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EVALUATION OF LOCAL SCOUR DEVELOPMENT AROUND PRISMATIC AND NON-PRISMATIC BRIDGE PIERS WITH DIFFERENT SHAPES

Hayder T. Nimnim[1], Maysam AbdulZahra Jabbar Al-Khaqani [2]

[1] Assistant Professor, University of Kufa/Faculty of Eng./ Civil Eng. Dept. /Najaf, Iraq/ hayder.alkhazaali@uokufa.edu.iq

[2] M. Sc. Researcher, University of Kufa/Faculty of Eng./ Civil Eng. Dept. /Najaf, Iraq/ maysamalkhagani_77@yahoo.com

ABSTRACT

In this study, laboratory experiments were conducted to evaluate the local scour around piers. Effects of many parameters on the maximum depth of scour and scour pattern around piers have been studied. The study considered the effects of upstream flow conditions, shape of pier, side slope angles, and type of soil. Three cross sections for pier (circular, elliptical and oblong) were used for different velocities and discharges to find the scour depth. Two types of uniform cohesionless soil with median grain sizes of d_{50}=0.25 (bed soil of Al-Kufa river), and d_{50}=0.66 were used as bed material. Four angles of pier side slope were selected 0° (prismatic pier) and 5°, 10° and 15° (non-prismatic piers). It has been observed that for circular cross section pier, the maximum reduction for the scour depth at the upstream of the pier with a side slope of 15° for the soil of d_{50}=0.25mm was about 63.64% and for the soil of d_{50}=0.66mm was about 54.55%. The reduction value was increased up to 80% and 75% for the same angle of pier side slope (Θ=15°) with oblong cross section for the soil of d_{50}=0.25mm and d_{50}=0.66mm respectively.

KEYWORDS: Non-prismatic; bridge pier; circular pier; elliptical pier; oblong pier; local scour; slope angle

حساب الانجراف الموقعي المتكون حول دعامات الجسور الموشورية واللاموشورية لأشكال مختلفة

أ. م. د. حيدر طالب نمنم **ميسم عبد الزهرة جبار الخاقاني**

الخلاصة

لقد تم في هذا البحث اعتماد التجارب المختبرية لحساب عمق الانجراف الموقعي حول الدعامات، حيث اخذت الدراسة بنظر الاعتبار تأثير ظروف الجريان في مقدم المنشأ وشكل الدعامة والميل الجانبي للدعامة ونوع تربة القاع وتأثير ذلك على عمق الانجراف الأعظم ونمط الانجراف حول الدعامة. استخدم ثلاث مقاطع عرضيه للدعامة (دائري وبيضوي ومستطيل) ولقيم مختلفة من السرع والتصاريف عليها لإيجاد عمق الانجراف, وتم استخدام نوعين من التربة ذات حبيبات منتظمة غير متماسكة (رمل) كمادة للقاع وبمتوسط حجم حبيبات (d_{50}=0.25 mm) (تمثل تربة قاع نهر الكوفة) و (d_{50}=0.66 mm). تم استخدام اربع زوايا للميل الجانبي للدعامة بحيث تكون الزاوية مع المحور العمودي 0° (مقطع موشوري) و 5°, 10°, 15° (مقطع لاموشوري) لإيجاد افضل زاوية تقلل عمق الانجراف. ومن النتائج العملية المستخرجة وجد ان اعلى نسبة تقليل للانجراف بالنسبة للمقطع الدائري وباستخدام تربة بمتوسط حجم حبيبات(d_{50}=0.25 mm) بحدود 63.64 % و بحدود 54.55 % للتربة ذات (d_{50}=0.66 mm) للدعامة بميل جانبي مقداره (Θ=15°). كما تم ايجاد ان اعلى نسبة تقليل للانجراف تصل الى (80)% و (75)% لنفس الميل الجانبي (Θ=15°) بالنسبة للمقطع المستطيل لحالة تربة بمتوسط حجم حبيبات (d_{50}=0.25mm) و (d_{50}=0.66 mm) على التوالي.

1. INTRODUCTION

Scour is a natural phenomenon caused by erosive action of the flowing water on the bed and banks of alluvial channels. Construction of bridges in alluvial channels causes a contraction in the waterway at the bridge. Contraction in the waterway causes significant scour at that site. Mohamed et al. (2007) studied a physical model to simulate the local scour around piers. Data gathered from experiments conducted on the physical model is used to study the effects of flow depth, velocity of approach, angle of pier inclination, and pier shape on the local scour depth. Negm et al. (2009) introduced a tool that maximize the reduction of the maximum local scour around bridge pier and hence ensure greater safety of the structure against the harmful local scour around the bridge pier. A rectangular collar of fixed width was used. Pourahmadi and Hakimzadeh (2011) conducted an experimental study for various slopes of conical piers using median size of sediment 0.78 mm. Shalmani and Hakimzadeh (2014) carried out an experimental study for scour around semi-conical piers (circular and elliptical) are presented to show the effect of their lateral slopes on the scour depth under steady current.

Studies of the aforementioned investigators have made important contributions to the knowledge of the phenomena of local scour around bridge piers in the relevant flow situations. The major goal of the present study is to evaluate the depth of local scour around bridge pier under different shapes of pier (circular, oblong, and elliptical), and side slope angles (0°, 5°, 10°, and 15°) which are defined with respect to the vertical axis. Also, study the effect of using different types of soil on the local scour around pier.

For clear water flow conditions approach, the maximum scour depth (ds max.) at a pier may be a function of the following parameters as shown in equations 1:

$$(d_s)=f\ \{B, S, \sigma_g, \rho, \rho_s, g, \mu, v_c, v, y, d_{50}, D_1, D_2, L_1, L_2\} \tag{1}$$

Where, B=the width of the channel, S=slope of the channel, σg =geometric standard deviation, ρ=density of fluid, ρs =density of the sediment, g=gravitational acceleration, μ=dynamic viscosity of fluid, vc=critical velocity, v=mean approach flow velocity, y=flow depth, $d50$ =medium particle grain size, D1= Top pier diameter, D2=Bottom pier diameter, L1=Top length of pier, L2=Bottom length of pier.

