Scour reduction around bridge piers using internal openings through the pier

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Scour around solid bridge piers was studied before for different kinds, shapes, and arrangements of piers. In this paper scours around bridge piers provided with internal openings wear experimentally studied. Results insure that the constructed openings through the pier reduce scour more than that happened in solid one. An equation based on experimental results was established to calculate maximum scour depth in case of pier provided with openings. The developed equation was compared with the others deduced for solid pier and results showed that openings have an effect on scour.

تعتبر الكبارى أحد المنشآت الهيدروليكية التى تقام خلال المجارى المائية والتى عادة ترتكز على دعامات وسطية خلال المجرى المائى. ويعتبر النحر حول دعامات الكبارى أحد الأسباب الرئيسية التى تؤدى إلى انهيارها. تهدف هذه الدراسة إلى إيجاد طريقة جديدة لتقليل النحر الذى يحدث حول دعامات الكبارى عن طريق عمل فتحات فى جسم الدعامة . وذلك عن طريق عمل ثلاث فتحات فى مستوى أفقى واحد, الفتحة الأولى تكون فى مقدمة الدعامة و الفتحة الثانية والثالثة تكون كل منهما على جانب من جانبى الدعامة. يتم توصيل الفتحة الأولى فى مقدمة الدعامة بالفتحتين الموجودتين على جانبى الدعامة باستخدام أنابيب. وعن طريق فرق الضغوط الموجود حول الدعامة يمكن دفع التيار من المقدمة إلى الجوانب وبهذه الطريقة يمكن تقليل الدوامات المتكونة أمام الدعامة وبالتالى تقليل النحر الذى يحدث حول الدعامة. وقد بلغ عدد التجارب التى تم إجراؤها ٥٦ تجربة وفيها تم تقسيم التجارب إلى أربعة عشر مجموعة وكل مجموعة تحتوى على أربعة تجارب . تم إجراء المجموعة الأولى على دعامة بدون فتحات وفى باقى المجموعات تم دراسة تأثير زاوية ميل الأنابيب الواصلة بين الفتحات وتأثير قطر الفتحات. وتترواح رقم فرويد بين ٠,١٤٥ إلي ٠,٢١٧ للتصرفات المستخدمة, و تم رفع كامل لحفرة النحر لبعض التجارب أما باقى التجارب تم فيها رفع قطاع طولى لمناسيب الرمل على محور الترعة لايجاد عمق النحر الأقصى. بتحليل ودراسة كل من النتائج المعملية والخرائط الكونتورية والقطاعات الطولية أمكن استخلاص النتائج التالية: استخدام أسلوب الفتحات فى جسم الدعامة يخفض قيمة كل من العمق الأقصى للنحر و حجم حفرة النحر وكانت اكبر قيمة لهذا التخفيض عند زاوية ميل للأنابيب مقدارها٩٠°.عند زاوية ميل للأنابيب مقدارها٩٠° و بتثبيت باقى المتغيرات, وجد أن عمق النحر يتناسب عكسياً مع قطر الفتحات الموجودة فى جسم الدعامة. لجميع التجارب وجد انه عمق النحر يتناسب طردياً مع رقم فرويد. عند زاوية ميل للأنابيب مقدارها٩٠° بلغت القيمة المتوسطة للتخفيض فى العمق الأقصى للنحر ٢٨% وكذلك أيضاً بلغت القيمة المتوسطة للتخفيض فى حجم حفرة النحر ٥٦%. تم استنباط معادلة وضعية تربط بين عمق النحر الأقصى وباقى المتغيرات المختلفة باستخدام التحليل الرياضى للنتائج المعملية.

