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EFFECT OF LOCAL SCOUR INTERFERENCE BETWEEN CIRCULAR BRIDGE PIER AND DIFFERENT SHAPES OF ABUTMENT

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Abstract

The behavior of local scour under different factors is a paramount topic for designing safe bridges and reduce the massive loss in human lives and economy resulted from bridges collapse. This research provides an experimental investigation on the impact of pier proximity to abutment on local scour behavior where circular pier and three shapes of abutment (vertical-wall, semicircular ended, 45° wing-wall) were utilized at three different spacing (23.5, 16, 9 cm). The experiments results showed an evident increase in scour depth with increasing flow intensity, Froude number and decreasing flow depth. Whereas scour value increased for pier by a percentage about (6.4-11.7) % and decreased for abutment shapes by percentages about (13.1-19) %, (10-13.8) % and (9.3-14.7) %, respectively, when lessening spacing ratio between them. Also, scour caused by vertical-wall abutment was more than semicircular by (4.8%) and more than 45° wing-wall by (10.7%). IBM SPSS 21 was used to derive new empirical equations with R^2 (0.958 and 0.977) for circular pier and vertical-wall abutment, respectively, to show the convergence between predicted and observed results.

Keywords: Abutment shapes, Circular pier, Local scour, Scour interference, Spacing ratio.

1. Introduction

Scour process known as the outcome of a natural transportation phenomenon resulting from natural flow variations or as a portion of the changes of river morphology [1]. Scour and collision alongside overloading are the prime causes of bridge failures [2], and resulted in massive losses whether in human lives, country economy, or local transportation [3]. A study performed in 1973 for FHWA declared that of 383 bridge collapse during flooding, 75% involved abutment damage and the remaining 25% involved pier damage [4].

Estimation of scour magnitude enticed great deal of researchers' interest and studies over years due to the irrevocable consequences and intricacies associated with this phenomenon. Many parameters have visible influence on local scour depth, primarily including fluid, flow, bed sediment and pier-abutment characteristics [5] which were investigated extensively by many researchers. However, only a few of them mentioned the impacts resulting from pier closeness to abutment on scouring development such as [6-9]. According to Nyarko and Ettema [7], pier proximity to the toe of spill-through abutment have caused reduce in abutment scour, unlike pier scour. While Memar et al. [9] inferred that in the case of single pier, pier influence on abutment scour was either reducing or insignificant, whereas using two tandem piers caused abutment scour to increase.

In spite of these endeavors, the effect of scour interference still ambiguous and need further investigation. The current study aims to inspect pier-abutment scour interference experimentally under clear-water conditions using physical models.

2. Materials

2.1. The experimental flume

The experiments in this study were conducted by using a laboratory flume (length= 5.64m, width= 0.61m, depth= 0.4m) made from fiberglass reinforced plastic material with steel-reinforcement as shown in Fig. 1.

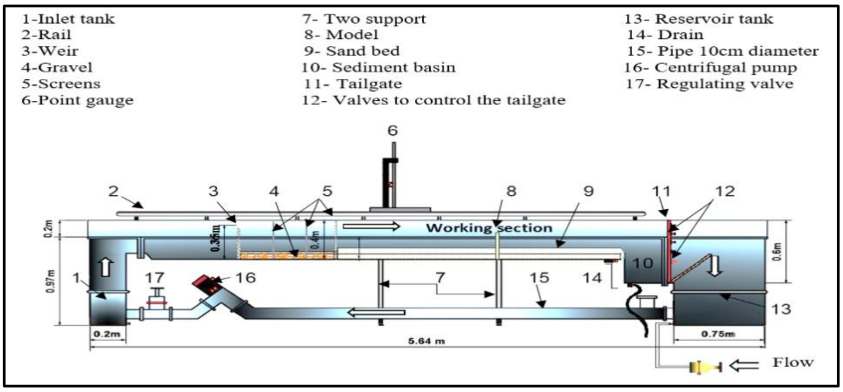


Fig. 1. Experimental flume drawing with details.

The flume splits into three parts (sections); The first section: includes an inlet tank situated at the upstream with dimensions (0.2×0.61×1.17m) for length, width and depth, respectively. The second section: includes the working section comprise a rectangular sharp-crested weir having (0.61m) width and (0.35m) height, and three screens to interdict all undesirable particles and debris from getting in the section. Also, a sediment basin with (0.4m) length and (0.3m) depth situated at the section end. A sand layer of (10 cm) thickness was distributed in the midst of the working section. Lastly, the third section: includes a reservoir has the dimensions (length= 0.75m, width= 0.61m, depth= 1.17m) used for water supplying by a centrifugal pump linked with an electric motor have a maximum capacity of (8.5 dm^3/sec). The water flow in the flume was controlled through a regulating valve and each depth mensuration were measured by a point gauge that moves through a couple of parallel rails supported on the flume sides.