Using non-dimensional analysis, equation 1 can be written as:

$$d_s/y = f\ (B/y, S, \sigma_g, v/(gy)^{0.5}, \rho/\rho_s, \rho v y/\mu, v/v_c, d_{50}/y, D_1/y, D_2/y, L_1/y, L_2/y) \tag{2}$$

As channel width is constant (40 cm) for all present cases, it can be disregarded B/y. Effect of changing channel width is implicitly considered in v/vc. Simplifying the equations 1 and 2, and eliminating the parameters with constant and negligible values, and applying the assumption (effect of viscosity and relative density), equation 2 can be written as:

$$ds/y = f\,(Fr,\ v/v_c,\ d_{50}/y,\ D_1/y,\ D_2/y,\ L_1/y,\ L_2/y) \qquad (3)$$

2. EXPERIMENTAL WORK

Experimental investigation were performed in an open channel at the Hydraulic Laboratory in Al-Najaf Technical Institute, Department of Civil Techniques. The flume used in this study is shown in Fig. 1, which has a net inner dimensions of 6.6 m in length, 0.4 m in width and 0.4 m in depth.

The flume includes two parts: an upstream inlet section of 1.0 m length connected to water tank, and a working section of 5.6 m in length. This section is divided into three parts. A layer of sand with 0.1 m depth was placed along 2 m of the middle parts of the flume. Upstream and downstream sections has 1.25 m length with bed surface level matching the middle (sand) level to obtain the same channel ground surface level.

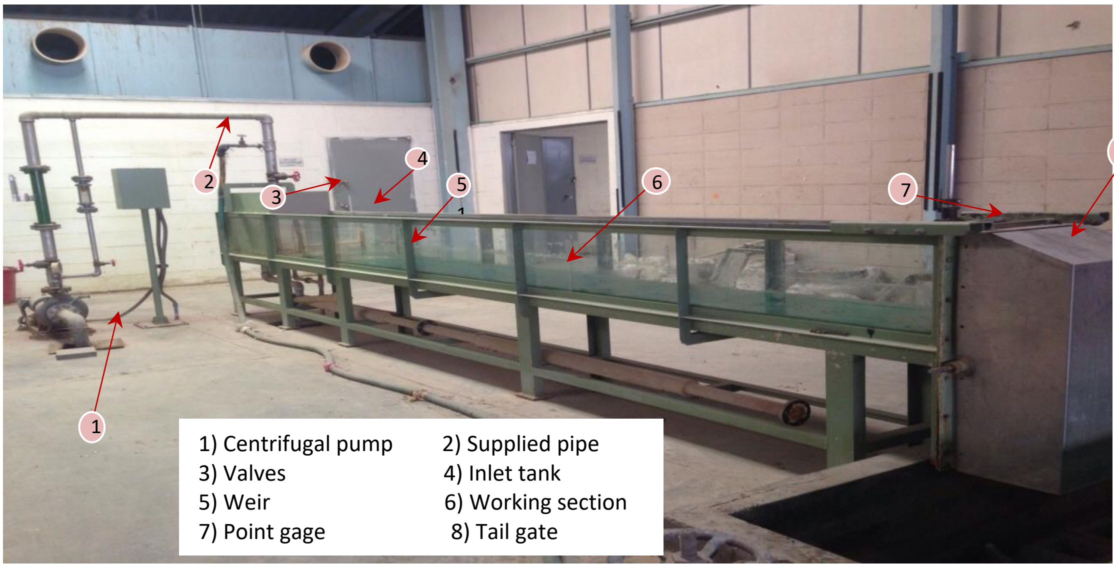


Fig. 1. The laboratory flume and its accessories.

The flow depth is controlled by an adjustable tail gate at the downstream of the trap basin. There is also a sharp crested rectangular weir to measure flow discharge. This weir is 0.4 m in width, and 0.25 m in height. All depth measurements were carried out using a point gauge with accuracy ±1 mm. It is mounted on a carriage. This carriage can move through the working area transversely and longitudinally.

To ensure conformity of measured discharge from weir with applied (actual) discharge, a calibration has been conducted. The standard method of capacity is used to examine the applied flow rate from which the accumulated volume of water is measured by known-volume container and stop watch. Fourteen different discharges were taken to increase the accuracy of the obtained relationship (USBR, 2001). A calibration curve is plotted as shown in Fig. 2, and the obtained relationship is used to calculate the actual required value of discharge.

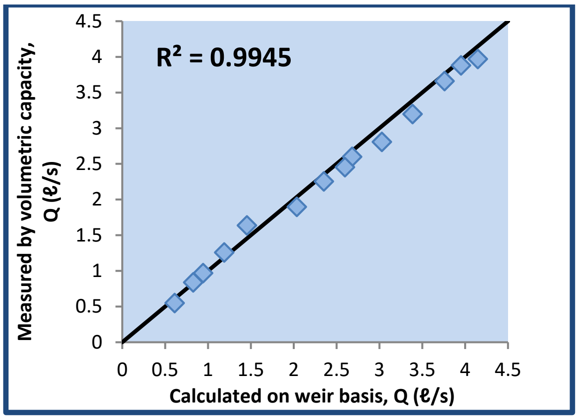


Fig. 2. Discharge calibration curve.

Two types of uniform texture, cohesionless were used as bed material. Each type was prepared by sieving analysis, the first type was fine sand which represent the soil of bed soil of Al-Kufa river with a medium particle size (d_{50}) of 0.25 mm and $\sigma_g = 2.15$, the second type was prepared by sieving analysis with a median particle size of 0.66 mm and $\sigma_g = 1.37$.

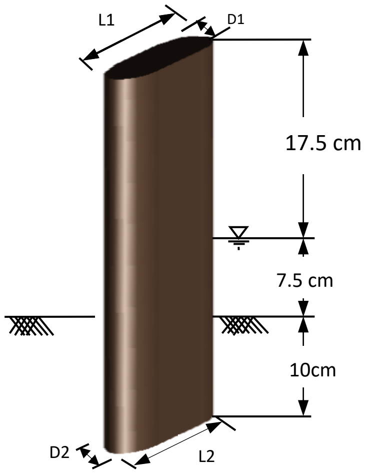
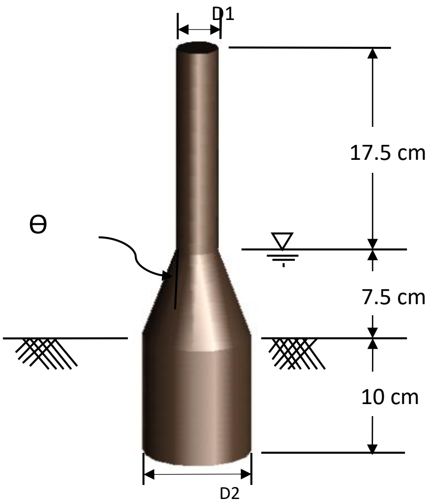
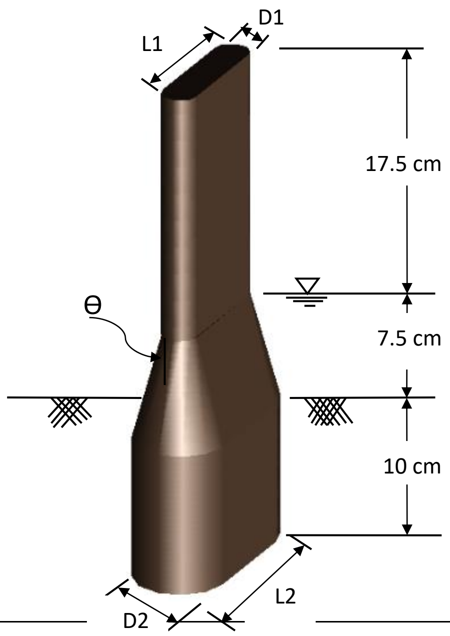
In the experiments, wood plates were used for all present models of piers with four different side slope angles (0°, 5°, 10° and 15°) and three cross-sections (oblong, circular and elliptical) as shown in Fig. 3. The angles are defined with respect to the vertical axis. The Schematic presentation for all prismatic and non-prismatic models are shown in Table 1.