Keywords: Scour, Pier , Vortex, Erosion

1. Introduction

Scour around solid cylindrical bridge piers was experimentally studied before on clear-water by Chiew [1], Laursen [2], Melville et al. [3], Nadana et al. [4], Raudkivi& Ettema [5], and Yassin& Rezk [6]. An analytical method for estimating the ultimate depth of scour based on experimental observation was made by Blaisdell [7]. A theoretical study was investigated by Johnson [8] to estimate the maximum local scour. Johnson [9] made a theoretical study, using a large set of field data for both live-bed and clear water scour, to compare seven bridge pier scour equations. Hoffmans et al. [10] made a theoretical study on local scour, using a morphological model, behind structures. Melville & Sutherland [11] developed a design method for estimating the equilibrium local scour depth at bridge piers. Larras [12] reported that equilibrium scour depth around bridge piers does not depend only on the pier Reynolds number but also on Froude number which is an essential element. Jain & Fisher [13] performed an experimental study on scour around circular bridge piers at high Froude numbers. Mirtskhoulava [14] discussed scouring processes of beds in cohesive and non cohesive soils. Hoffmans et al. [15] suggested several method to prevent scour around bridge piers such as riprap protection, piles protection, and deflectors protection. Virender Kumar et al. [16] made an experimental study on local scour around bridge piers using pier slots an collar to reduce scour. Abdel-Motaleb [17] investigated experimentally local scour around bridge pier using openings through the pier and explained the reduction happened due to these openings in both scour depth and value of scoured materials.

In this study a pier provided with openings was used to investigate the effect of both the angle and the diameter of openings on the value of the maximum sour depth. Study insure that these openings have noticeable effect on scour depth.

2. Experimental set up

The experiments were conducted in the glass-walled flume located in the hydraulic laboratory at the Hydraulic Research Institute, National Water Research Center, Cairo, Egypt. The working section of the flume is rectangular in cross-section, 24 meters long, 74 centimeters wide, and 100 centimeters deep. Fig. (1) shows details for the flume. The bottom of the flume was covered with 30 centimeters thick stratum of sand. The main distinguishing parameters and characteristics of the sand used in experiments are: The geometric mean size, d50, = 0.635mm; The standard deviation, σg, = 1.493; Specific gravity = 2.65. Flume discharge was measured by an ultrasonic flowmeter ("sonic sounder"). The depth of the flow for all runs was fixed at 20 centimeters. The value of the discharge varied between 30 liter/second and 45 liter/second. The value of Froude number varied from 0.145 to 0.217. By using a point gauge with circular flat end provided with vertical scale and vernier (precision 0.01 centimeter) and mounted on a lifting carriage, the elevation of the bed was measured. Fourteen circular piers, 10 centimeter in diameter, were made from plastic tube. Fourteen different shape of openings arrangement were tested as shown in fig. 2 and fig. 3. The opening on the front of the pier was connected to the openings on the sides of the piers by a system of tubes.

3. Description of the experimental program

A series of laboratory experiments were conducted, the case of clear water scour was investigated throughout the experimental program. Fourteen groups contain, 56 runs were conducted as follow:

1. Group one was performed on the solid pier for Froude number ranges from 0.145 to 0.217.
2. For a constant value of d/D =0.125 , groups 2 to 9 were performed for values of θ = 30^0, 45^0, 60^0, 90^0, 120^0, 135^0, 150^0, and 180^0, respectively.
3. For a constant value of d/D = 0.125, and θ = 90^0 , groups 10 and 11 were performed for values of X_0/D = 0.25, and 0.75, respectively.
4. For a constant value of θ = 90^0, and X_0/D = 0.50 groups 12 to 14 were performed for values of d/D = 0.063, 0.188, and 0.25, respectively.

The following procedures were considered in all experiments

1-The bed sediment was gradually saturated with water to release air voids.

2-The flume was gradually filled with water by using a rubber hose until an initial tail water depth was reached after that the pump motor was turned on and the control valve released gradually to obtain the required discharge.

3-The weir at the end of the flume was adjusted to maintain the water depth at 20 centimeter.

4-Water flow was recirculated till an equilibrium scour hole was practically achieved.

5-At the end of each run the flume was emptied gradually to avoid the effect of the sudden lowering of the flow depth on the performed scour hole.

6-Levels of the scour hole were measured around the pier in both longitudinal and transversal directions and the difference between readings before and after the run setup provides the change in elevation.