2.2. The laboratory models

The models used in the experiments manufactured from plastic with smooth surface. For pier, circular shape was utilized having (3.5 cm) diameter and (20 cm) height. The pier diameter was chosen with considering that the width of laboratory flume is greater than eight times the pier width for clear-water conditions [10]. While, for abutment three different shapes (vertical-wall, semicircular ended, 45° wing-wall) were used having the dimensions (3.5×5×20 cm) for width, length and height, respectively, as shown in Fig. 2. All models were fastened vertically in center of the working section in order to get a good established flow.

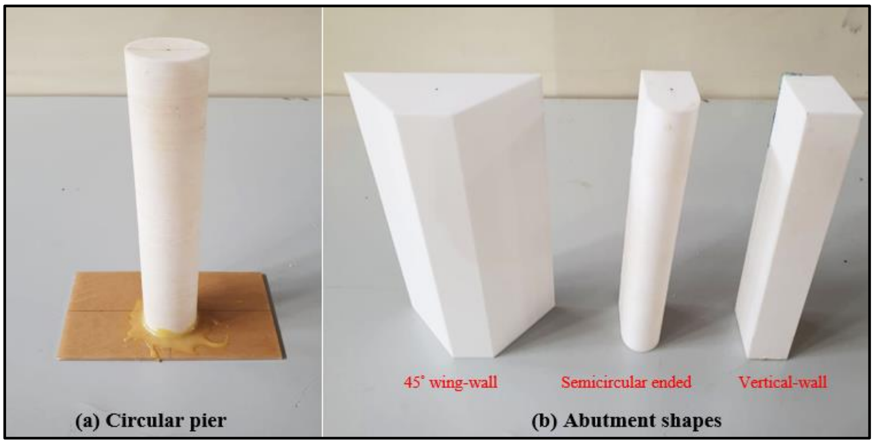
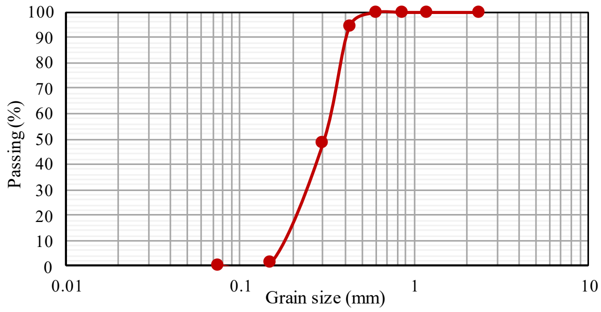


Fig. 2. The plastic models of pier and abutment.

2.3. The bed materials

For classifying the bed material features used during the experimental work, mechanical sieve analysis was performed at the soil laboratory. The test results shown that the bed sediment composes of cohesionless sand with the mean partial size (d_{50}=0.3mm) and geometric standard deviation (σ_g =1.32) that used to characterize the level of uniformity distribution particle size, where ($\sigma_g = \sqrt{d_{84}/d_{16}}$). Mostly, it is agreeable that the sediment likely deems as uniform when (σ_g < 1.4) and non-uniform otherwise [11]. Figure 3 presents the approved specification as a grain size distribution curve.



3. Results and Discussion

Analysing and discussing the results gained from laboratory experiments considered as a requisite stride for implementation of safe bridges. In this study, all the laboratory work was conducted in steady sub-critical flow and under clear-water conditions, the data obtained are listed in Table 1.

Table 1. The experimental results.

