gradually and reaches to that of an isolated pier at lateral pier spacing $Z_c/b=8$.

Characteristics of scour hole

It was experimentally observed that the flow accelerated between the piers placed at right angles to flow at shorter pier spacings 'Z_c/b' which resulted in an increase in the strength of horseshoe vortices at two piers. As a result, the scour depth increased for same flow, sediment and pier conditions. The characteristics of scour hole vary with the variation in lateral pier spacing 'Z_c/b'. The analysis of important characteristics of scour holes like, length and slope of scour holes at the upstream and downstream face of piers, length of sediment deposition at downstream face of piers, width of scour holes and areal extent of scour are discussed in the following sections.

Since the knowledge of scour hole dimensions is imperative in determining the extent of countermeasures needed to prevent/control scour at piers, various parameters explained as under using present experimental data are determined.

(a) Length of scour hole at upstream faces of piers

The relative lengths of scour hole at upstream face of piers '$L_{shu(L)}/L_{shu(i)}$' are plotted against lateral pier spacing 'Z_c/b' as shown in Figure 3.
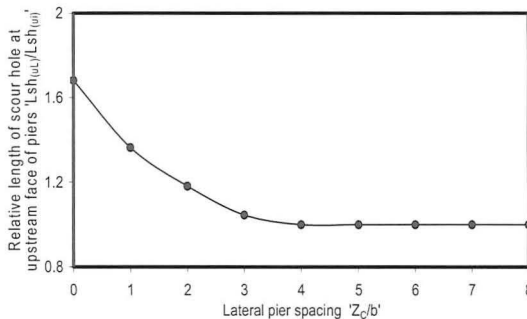

Figure 3. Variation of relative length of scour holes at upstream '$L_{shu(l)}/L_{shu(i)}$' with pier spacing 'Z_c/b'(where $L_{shu(L)}$ = length of scour hole at upstream face of lateral piers , $L_{shu(i)}$ = length of scour hole at upstream face of an isolated pier).

It is observed that the length of scour hole '$L_{shu(L)}$' at Z_c/b=0, is about 1.68 times more, than at an isolated pier. This increment occurs due to more frontal width of piers at Z_c/b=0. As the pier spacing Z_c/b increases, frontal width decreases due to gap created between two piers as a result of which '$L_{sh\ u(L)}/L_{shu(i)}$' decreases and a decrement of about 63.6 % is noticed at Z_c/b=3. Thereafter, a gradual decrease in the length of scour hole '$L_{shu(L)}/L_{shu(i)}$' is observed. This decrease is caused due to the reduction in the effect of compression of horseshoe vortices at piers with increasing pier spacing Z_c/b. The values of '$L_{shu(L)}/L_{shu(i)}$' gradually reaches close to unity at Z_c/b=8, which indicates the disappearance of effect of mutual interference between the piers.

(b) Length of scour hole at downstream faces of piers

The relative length of scour holes at the upstream face of piers '$L_{shd(l)}/L_{shd(i)}$' are plotted against lateral pier spacing 'Z_c/b' as shown in Figure 4.
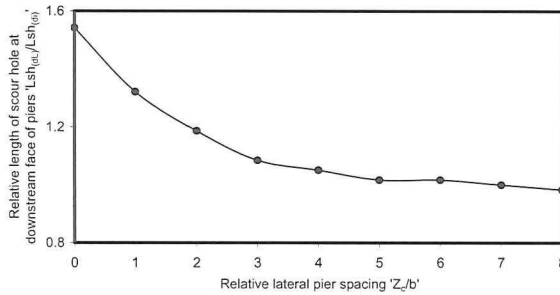

Figure 4. Variation of relative length of scour holes at downstream faces of piers '$L_{shd(l)}/L_{shd(i)}$' with pier spacing 'Z_c/b' (where $L_{shd(l)}$ = length of scour hole at downstream face of lateral piers, $L_{shd(i)}$ = length of scour hole at downstream face of an isolated pier).

Figure 4 reveals that the length of scour hole '$L_{shd(L)}$' at pier spacing Z_c/b=0, is about 1.51 times more than what is observed at an isolated pier. This increment in the value of '$L_{shd(L)}/L_{shd(i)}$' occurs due to more frontal width of piers at Z_c/b=0. As the pier spacing Z_c/b increases, separation of piers causes a decrease in the value of '$L_{shd(L)}/L_{shd(i)}$' and a decrement of about 42.6% in the value of '$L_{shd(L)}/L_{shd(i)}$' is noticed at pier spacing Z_c/b=3. Further increase in pier spacing Z_c/b causes a reduction in the effect of compression of horseshoe vortices between the two piers which consequently causes a decrease in the value of '$L_{shd(L)}/L_{sh\ d(i)}$'. At pier spacing Z_c/b=8, the value of '$L_{shd(L)}/L_{shd(i)}$' approaches to unity which suggests the disappearance of the effect of compression of horseshoe vortices between the two piers.