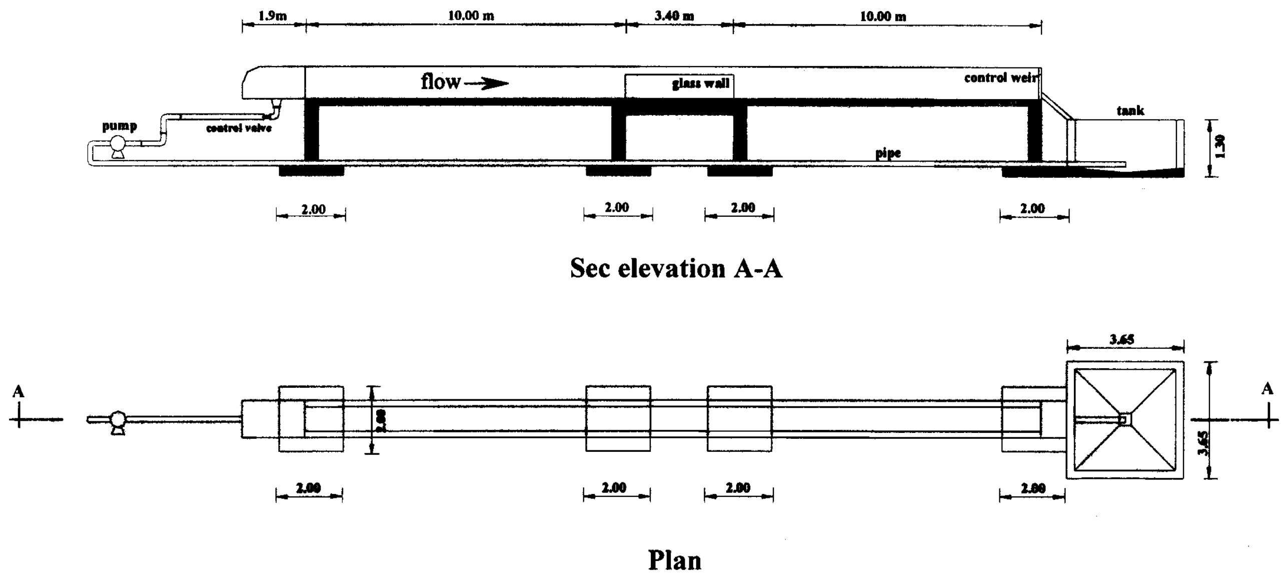

Fig. 1. Schematic layout of the flume.

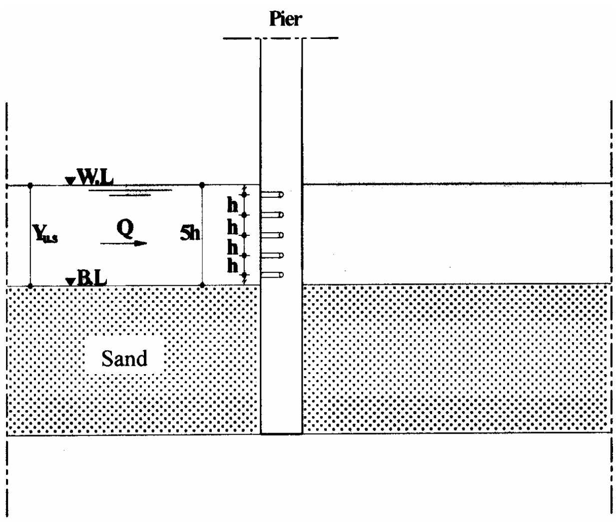

Fig. 2. Opening arrangement in evaluation.

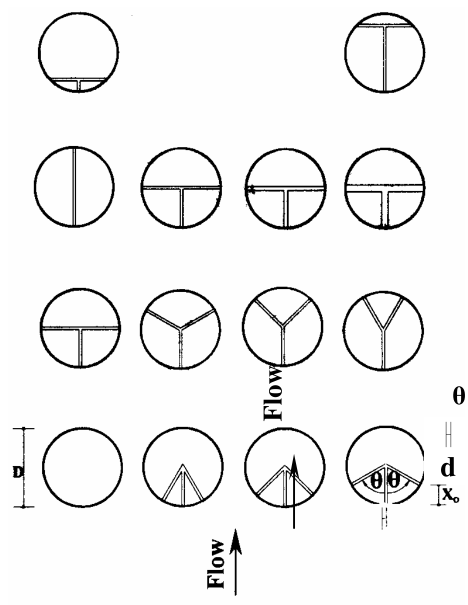

Fig. 3. Plan of the openings.