Fig. 3. Sketch of the oblong, circular and elliptical piers model.

To prevent any roughness, these models were smoothly finished and painted. The location of these models (piers) was chosen to be within the second third to achieve a well-established flow. Every pier was fixed vertically in the center of the channel base through the sand bed.

In order to find a more realistic equilibrium scour time, eight preliminary tests have been made on prismatic circular and oblong piers for two types of soil (soil 1, d50=0.25 and soil 2, d50=0.66) for different velocities. Scour is recorded at different time intervals using a point gauge to measure the maximum scour at the nose of upstream pier. The scour depth has sharply increased during first half of test duration and the development of scour has become approximately constant. Values of scour depth at various test duration as a percentage of final scour depth can be calculated. It is noticed that 98 % of the local scour can be achieved in 3 hours as shown in Fig. 4. For more accuracy, equilibrium scour time of 4 hours was adopted in this study for all cases to eliminate the time effect.

Table 1. Schematic presentation for prismatic and non-prismatic tested models.

<table>
<tr><td>Piers model</td><td colspan="2">Angle (Θ) (degree)</td><td>0</td><td>5</td><td>10</td><td>15</td></tr>
<tr><td rowspan="4">Elliptical pier model

</td><td rowspan="2">Diameter (cm)</td><td>(D1)</td><td>2.5</td><td>--</td><td>--</td><td>--</td></tr>
<tr><td>(D2)</td><td>2.5</td><td>--</td><td>--</td><td>--</td></tr>
<tr><td rowspan="2">Length (cm)</td><td>(L1)</td><td>10</td><td>--</td><td>--</td><td>--</td></tr>
<tr><td>(L2)</td><td>10</td><td>--</td><td>--</td><td>--</td></tr>
<tr><td rowspan="2">Circular pier model

</td><td rowspan="2">Diameter (cm)</td><td>(D1)</td><td>2.5</td><td>2.5</td><td>2.5</td><td>2.5</td></tr>
<tr><td>(D2)</td><td>2.5</td><td>3.8</td><td>5.1</td><td>6.5</td></tr>
<tr><td rowspan="4">Oblong pier model

</td><td rowspan="2">Diameter (cm)</td><td>(D1)</td><td>2.5</td><td>2.5</td><td>2.5</td><td>2.5</td></tr>
<tr><td>(D2)</td><td>2.5</td><td>3.8</td><td>5.1</td><td>6.5</td></tr>
<tr><td rowspan="2">Length (cm)</td><td>(L1)</td><td>10</td><td>10</td><td>10</td><td>10</td></tr>
<tr><td>(L2)</td><td>10</td><td>11.3</td><td>12.6</td><td>14</td></tr>
</table>

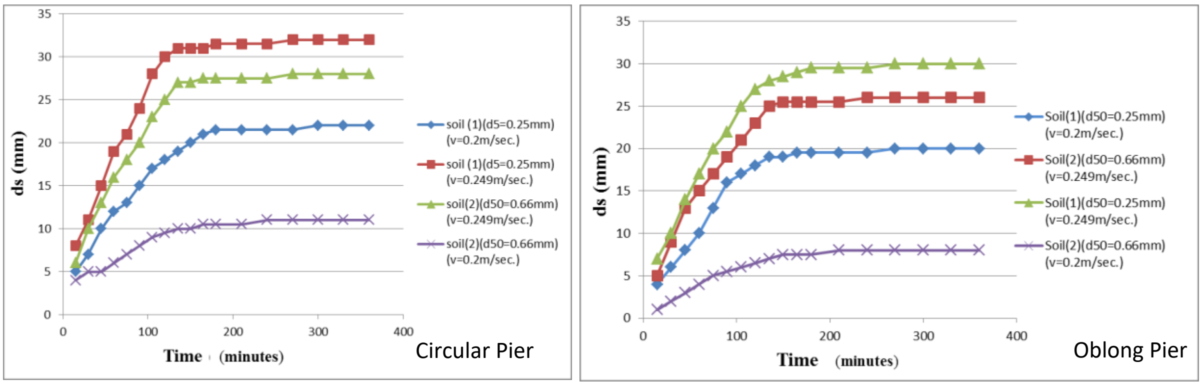


Fig. 4. Scour depth with time for circular and oblong piers.

Steady subcritical flow is used for performing all the experiments at a clear water conditions with plain bed. The flume fills in the working section with 10cm thickness of the sand bed relative to flume solid bed, and this might be a useful tool to scrape the sand bed to a desired level, i.e., 10cm at any point of working section. Point gauge was used to check all levels. The tail gates is raised and the working area is filled with water by hose from downstream portion of the flume in order to allow any air bubble to peculate out of the bed to avoid any settlement around the pier, and to prevent any abrupt high velocity which causes the disturbance in the sand bed after starting pumping.

After starting pumping, the tail gate is gradually lowered until the required water depth established in the flume. At the equilibrium time the scour depth is recorded by using a point gauge at the upstream nose of pier, at which the expected higher scour occurs. After this, the flow is stopped and the flume is drained slowly to avoid any change in the scour hole, the sand is allowed to dry and the required measurements of sand bed upstream, downstream longitudinally and transversely are recorded.

A total of 96 runs with total time of 384 hours have been carried out throughout the experimental work. Nine parameters studied influencing scour depth. Some of those parameters are related to the pier as angle (expressed of diameter and length), and shape. Others are related to flow conditions like depth, velocity and Froude number, also with regard to sediment.