Run No.	x (cm)	y (cm)	Q (dm^3/s)	v (m/s)	v_c (m/s)	Fr	Pier ds (cm)	Abutment ds (cm)
Circular pier with vertical-wall abutment								
1	23.5	3.5	2.529	0.118	0.223	0.201	2.5	1.6
2	23.5	3.5	2.979	0.139	0.223	0.237	3.4	2.45
3	23.5	3.5	3.404	0.159	0.223	0.271	3.95	3.1
4	23.5	3.5	3.527	0.165	0.223	0.281	4.25	3.55
5	23.5	3.5	3.773	0.176	0.223	0.30	4.7	4.2
6	23.5	3	3.773	0.206	0.217	0.379	5.35	4.55
7	23.5	4	3.773	0.154	0.227	0.245	4.3	3.3
8	23.5	4.5	3.773	0.137	0.231	0.206	3.8	2.6
9	23.5	5	3.773	0.123	0.235	0.175	3.25	2.2
10	16	3.5	2.529	0.118	0.223	0.201	2.85	1.4
11	16	3.5	2.979	0.139	0.223	0.237	3.75	2.15
12	16	3.5	3.404	0.159	0.223	0.271	4.25	2.8
13	16	3.5	3.527	0.165	0.223	0.281	4.5	3.1
14	16	3.5	3.773	0.176	0.223	0.30	5	3.65
15	16	3	3.773	0.206	0.217	0.379	5.5	4.1
16	16	4	3.773	0.154	0.227	0.245	4.45	2.9
17	16	4.5	3.773	0.137	0.231	0.206	3.85	2.5
18	16	5	3.773	0.123	0.235	0.175	3.1	2.05
19	9	3.5	2.529	0.118	0.223	0.201	3.1	1.3
20	9	3.5	2.979	0.139	0.223	0.237	3.9	2
21	9	3.5	3.404	0.159	0.223	0.271	4.45	2.5
22	9	3.5	3.527	0.165	0.223	0.281	4.75	2.85
23	9	3.5	3.773	0.176	0.223	0.30	5.25	3.4
24	9	3	3.773	0.206	0.217	0.379	5.8	3.8
25	9	4	3.773	0.154	0.227	0.245	4.6	2.55
26	9	4.5	3.773	0.137	0.231	0.206	3.5	2.2
27	9	5	3.773	0.123	0.235	0.175	2.9	1.9
Circular pier with semicircular ended abutment								
28	23.5	3.5	3.773	0.176	0.223	0.30	4.7	4
29	16	3.5	3.773	0.176	0.223	0.30	5.1	3.6
30	9	3.5	3.773	0.176	0.223	0.30	5.3	3.45
Circular pier with 45° wing-wall abutment								
31	23.5	3.5	3.773	0.176	0.223	0.30	4.75	3.75
32	16	3.5	3.773	0.176	0.223	0.30	5	3.4
33	9	3.5	3.773	0.176	0.223	0.30	5.2	3.2

3.1. Flow intensity (v/v_c) influence on scouring (*ds/y*)

Some experiments were performed beneath five variant velocities to test flow intensity impact on scour development at pier and abutment while keeping the other factors constant. The results revealed that scour depth increased almost linearly with flow intensity increasing, as illustrated in Fig. 4, for velocities values below the threshold value.

As well, it was observed that the increasing in flow intensity caused an augmentation in width and volume of the scour hole, that likely attribute to the increasing in separation zone in the downstream side consequently more eddies (vortices) will be created and as a result causing more scour. Figure 5 shows the serious effect of flow intensity on scouring.

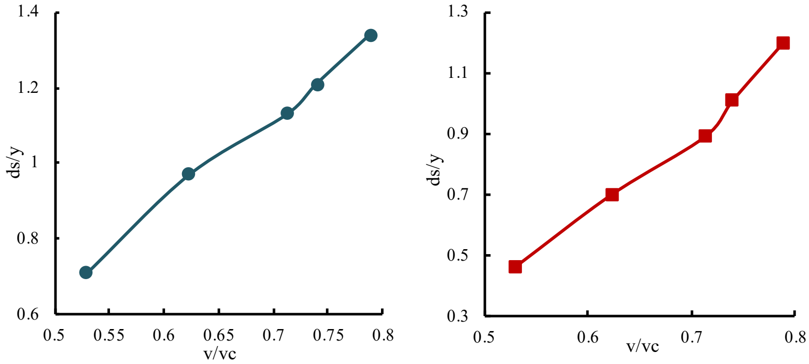


Fig. 4. Intensity of flow (*v/vc*) effect on scour depth at constant flow depth.