4. Results and analysis

About 56 experiments were done and the shape of the scour hole in plan and cross section through the canal centerline were plotted to find the maximum scour depth and the volume of scoured material as show in fig. 4, and fig. 5, respectively.

4.1. Influence of the inclination of the tube connecting the openings (θ)

As shown in table 1-a the relative angle, $\theta/180$, was changed from $\theta/180$ = 0.167 to $\theta/180$ = 1 with a constant diameter of the

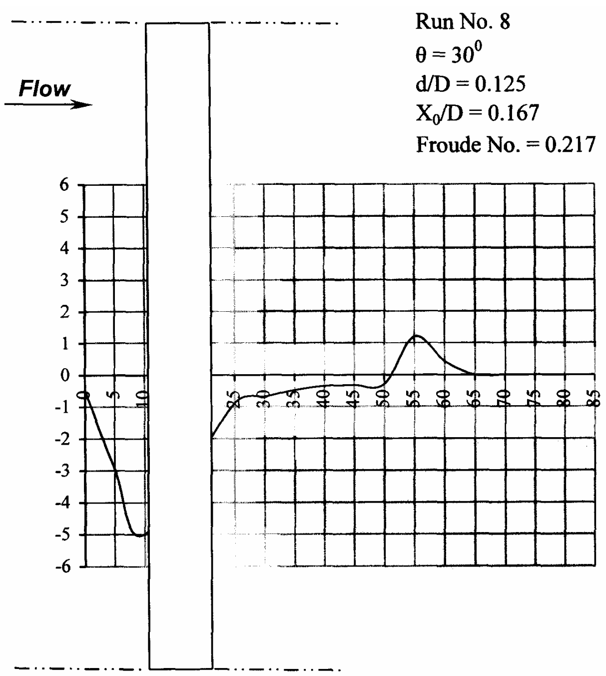

Fig. 4. Logitudinal cross section(a-a) through the scour hole, run No. 8.

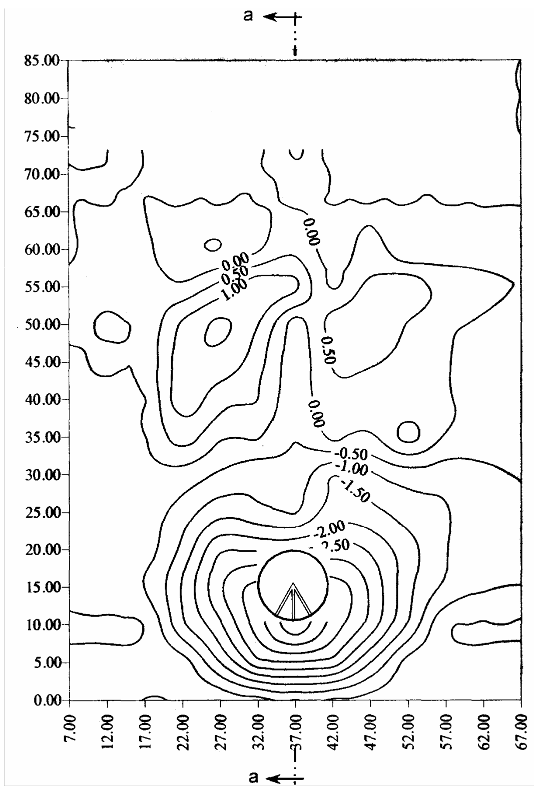

Fig. 5. Contour map of the scour hole, run No. 8.

openings. Fig. 6, shows the relation between the relative scour depth, ($d_{s\text{-opening}}$ / $d_{s\text{-solid}}$), and the relative angle, ($\theta^0/180$). It is observed from the Figure and table 1-a that the minimum scour depth occurs at pier provided with openings occurs at $\theta^0 = 90^0$.