3. RESULTS AND DISCUSSION

3.1. Effect of Pier's Shape on the Scour Depth

The shape of pier has a direct influence on the scouring process. Also, it is observed that, the scour at upstream of the pier is larger than at the downstream, this is due to the strength of the horseshoe vortex which is proportional to pier shape.

Fig. 5 shows clearly, that there is a match in the value of the scour (ds) for different velocities for elliptical and oblong shapes, and this will be focus to study the other parameters on the circular and oblong piers only in the present study. Also, it can be seen that the oblong piers caused scour depth less than the circular piers in range of 5.3% to 25%. The contour map and 3D representation of scour hole are also shown for comparison, see Fig. 6 and 7.

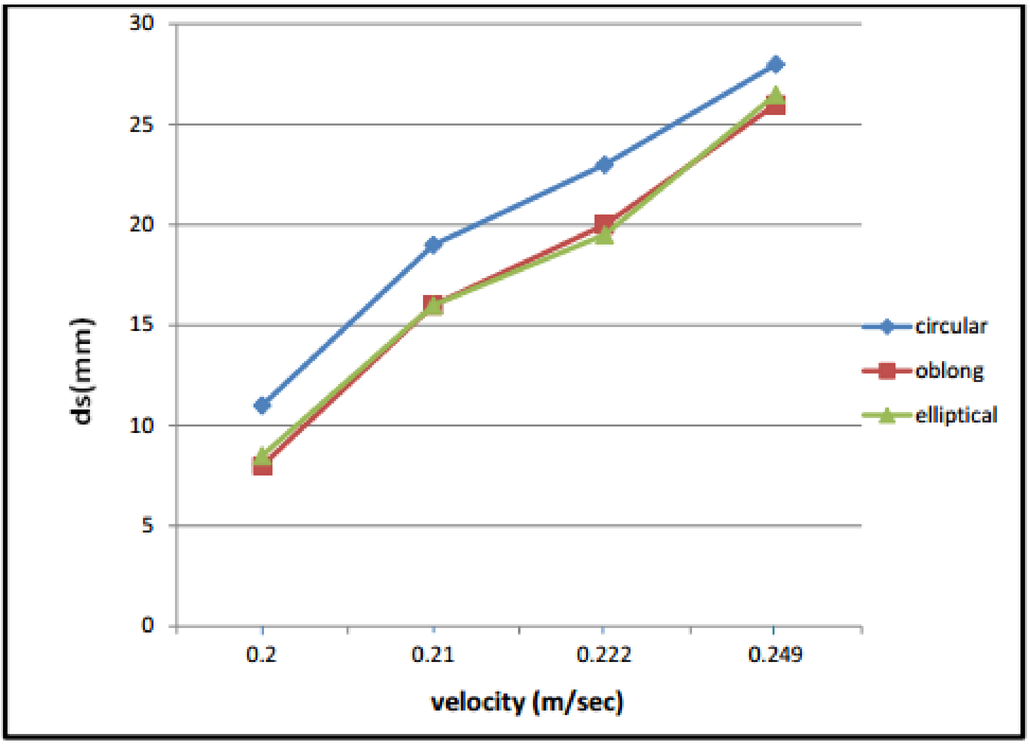
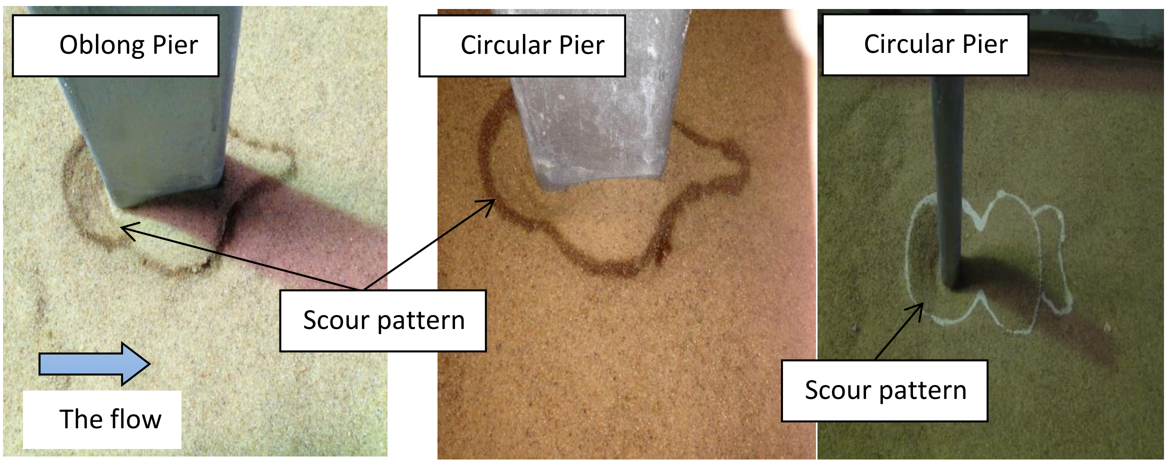


Fig. 5. Scour depth with the velocity for different shape of piers



(a) (b) (c)

Fig. 6. Depth of scour for different shapes of pier (a) elliptical, (b)oblong *and (c)the circular piers model.*