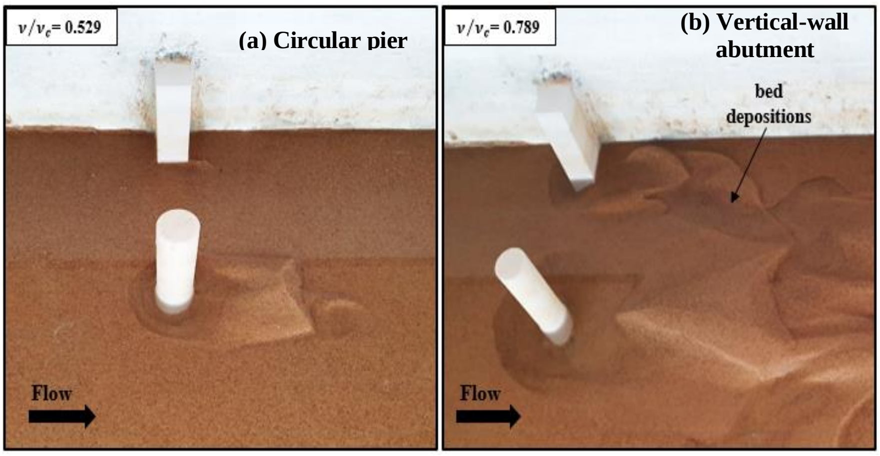
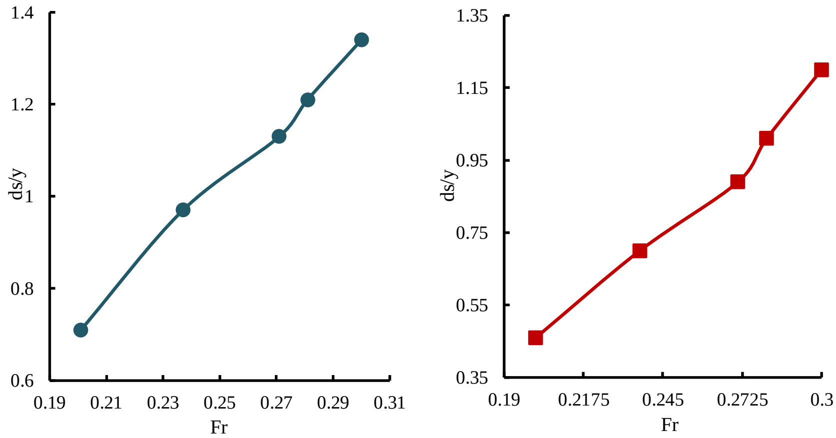


Fig. 5. The impact of flow intensity (v/v_c) on scouring development (*ds/y*).

3.2. Froude number (Fr) influence on scouring (*ds/y*)

Based on experiments results, Froude number has considerable effect on scour depth, where each increasing in Froude number accompanied by an increase in scour depth under the same parameters, as displayed in Fig. 6.

These results shown an agreement with Froude number law (i.e. $Fr = v/\sqrt{gy}$). According to this law, there is a direct relationship between Froude number and flow velocity as the increase in Froude number corresponds to an increase in flow velocity and as a result will lead to an increase in scour dimensions. Figure 7 shows Froude number effect when increasing from (0.201 to 0.30). At Fr=0.201 fewer sediments, with small camber, were distributed around the scour hole. While, at Fr=0.30 the sediments, with very high camber, will collect around the hole sides, posteriorly the sediments will start to gradually reduce and disappear at the far downstream side of pier and abutment.



(a) Circular pier. **(b) Vertical-wall abutment.**

Fig. 6. Effect of Froude number (Fr) on local scour ratio (*ds/y*).

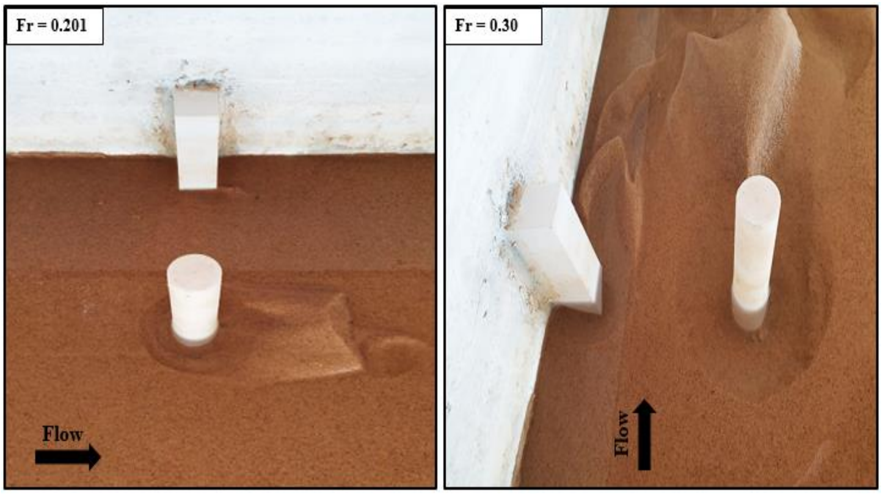
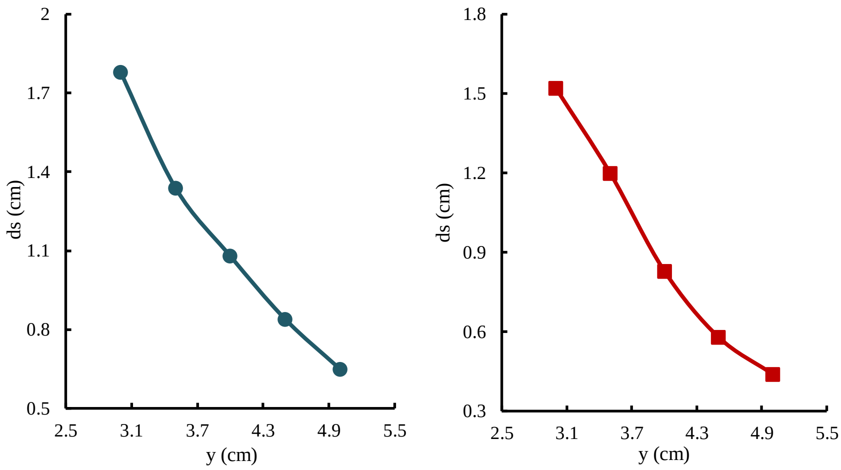