Fig. 7, shows the relation between the relative volume of the scoured material, ($V_{s\text{-opening}}/V_{s\text{-solid}}$), and the relative angle, ($\theta/180$). It is observed from the Figure and table 1-b that for F_r= 0.217, that the minimum volume of the scoured material at pier provided with openings occurs at $\theta^0 = 90^0$.

4.2. Influence of the distance of the side openings (x_0)

Fig. 8, shows the relation between the relative scour depth ($d_{s\text{-opening}}$ / $d_{s\text{-solid}}$) and the relative istance (X_0/D). It is observed from

Table 1-a
Influence of the inclination of the tube connecting the openings, θ, on scour depth

$\frac{\theta^0}{180}$	F_r=0.145 $\frac{d_{s\text{-openings}}}{d_{s\text{-solid}}}$	F_r=0.217 $\frac{d_{s\text{-openings}}}{d_{s\text{-solid}}}$
0.167	0.958	0.962
0.25	0.917	0.927
0.333	0.842	0.842
0.50	0.661	0.731
0.667	0.783	0.779
0.75	0.825	0.817
0.833	0.863	0.869
1.00	0.929	0.942

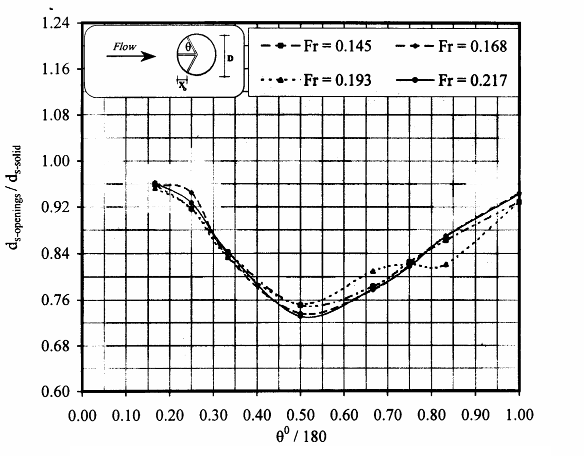

Fig. 6. Relative scour depth ($d_{s\text{-openings}}/d_{s\text{-solid}}$) versus relative angle of inclination of the tube connecting the openings (θ/80). (d/D = 0.125).

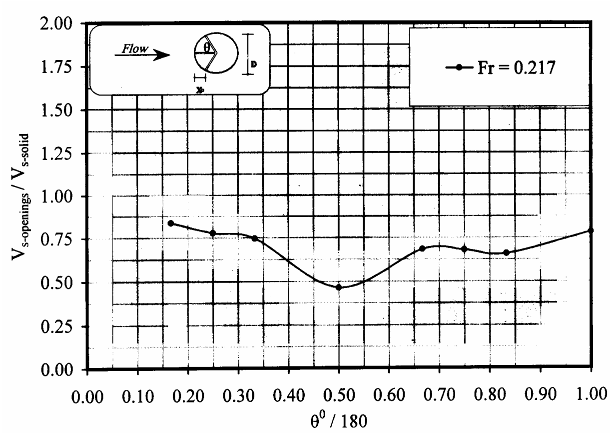

Fig. 7. Relative scour depth ($V_{s\text{-openings}}/v_{s\text{-solid}}$) versus relative angle of inclination of the tube connecting the openings (θ/80). (d/D = 0.125).

Table 1-b
Influence of the inclination of the tube connecting the openings, θ, on the volume of the scour hole

$\frac{\theta^0}{180}$	$F_r = 0.217$ $\frac{V_{s\text{-openings}}}{V_{s\text{-solid}}}$
0.167	0.837
0.25	0.779
0.333	0.747
0.50	0.464
0.667	0.684
0.75	0.681
0.833	0.659

Table 2-a
Influence of the relative distance of the side openings, (X_0/ D), on scour depth