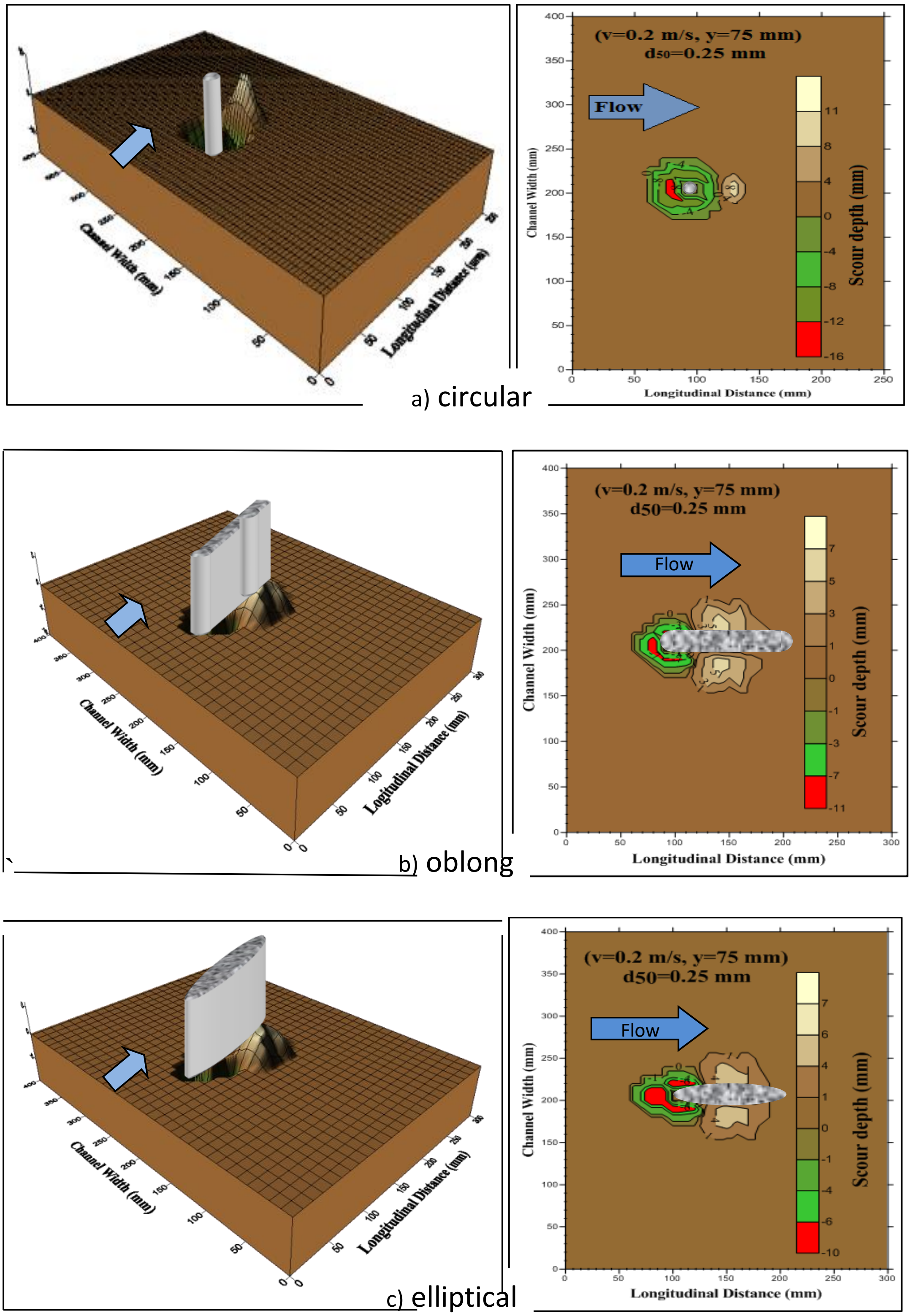


Fig. 7. Contour map and 3D sketch for scour around different shapes of piers

(a) Circular pier, (b) oblong pier, (c) elliptical pier.

3.2. Effect of Side Slope Angle on the Scour Depth

To investigate the influence of side slope angles on the scouring process and hence on the depth of scour at the upstream of bridge pier, four side slope angles are used in the present experimental work. Fig. 8 and 9 illustrate the influence of side slope angles (using prismatic and non-prismatic piers) on the scour depth at upstream of the circular and oblong piers. It can be seen that, the scour depth tends to decrease with increasing side slope angles.

Fig. 10 shows that the depth of scour for pier side slope angles (Ɵ=0°, Ɵ=5°, Ɵ=10°, Ɵ=15°) with the oblong section is less than these of circular section. Fig. 11 shows that the reduction of scour for pier side slope angles decrease with increase in velocity for non-prismatic circular and oblong piers. This indicates the use of non-prismatic piers practically in low-lying rivers with velocities.

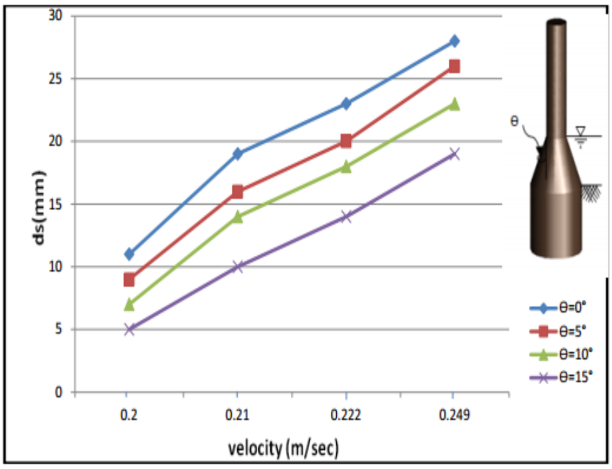


Fig. 8. Scour depth with different side slope angle for circular shape of pier

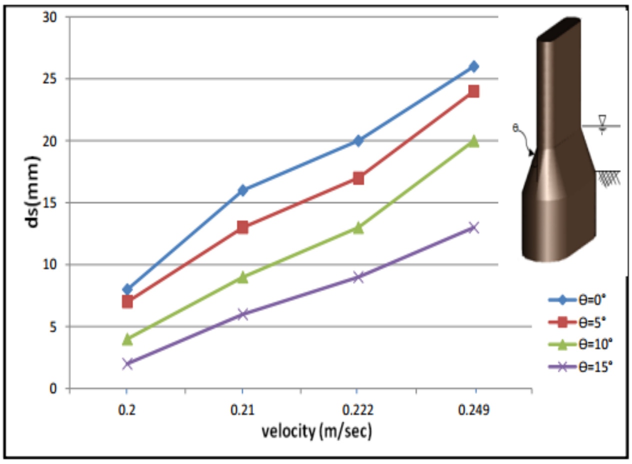


Fig. 9. Scour depth with different side slope angle for oblong shape of pier

It was found that the reduction in scour increase by 75% and 54.6% for oblong and circular sections respectively for median particle size (d_{50}) of 0.66 mm and in the rate of 80% and 63.6% for oblong and circular sections respectively for finer sand with a medium particle size (d_{50}) of 0.25 mm. It can be concluded that, the use of non-prismatic oblong cross-section piers could contribute effectively to the reduction percentage of scouring effect.

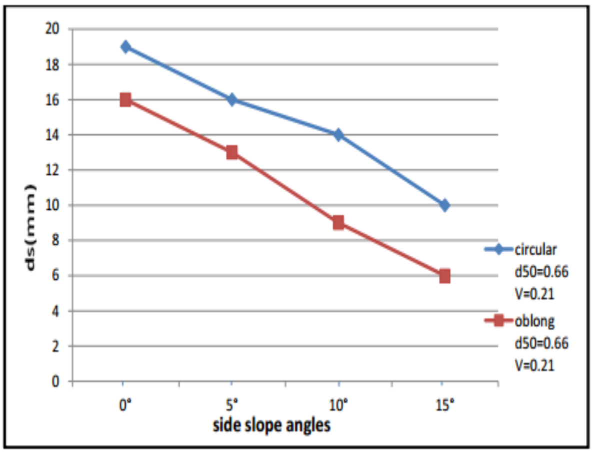


Fig. 10. Effect of pier side slope angles on scour depth for circular and oblong piers.