Fig. 7. The impact of Froude number (Fr) on scouring development.

3.3. Effect of flow depth (*y*) on scour depth (*ds*)

Under constant value of maximum flow discharge (Q), a set of experiments were performed to confirm the impact of flow depth on local scour. It is noticed that flow depth does make visible difference in scour dimensions, in which decreasing flow depth led to increase in scour hole volume. This is due to the reducing in capability of horseshoe vortices to pick up and entrain bed sediments which resulted from the practically absent of the recirculating motions near the free surface at high depths of flow. The results illustrated in Fig. 8 indicate the inverse relationship between flow depth and depth of scour, while Fig. 9 shows some selected photos of the laboratory experiments.



(a) Circular pier. **(b) Vertical-wall abutment.**

Fig. 8. Impact of flow depth (*y*) on depth of scour (*ds*).

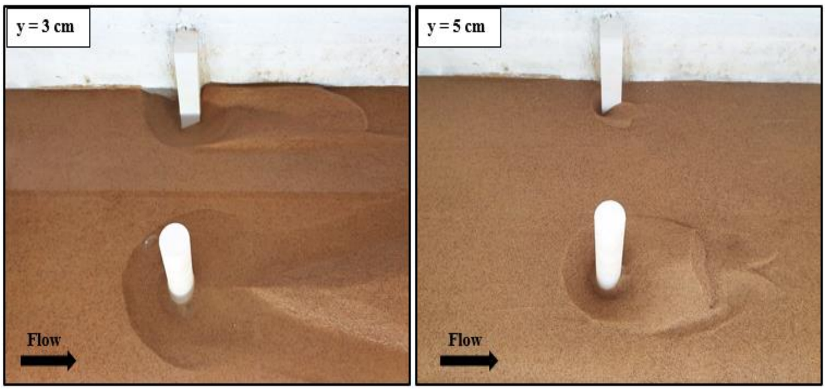


Fig. 9. Photos that clarify flow depth effect on scouring process.

3.4. Spacing ratio (*x/y*) influence on scouring process (*ds/y*)

To get more knowledge about the consequences of increasing or decreasing the spacing (*x*), the pier was installed in the flume at three different locations (23.5, 16, 9 cm) relative to the abutment location, the results acquired from conducting the experiments under similar flow conditions were plotted in Figs. 10, 11 and 12.

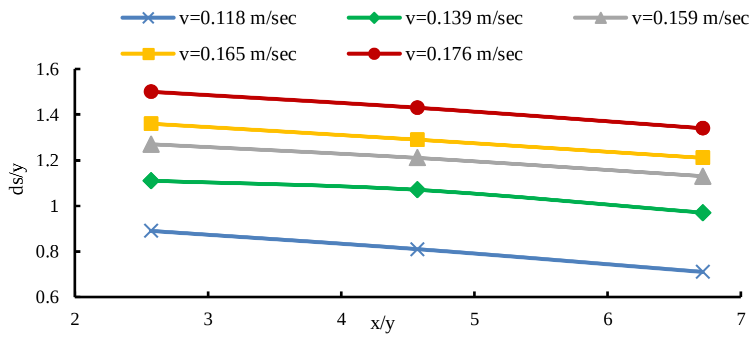


Fig. 10. Effect of spacing ratio (*x/y*) on scour depth ratio (*ds/y*) at different flow velocities and constant flow depth (*y*) for circular pier.