(c) Slope of scour holes
(i) Slope of scour holes at upstream faces of piers

The relative slopes of scour holes observed at the upstream face of two piers '$S_{lu(L)}/S_{lu(i)}$' are plotted against lateral pier spacing 'Z_c/b' as shown in Figure 5.
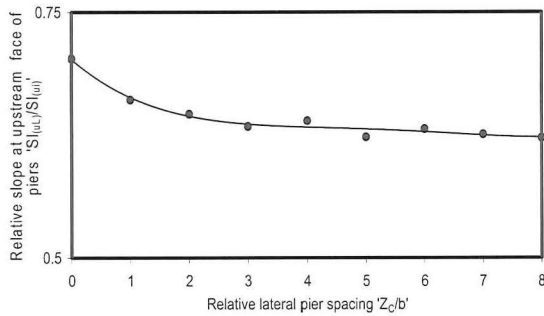
Figure 5. Variation of relative slopes of scour holes at upstream face of piers '$S_{lu(l)}/S_{lu(i)}$' with pier spacing 'Z_c/b' (where $S_{lu(l)}$ = slope of scour hole at upstream face of lateral piers, $S_{lu(i)}$ = slope of scour hole at upstream face of an isolated pier).

At Z_c/b=0, frontal width of piers is more, therefore, the size of scour hole is more, however, increase in length of scour hole is not proportional to the increase in the scour depth. As a result, higher value of '$S_{lu(L)}/S_{lu(i)}$' can be seen in Figure 5 at Z_c/b =0. As the pier spacing Z_c/b increases, frontal width decreases due to separation of piers. With further increase in pier spacing Z_c/b, the slope '$S_{lu(L)}/S_{lu(i)}$' approaches to unity which is a pointer towards the state of two piers being free from mutual interference.

(ii) Slope of scour holes at downstream faces of piers

Figure 6 shows the relative slope of scour holes at the downstream face of two piers '$S_{ld(L)}/S_{ld(i)}$' with respect to the lateral pier spacing 'Z_c/b'.
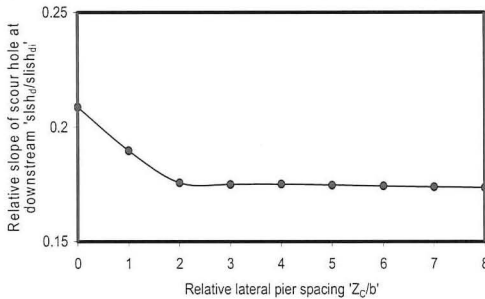

Figure 6. Variation of relative slopes of scour holes at downstream face of piers '$S_{ld(L)}/S_{lu(i)}$' with pier spacing Z_c/b (where $S_{ld(L)}$ = slope of scour hole at downstream face of lateral piers, $S_{ld(i)}$ = slope of scour hole at downstream face of an isolated pier).

At shorter Z_c/b, inner arms of horseshoe vortices at downstream faces of two piers are compressed as a result of which the flow is accelerated between the piers and causes increased scour depths to occur, however, as shown in Figures 2 and 4, this

increment in scour depth is not in proportion to the increase in the length of scour hole. Consequently, increased values of '$S_{ld(L)}/S_{ld(i)}$' at pier spacing $Z_c/b=2$ are resulted. However, as noticed in Figure 6, at pier spacings $Z_c/b \geq 2$, the of slope of scour holes at the downstream face of piers is close to that observed at an isolated pier which indicates the diminishing state of mutual interference effect of piers.

(d) Variation of area of scour extents with pier spacing

The areal extents of scour around the piers are plotted for typical pier spacings 'Z_c/b' and shown in Figures 7 and 8 respectively. It can be seen in Figure 7 that the areal extent of scour around the two piers overlap each other upto pier spacing $Z_c/b=6$.
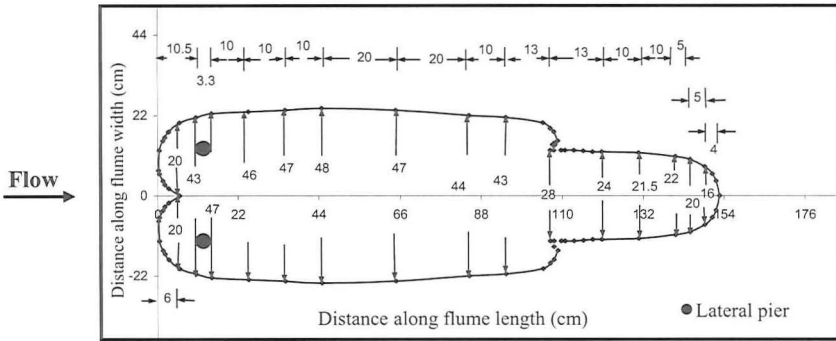