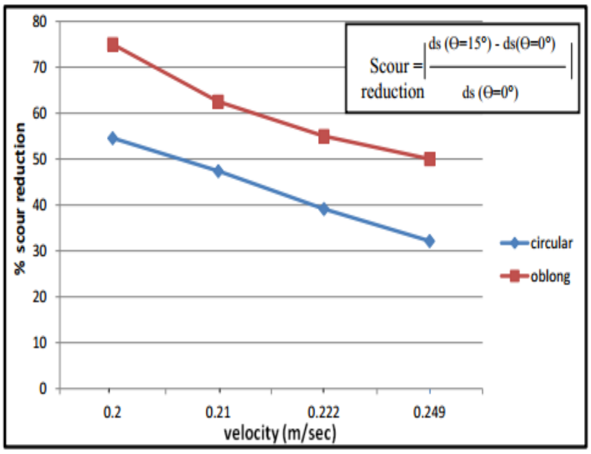


Fig. 11. Effect of velocity on scour reduction for non-prismatic circular and oblong pier s.

The contour map and 3D representation of scour hole are also shown in Fig. 11, 12-a and 12-b, and 13-a and 13-b.

(θ=0 (prismatic)) (θ=5° (non-prismatic)) (θ=10° (non-prismatic)) (θ=15° (non-prismatic))

Fig. 12. Depth of scour around prismatic and non-prismatic circular piers for constant velocity.

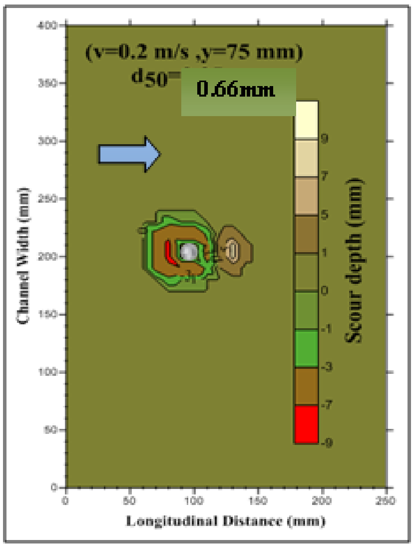


Fig. 13-a. Contour map for scour around the circular shape of pier with angle 0°.

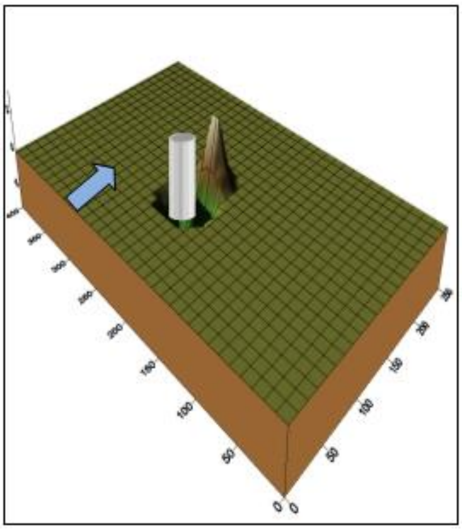


Fig. 13-b. 3D representation of scour hole around the prismatic circular pier (with angle 0°).

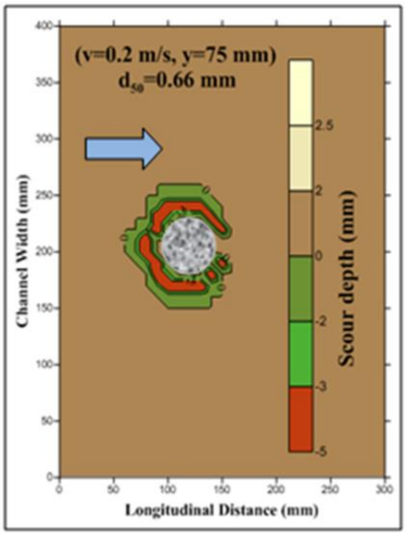


Fig. 14-a. Contour map for scour around the non-prismatic circular shape of pier with angle 15°.

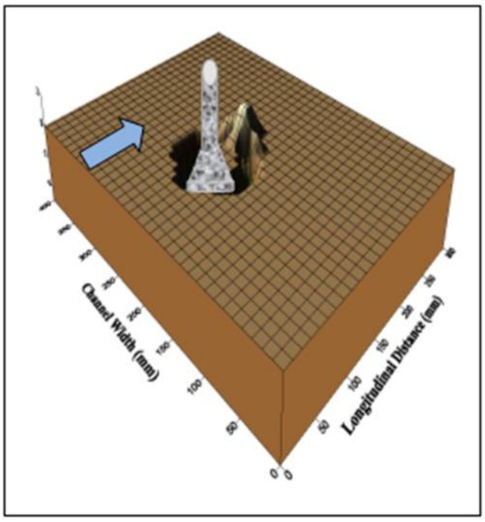


Fig. 14-b. 3D representation of scour hole around the non-prismatic circular shape of pier with angle 15°.

3.3. Effect of Soil Type on the Scour Depth

Two different type of cohesionless (soil) as bed material are used in experimental work. Fig. 15 illustrates the influence of sediment size on the scour depth at upstream of the pier for the same flow depth and velocity. It can be seen from that figure the scour depth tends to decrease with the increase in sediment size. Also at lower stages of flow velocities the lag between two curves seems greater than that at higher velocities, this may be attributed to that at higher velocities the action of down flow velocity increases leading to increasing the size of "rim" that forms at the base of scour hole in front of the pier. Hence, the large particles can be picked up from the rim leading to an increase in the scour depth as shown in Fig. 16. Figs. 17- a, 17-b, 18-a and 18-b show the effect of soil type on the contour map and 3D representation of scour hole.