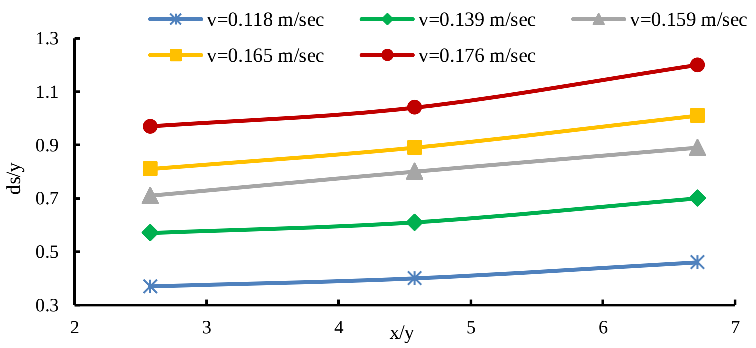
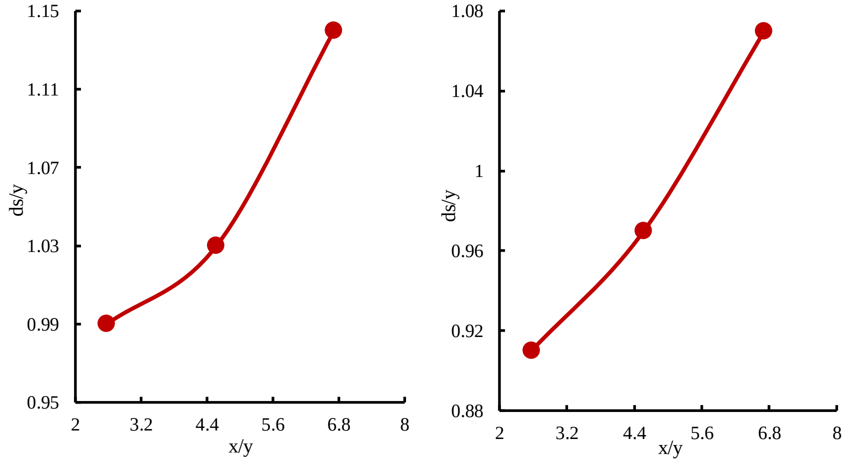


Fig. 11. Effect of spacing ratio (*x/y*) on scour depth ratio (*ds/y*) at different flow velocities and constant flow depth (*y*) for vertical-wall abutment.



(a) Semicircular ended abutment. **(b) 45° wing-wall abutment.**

Fig. 12. Effect of spacing ratio (*x/y*) on scour depth ratio (*ds/y*) at maximum velocity (*v*), and constant flow depth (*y*).

It is deduced that, pier presence in the abutment vicinity may affect scour rate of them in which maximum depth of scouring tends to increase for circular pier when spacing reduced from (23.5 to 16 cm) and then from (23.5 to 9 cm) by a percentage of (6.4 % and 11.7 %), respectively. **While** abutment scour decreased by percentages (13.1 %, 10 %, 9.3 %) when reducing spacing from (23.5 to 16 cm) for (vertical-wall, semicircular ended, 45° wing-wall) shape, and (19 %, 13.8 %, 14.7 %) when reducing spacing from (23.5 to 9 cm) for the same sequences. This resulted from the interference between the horseshoe vortex for pier and abutment, and the formation of strong vortex flows. The scour holes for pier and abutment will interfere and merge together creating one wide region, this is apparent specifically at spacing (x = 9 cm), causing filling of sediment particle for abutment thus reducing scour depth. Figures 13, 14 and 15 show the influence of decreasing spacing amidst a circular pier and three shapes of abutment.

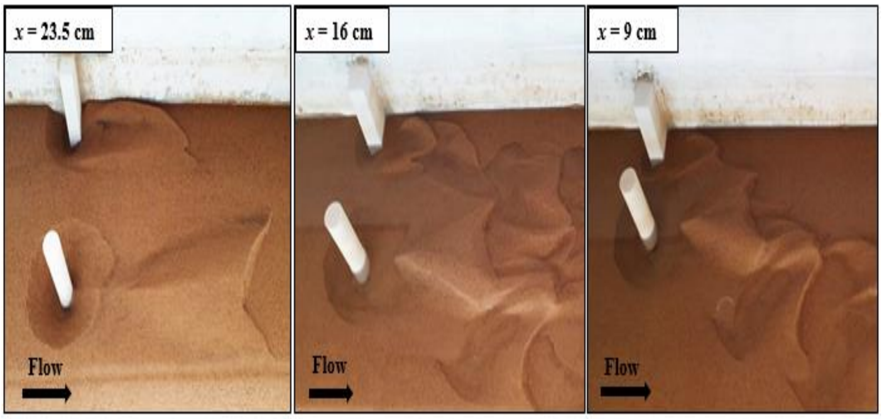


Fig. 13. Spacing variable influence amidst pier and vertical-wall abutment.