Figure 7. Areal extent of scour around the piers placed in lateral arrangement at $Z_c/b=6$

However, at pier spacing $Z_c/b=8$, as illustrated in Figure 8, the areal extents of scour get completely separated from each other and become similar in shape and size to that around an isolated pier, demonstrating that the two piers become free of effects of mutual interference.
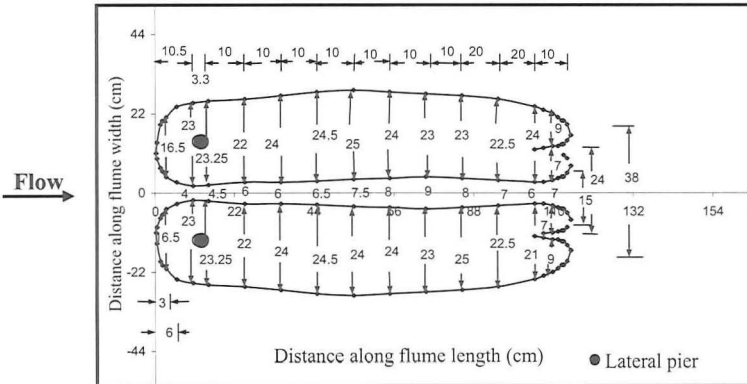

Figure 8. Areal extent of scour around the piers placed in lateral arrangement at $Z_c/b=8$

The areas of scour extents around the piers are divided by twice the area of scour extent estimated for an isolated pier to obtain the relative areas of the scour extent '$A_L/2A_i$' and the same are plotted against lateral pier spacing 'Z_c/b' as shown in Figure 9.
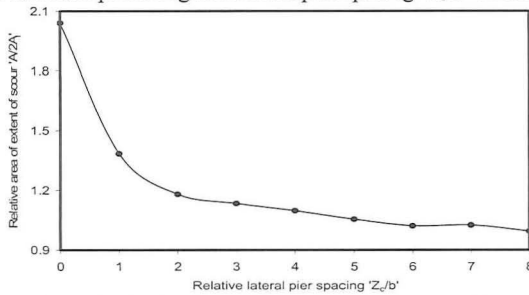

Figure 9. Variation of relative area of scour extent around two piers '$A_L/2A_i$' with pier spacing Z_c/b (where A_L = area of scour extent around the lateral piers, A_i = area of scour extent around an isolated pier).

It is noticed that the value of '$A_L/2A_i$' is maximum at pier spacing Z_c/b=0. This maxima occurs, since, as the frontal width of piers at this pier spacing is twice that of an isolated pier. At Z_c/b=1, a rapid decrease of 65.55 % in the value of '$A_L/2A_i$' is observed.

At pier spacing Z_c/b=1,2,3,4 and 5, the values of areas of scour extent '$A_L/2A_i$' are about 38.5%, 18%, 13.45,10% and 5.4% times more than that at an isolated pier. The values of areas of scour extent '$A_L/2A_i$' gradually decrease and reach close to that at an isolated pier at pier spacing Z_c/b=8. When the pier spacing between two piers Z_c/b increases beyond 1, the flow pattern around two piers become similar to around an isolated pier due to which area of scour extent '$A_L/2A_i$' decreases and approaches to that of an isolated pier.

(e) Width of scour holes

The top width of scour hole of a single pier can be estimated from the relationship of Richardson *et al.* 1993, therefore, top widths 'W_L' are divided by twice the top width of an isolated pier to obtain the relative width $W_L/2W_i$, which are plotted against relative pier spacing Z_c/b as shown in Figure 10.
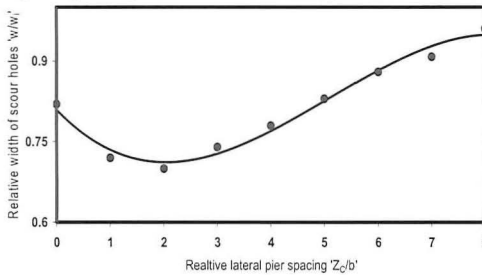

Figure 10. Variation of relative width of scour holes of piers $W_L/2W_i$ with pier spacing Z_C/b. (where W_L = width of scour hole of two lateral pier, W_i = width of isolated pier).