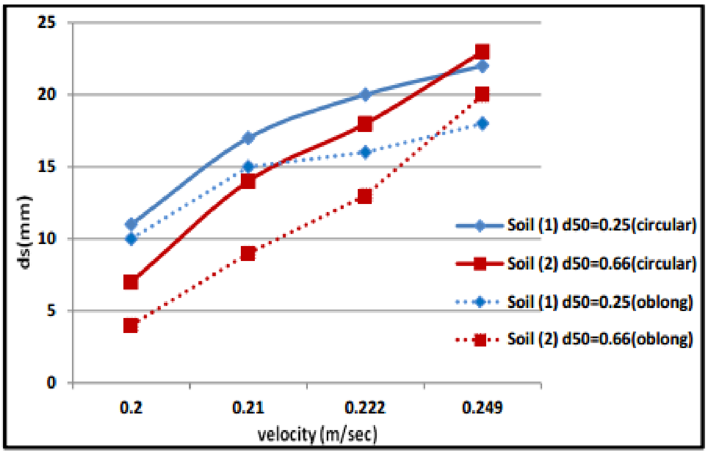
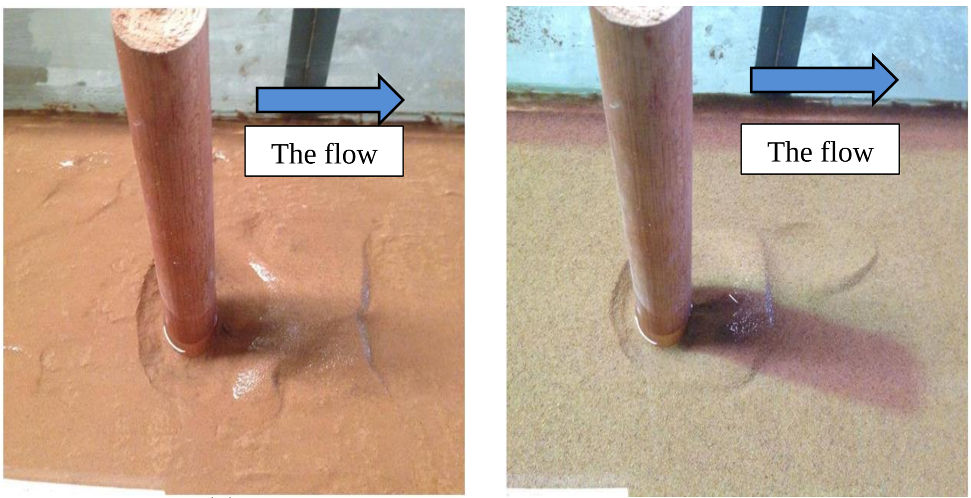


Fig. 15. Influence of sediment size on scour depth for circular and oblong piers.



(a) *(b)*

Fig. 16. Depth of scour for circular shape of pier with different sediment size ((a) soil $_{(1)}$ (d_{50}=0.25), (b) soil $_{(2)}$ (d_{50}=0.66))

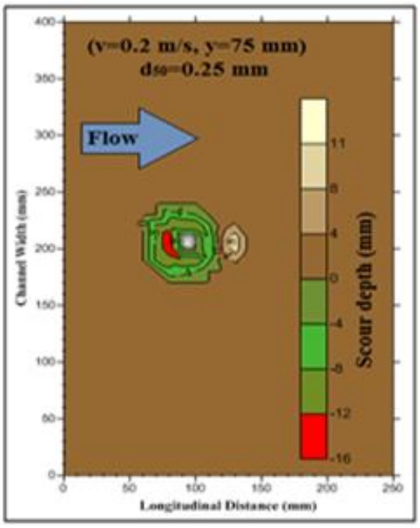


Fig. 17-a. Contour map for scour around the circular shape of pier with soil $_{(1)}$ (d_{50}=0.25mm)

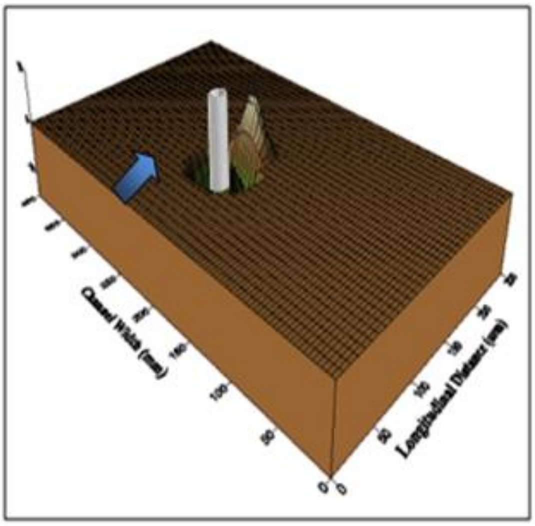


Fig. 17-b. 3D development of scour hole around the circular shape of pier with soil $_{(1)}$ (d_{50}=0.25mm)

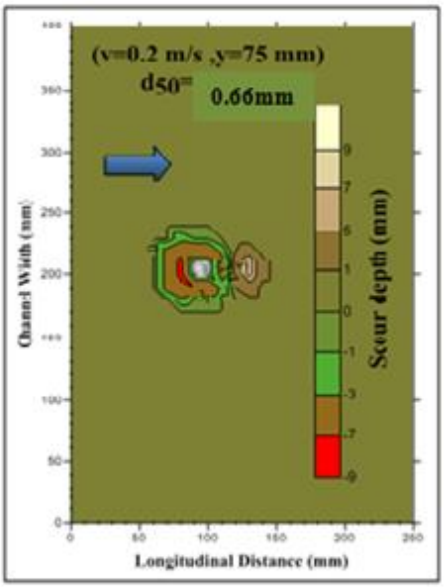


Fig. 18-a. Contour map for scour around the circular shape of pier with soil $_{(2)}$ (d_{50}=0.66mm)

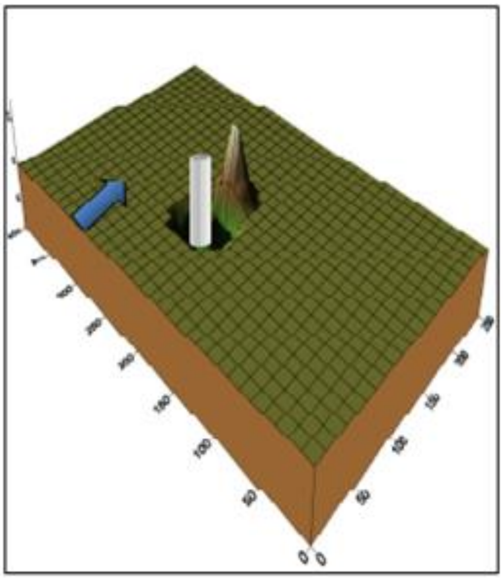


Fig. 18-b. 3D development of scour hole around the circular shape of pier with soil $_{(2)}$ (d_{50}=0.66mm)

3.4. Effect of Flow Velocity and Froude Number on the Scour Depth

The present dimensional analysis has shown that the Froude number ($F_r = v/\sqrt{gy}$) is an important parameter for scour around pier. Therefore, sixty four runs are conducted for two shapes of pier and four side slop angle for two types of soil with Froude Numbers of 0.233, 0.245, 0.256 and 0.29 to cover the desired range for subcritical flow. To investigate the effect of Froude Number on scour depth, it may be worth to discuss effect of flow velocity separately. Fig. 19 elucidate that variation of scour reduction is proportional with flow velocity keeping water depth constant as well as other parameters. Generally, a linear increase of scour depth with velocity is observed for velocities below the threshold value.