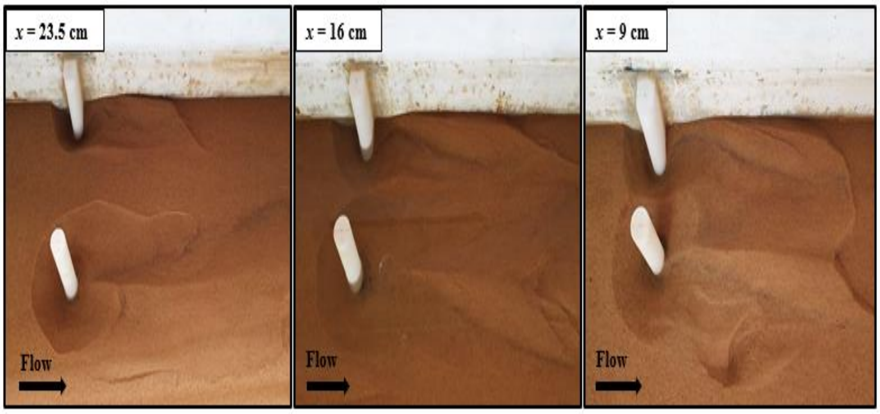


Fig. 14. Spacing variable influence amidst pier and semicircular abutment.

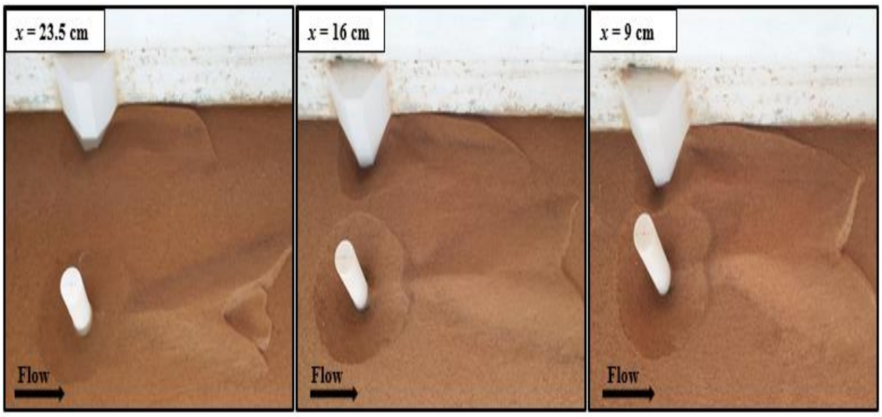


Fig. 15. Spacing variable influence amidst pier and 45° wing-wall abutment.

4. Dimensional Analysis and Development of New Formula

The dimensional analysis technique functions an influential part in clarifying the relevance between different physical quantities, moreover, help to understand the physical mechanism of scour phenomenon. By applying this technique, the maximum scour depth beneath clear-water conditions might be written as a factional relationship, as follows:

$$ds = F\left(b, L, \alpha, x, y, v, v_c, d_{50}, \sigma_g, \rho_s, B, S_\circ, \rho, g, \mu\right) \tag{1}$$

The Buckingham Π-theorem method was used and with applying the hypothesis to exclude terms having constant values: (1) constant size of bed sediment, (2) constant relative density, (3) steady viscosity, (4) constant width and length for models with alignment to the direction of flow, (5) constant flume bed width and horizontal slope without any inclination ($S_\circ$). Consequently, the above relationship after simplification may be written as:

$$\frac{ds}{y} = F\left(\frac{x}{y}, \frac{v}{v_c}, Fr\right) \tag{2}$$

To develop Eq. (2) which exhibits an expression for maximum scour depth around pier and abutment, the computer package (IBM SPSS Statistics 21) was utilized to analysis formula for circular pier and vertical-wall abutment through non-linear regression analysis as below:

$$\frac{ds}{y} = C_1 \left(\frac{x}{y}\right)^{C_2} \left(\frac{v}{v_c}\right)^{C_3} (Fr)^{C_4} \tag{3}$$

For circular pier:

$C_1 = 6.738$, $C_2 = -0.098$, $C_3 = 0.266$, $C_4 = 1.146$

Thus, the equation becomes;