$\frac{X_0}{D}$	F_r=0.145 $\frac{d_{s\text{-openings}}}{d_{s\text{-solid}}}$	F_r=0.217 $\frac{d_{s\text{-openings}}}{d_{s\text{-solid}}}$
0.25	0.938	0.923
0.50	0.75	0.731
0.75	0.854	0.846
1.00	0.929	0.942

the figure and table 2-a that for F_r= 0.145 and 0.217, the percentage of maximum scour depth in case of pier provided with openings to the solid one reaches to a minimum value of 0.75 and 0.731 at (X_0/D) = 0.50. Fig. 9, shows the relation between the relative volume of the scoured material ($V_{s\text{-opening}}$ / $V_{s\text{-solid}}$), and the relative distance (X_0/D). It is observed from the Figure and table 2-b that at F_r= 0.217, the percentage of the volume of the scoured material in case of pier provided with openings to the solid one reaches to a minimum value of 0. 64 at (X_0 / D)= 0.50.

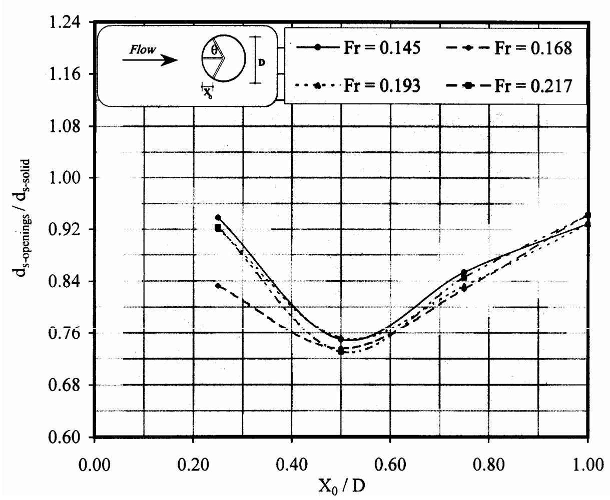

Fig. 8. Relative scour depth ($d_{s\text{-openings}}$/ $d_{s\text{-solid}}$) versus relative distance of the side openings (X_o/D). (d/D = 0.125, θ/180 = 0.50).

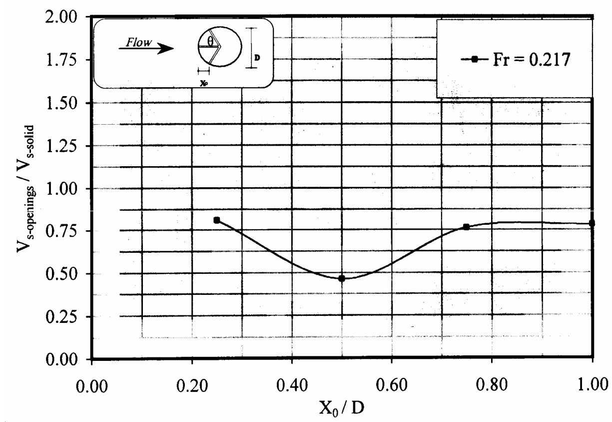

Fig. 9. Relative volume of scoured material ($V_{s\text{-openings}}$ / $V_{s\text{-solid}}$) versus relative distance of the side openings (X_o/D). (d/D = 0.125, θ/180 = 0.50).

Table 2-b
Influence of the relative distance of the side openings, (X_0 / D), on the volume of scour hole

$\frac{X_0}{D}$	F_r=0.217 $\frac{V_{s\text{-openings}}}{V_{s\text{-solid}}}$
0.25	0.808
0.50	0.464
0.75	0.764
1.00	0.784

4.3. Influence of the openings diameter (d)

Fig. 10, shows the relation between the relative scour depth ($d_{s\text{-}opening}$ / $d_{s\text{-}solid}$) and the relative diameter of openings (d / D). It is observed from the Figure and table 3-a that, the percentage of maximum scour depth in case of pier provided with openings to the solid one decreases with increasing the relative diameter of openings, (d/D), . It means that, the maximum scour depth is inversely proportional to the relative diameter of openings.