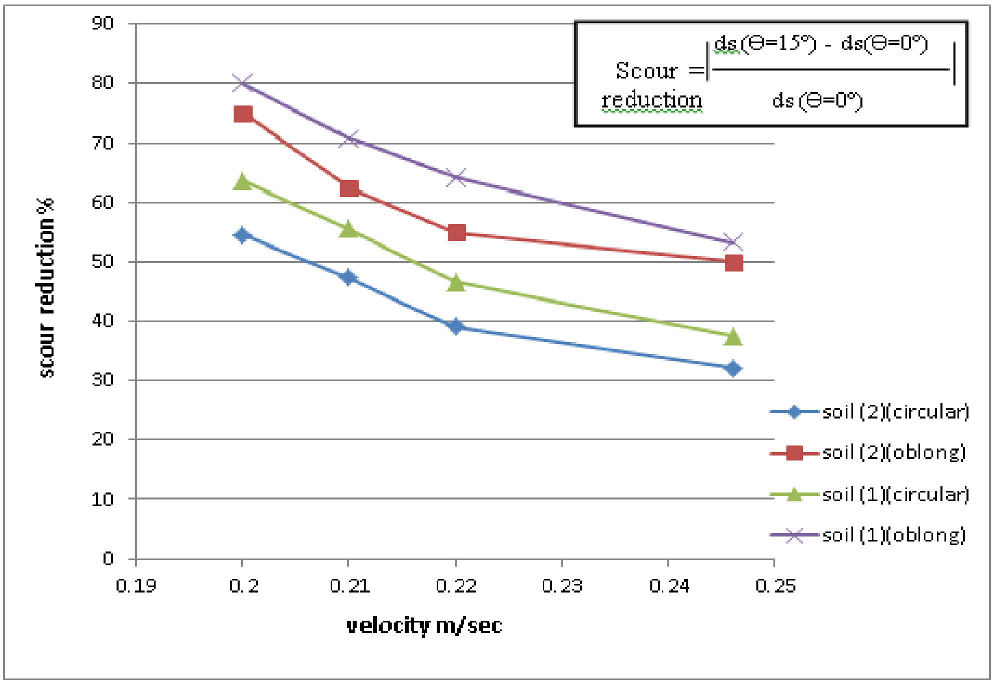


Fig. 19. Effect of flow velocity on the reduction of scour with different shapes of pier

In order to deduce the effect of Froude number (Fr) on the scour depth the results are used to plot a relationship between scour reduction and Froude number. It was found that the scour reduction decreases with increasing Froude number because Froude number ($Fr = v/\sqrt{gy}$) and the scour increases with increasing flow velocity at constant flow depth as shown in Fig. 20.

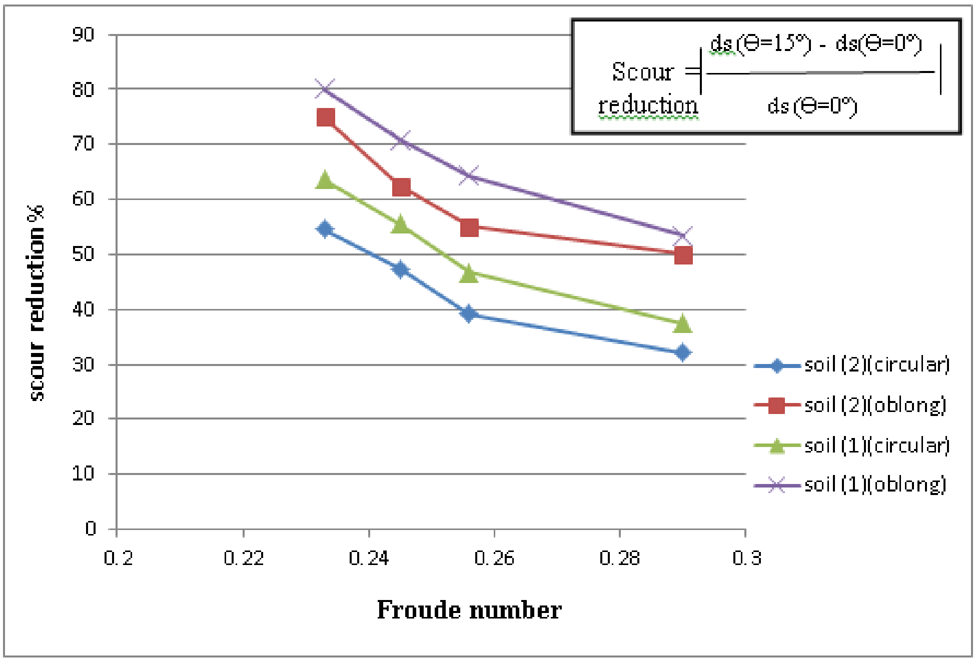


Fig. 20. Development of the scour reduction with Froude number for different shapes of pier.

4. CONCLUSIONS

1. The maximum reduction of the relative scour depth at the upstream of the piers with a side slop angle of ϴ=15° for soil of (d_{50}=0.25mm) was about 63.64% and for soil of (d_{50}=0.66mm) was about 54.55% for the circular cross section piers. The reduction value was increased up to 80% and 75% for the same side slope angle pier (ϴ=15°) with oblong cross section for soil of (d_{50}=0.25mm) and (d_{50}=0.66mm) respectively.

2. The use of non-prismatic circular or oblong piers is better than prismatic piers to reduce the maximum depth of scour. The use of non-prismatic oblong cross-section piers could contribute effectively to the reduction percentage of scouring effect.

3. The velocity measurements of this study shows that the frequency and the power of the dominant frequency of vortex shedding were decreases with the increase of the side slopes of the piers.

4. Generally, a linear increase of scour depth with velocity is observed for velocities below the threshold value. It can be observed that oblong cross-sections could contribute to the reduction scour upstream of the side slope angles pier and it can be used in low-lying rivers with velocities.

5. REFERENCES

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