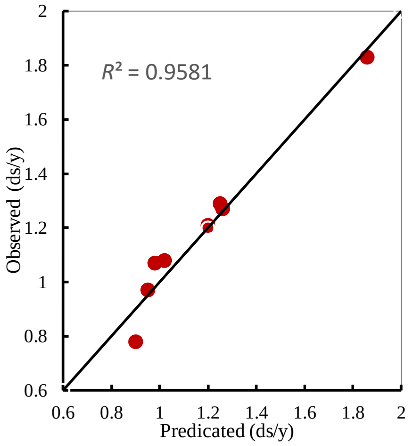
$$\frac{ds}{y} = 6.738 \times \left(\frac{x}{y}\right)^{-0.098} \left(\frac{v}{v_c}\right)^{0.266} (Fr)^{1.146} \tag{4}$$

For vertical-wall abutment:

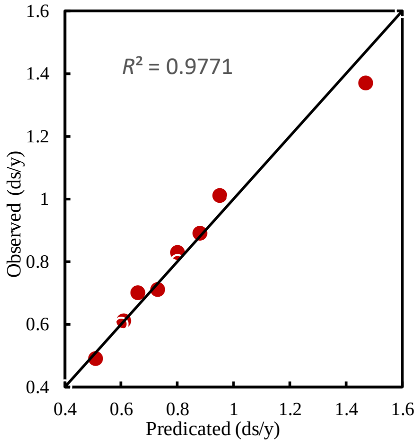
$C_1 = 0.545$, $C_2 = 0.191$, $C_3 = 2.968$, $C_4 = -0.853$

$$\frac{ds}{y} = 0.545 \times \left(\frac{x}{y}\right)^{0.191} \left(\frac{v}{v_c}\right)^{2.968} (Fr)^{-0.853} \tag{5}$$

The coefficient of determination (R^2) was (0.981) for pier and (0.984) for abutment. Both equations were derived by using 70% of experimental results, whereas the accuracy was tested by using 30% of the residual data. A comparison was made between the results from substituted the residual data in Eqs. (4) and (5) and the laboratory results to present the predicted convergence to observed records between (ds/y) from the formulas to (ds/y) from the experiments. Figure 16 shows a statistical comparison of these equations, and the coefficient of determination values (R^2) were (0.958) for pier and (0.977) for abutment.



(a) Circular pier.



(b) Vertical-wall abutment.

Fig. 16. Validation of Eqs. (4) and (5) as derived from SPSS program with experimental data.

5. Conclusions

The current study is focused on describing the diversity in local scour conduct beneath different conditions where the influence of various parameters, especially spacing parameter, on reducing and controlling scouring process around bridge foundations was investigated. According to the results acquired, the conclusions deduced from the study:

- Maximum scour depth was remarked when intensity of flow and Froude number increased, whilst the augmentation in flow depth resulted in a diminution in scour dimensions.
- As for spacing variable between pier and abutment, reducing spacing produced a dissimilar effect on scour as an outcome of the horseshoe vortex interference. When spacing reduced from (23.5 to 16 cm), scour for circular pier increased by a percentage of 6.4%, while abutment scour decreased by percentages of (13.1%, 10%, 9.3%) for (vertical-wall, semicircular ended, 45° wing-wall) shape, respectively. Also, reducing spacing from (23.5 to 9 cm) increased pier scour by a percentage of 11.7% and decreasing abutment scour by (19 %, 13.8 %, 14.7 %) for the same previous sequence of abutment shapes.

- The maximum scour depth around vertical-wall shape of abutment was more than semicircular ended and 45° wing-wall shape by percentages about (4.8 % and 10.7 %), respectively, at similar conditions of maximum Froude number (Fr).
- The newly developed formulas derived by IBM SPSS 21 showed good convergence between predicted (from formulas) and observed (from experiments) results, where (R^2 = 0.958 and 0.977) for circular pier and vertical-wall abutment, respectively.

Nomenclatures

B	Width of flume, m
b	Model width, cm
d_{16}	Sediment diameter corresponding to (16%) finer, mm
d_{50}	Median particle grain size, mm
d_{84}	Sediment diameter corresponding to (84%) finer, mm
ds	Scour depth, cm
Fr	Froude number
g	Gravitational acceleration, m/sec^2
L	Model length, cm
Q	Flow discharge, dm^3/sec
R^2	Correlation coefficient
$S_\circ$	Slope of channel bed
v	Mean velocity, m/sec
v_c	Critical velocity, m/sec
x	Spacing (distance) amidst pier and abutment, cm
y	Flow depth, cm

Greek Symbols

α	Angle of attack for model, deg.
μ	Dynamic viscosity of the fluid, kg/m.s
Π	Number of terms
ρ	Density of fluid, kg/m^3
ρ_s	Density of sediment, kg/m^3
σg	Geometric standard deviation

Abbreviations

FHWA	Federal Highway Administration
IBM	International Business Machines
SPSS	Statistical Package for the Social Sciences

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