For (θ^0/180) = 0.50 and F_r ranges from 0.145 to 0.217 and for the values (d/D) = 0.06, 0.125, 0.188& 0.25, the corresponding values of ($d_{s\text{-}opening}$ / $d_{s\text{-}solid}$) can be considered 0.84, 0.74, 0.68& 0.62, respectively. Results show reduction in scour due to openings by an average value of 0.28 in case of (θ^0 / 180) = 0.50.

Fig. 11, shows the relation between the relative volume of the scoured material ($V_{s\text{-}opening}/V_{s\text{-}solid}$), and the relative diameter of openings (d/D). It is observed from fig. 9 and table 3-b that the percentage of the volume of the scoured material in case of pier provided with openings to the solid one decreases with increasing the relative diameter of openings (d/D).

Table 3-a
Influence of the relative diameter of the openings, (d/D), on Scour depth.

$\frac{d}{D}$	F_r=0.145 $\frac{d_{s\text{-openings}}}{d_{s\text{-solid}}}$	F_r=0.217 $\frac{d_{s\text{-openings}}}{d_{s\text{-solid}}}$
0.063	0.833	0.846
0.125	0.750	0.731
0.188	0.667	0.673
0.25	0.625	0.606

Table 3-b
Influence of the relative diameter

$\frac{d}{D}$	F_r=0.217 $\frac{V_{s\text{-openings}}}{V_{s\text{-solid}}}$
0.063	0.470
0.125	0.464
0.188	0.378
0.25	0.417

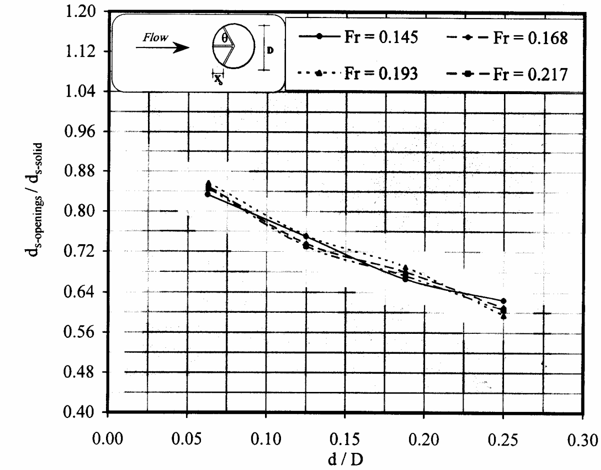

Fig. 10. Relative scour depth ($d_{s\text{-}openings}/d_{s\text{-}solid}$) versus relative diameter of the openings (d/D). (X_o/D = 0.50, θ/180 = 0.50).

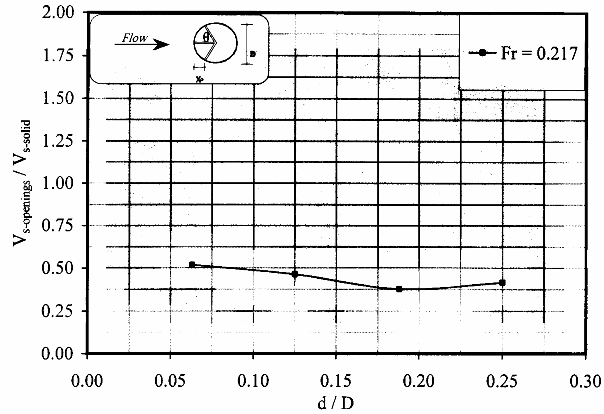

Fig. 11. Relative volume of scoured material ($V_{s\text{-}openings}/V_{s\text{-}solid}$) versus relative diameter of the openings (d/D). (X_o/D = 0.50, θ/180 = 0.50).