The top width $'W_L'$ measured at $Z_c/b=0$ is 1.64 times of top width of a single $'W_i'$ pier. This increase in width of scour hole is attributed to more frontal width of piers at this pier spacing as the depth of scour and hence the top width of scour hole is directly proportional to the frontal width of pier. When the two piers are separated from one another, the frontal width decreases as a result of which the scour depth decreases and consequently the top width of scour hole decreases. Figure 10shows that the value of $'W_L/2W_i'$ reduces to 0.72 at pier spacing $Z_c/b=1$. However, the value of $'W_L/2W_i'$ increases between pier spacings $Z_c/b=1$ and 8. This increase in the values of $'W_L/2W_i'$ is caused due to an increase in pier spacing $'Z_c/b'$ since the lateral distance between the outer edges of scour extent increases with pier spacing Z_c/b. The value of $'W_L/2W_i'$ approaches nearly equal to 0.92 at pier spacing $Z_c/b=8$, which indicates the diminishing state of mutual interference of piers.

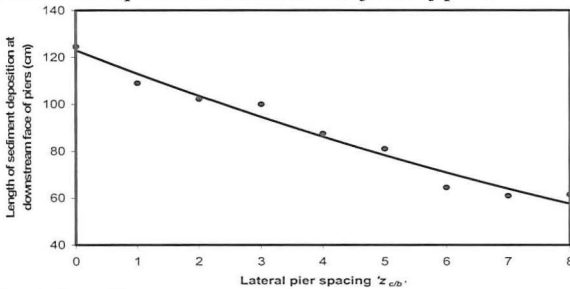*(f) Length of sediment deposition at downstream faces of piers*

Figure 11. Variation of length of sediment deposition at downstream face of two piers 'L$_{dep(l)}$'with pier spacing 'Z_c/b'

The lengths $'L_{dep(L)}'$ are divided by the length of sediment deposition $'L_{dep\,(i)}'$ occurring at the downstream face of an isolated pier and the values of relative length of sediment deposition $'L_{dep(L)}/L_{dep(i)}'$ are plotted with respect to the pier spacing $'Z_c/b'$ as shown in Figure 11.

It can be seen that at pier spacing $Z_c/b=0$, the value of $'L_{dep}/L_{dep(i)}'$ is maximum. This maxima is due to the fact that at $Z_c/b=0$, frontal width of piers is equal to twice the width of an isolated pier. It is also evident that $'L_{dep}/L_{dep(i)}'$ decreases with an increase in pier spacing Z_c/b, since, the increment in pier spacing Z_c/b causes decrease in frontal width and thereby a decrease in the length of sediment deposition. At pier spacing $Z_c/b=8$, the length of sediment deposition approaches to that measured at an isolated pier. Photographs shown in Figure P1 authenticate the interpretation of results on scour characteristics analyzed and discussed above.

CONCLUSIONS

At zero lateral pier spacing, the scour depth is 1.95 times of that occurring at an isolated pier. At lateral pier spacing of one pier diameter, though the scour depth at two piers quickly decreases, nevertheless, it remains 21 % higher than that of an isolated pier. At lateral pier spacing of 8 times the pier diameter, although, the scour depth at two piers becomes same as that of an isolated pier, but the size of the scour holes are not identical to that for an isolated pier. These findings suggest that the two

piers should be placed at lateral pier spacing $Z_c/b>8$. According to Raudkivi (1986), the scour depth at five-pier diameter spacing is 1.2 times the local scour at single pier.
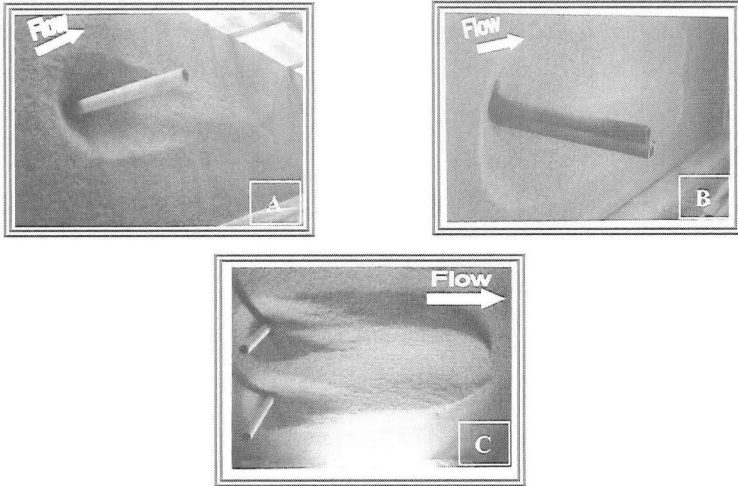

Figure P1. Scour and Deposition Patterns around (A) Single Pier (B) Z_c/b=0 (C) Z_c/b=7

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