4.4. Developed formula for estimation of the scour depth

The multi regression analysis technique is used to develop an equation to predict the maximum scour depth in case of pier provided with openings. The following equation was derived based on the experimental measured data for the case study:

$$\frac{d_s}{Y_{u.s}} = 1.656 \frac{(F_r)^{1.844} \left(\frac{\theta}{180}\right)^{0.240}}{\left(\frac{X_0}{D}\right)^{0.188} \left(\frac{d}{h}\right)^{0.296}} . \quad (1)$$

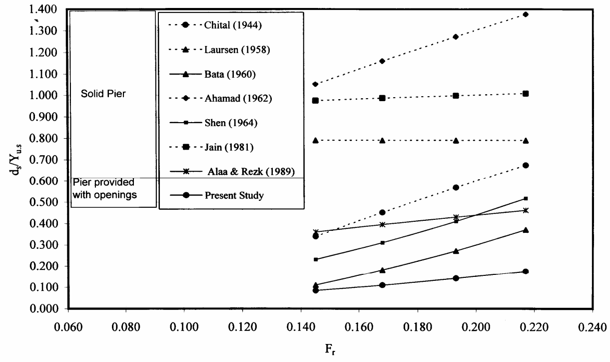

Fig. 12. Comparison between deduced equations for solid pier and that given by the author for pier provided with openings.

A comparison between the developed equation and those given by Chital, Laursen, Bata , Ahamad, and Jain as reported in [18], Shen [19], and Alaa & Rezk [6] is shown in fig. 12. Results in table 4 show that the method proposed has a notable effect on minimizing of scour depth around a circular cylinder.

5. Conclusions

The analysis of the experimental data permits the following conclusions:

1. For d/D = 0.125, the percentage of maximum scour depth in case of pier provided with openings to the solid one, ($d_{s\text{-opening}}/d_{s\text{-solid}}$) for F_r= 0.145 to 0.217 , reaches to a minimum value at (θ^0/180)= 0.50 .It means that the openings reduce the maximum depth of scour , and the maximum value for this reduction occurs at θ = 90^0 , and has an average value of 30.4% .
2. For F_r = 0.217, and d/D = 0.125, the percentage of the volume of the scoured material in case of pier provided with openings to the solid one reaches to a minimum value at (θ^0/ 180) = 0.50. It means that the openings reduce the volume of the scoured material, and the maximum value for this reduction occurs at θ = 90^0 , and has an average value of 54% .
3. For θ= 90^0, d/D = 0.125,and F_r= 0.145 to 0.217, the percentage ($d_{s\text{-opening}}$ / $d_{s\text{-solid}}$) reaches to a minimum value at (X_0 / D) = 0.50. And for F_r = 0.217, the percentage ($V_{s\text{-opening}}$ / $V_{s\text{-solid}}$) reaches to a minimum value at (X_0 / D)= 0.50.
4. For θ = 90^0, X_0 / D = 0.50 and for the values (d / D) = 0.06, 0.125, 0.188& 0.25, the maximum scour depth was found to be inversely proportional to the relative diameter of openings. Results show reduction in scour depth due to openings has an average value of 0.28, and reduction in the volume of the scoured material has an average value of 0.56
5. The maximum scour depth and the volume of the scoured material are directly Proportional with Froude number, Pier Reynolds Number, and Sediment Number for all runs.
6. An equation to predict the maximum scour depth was derived from the regression of the experimental measured data for the case study.

Nomenclature

d_s	is the maximum scour depth,
$Y_{u.s}$	is the upstream water depth,
F_r	is the froude number = $\frac{U}{\sqrt{g\,Y_{u.s}}}$,
U	is the Mean velocity of the flow,
θ	is the the angle of inclination of the tube connecting the openings,

Table 4
Comparison between deduced equations for solid pier and that given by the Present study for pier provided with openings

F_r	$\frac{d_s}{Y_{u.s}}$							
	Chital (1944)	Laursen (1958)	Bata (1960)	Ahmad (1962)	Shen (1964)	Jain (1981)	Alaa&Rezk (1989)	Present study
0.145	0.339	0.791	0.110	1.0516	0.231	0.975	0.360	0.084
0.168	0.452	0.791	0.182	1.1602	0.310	0.987	0.395	0.109
0.193	0.569	0.791	0.272	1.2728	0.410	0.998	0.430	0.141

0.217	0.675	0.791	0.371	1.3764	0.518	1.008	0.462	0.176

X_0 is the distance between the side openings and the front of the pier,
D is the diameter of the pier,
D diameter of the openings, and
h is the vertical distance between the openings.

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