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The study of the local scour behaviour due to interference between abutment and two shapes of a bridge pier

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Abstract: Although the complexities and irrevocable consequences associated with bridge scour have attracted researchers interest, their studies scarcely indicated the effect of a bridge pier proximity to an abutment. This research aims to measure maximum scour depth and exhibit the impact of pier-abutment scour interference based on laboratory experiments where vertical-wall abutment and two shapes of a pier (oblong and lenticular) were used at three different spacings (23.5, 16.0, 9.0 cm). The results showed an obvious increase in the scour depth ratio when increasing flow intensity, Froude number, and a decreasing flow depth. They also showed that reduced pier-abutment spacing was accompanied by increase in pier scour for both shapes while decrease in abutment scour. The maximum scour depth that caused by an oblong shape was more than a lenticular shape by about 10.8%. Furthermore, new empirical equations were derived using IBM SPSS Statistics 21 with determination coefficients of 0.969, 0.974, and 0.978 for oblong, lenticular and abutment, respectively. They showed the correlation between predicted and observed data.

Keywords: local scour, pier shape, scour interference, spacing effect, vertical wall abutment

INTRODUCTION

The prediction of scour magnitude around bridges foundations is a topic of great importance to hydraulic engineers. Over years, several researchers investigated and developed various equations to estimate maximum scour depth under different conditions around pier or abutment in isolation such as Laursen [1958], Shen *et al.* [1969], Melville and Sutherland [1988], Chiew [1995] Richardson and Davis [2001], Barbhuiya and Dey [2004], Raikar and Dey [2008], and Masjedi *et al.* [2010] and more others, but only few considered the consequences of a bridge pier closeness to the abutment. So the present research focuses on the interference of local scour and its behaviour due to decreasing spacing between the abutment and the neighbouring pier.

Scouring known as the consequence of natural transportation phenomenon occurring due to natural flow changes or as portion of the changes of river morphology [Meyering 2012]. This phenomenon is considered as one of the three main causes of bridge collapse besides collision and overloading [Xiong *et al.* 2016] that led to major loss in life, economy, and local transportation [Shepherd, Frost 1995]. A study carried out for the Federal Highway Administration – FHWA (USA) in 1973 stated that of 383 bridge failures due to flooding, 25% included pier damage and 75% abutment damage [Arneson *et al.* 2012]. Total scour composed of two main types, general and localised scour, with the latter divided into local and contraction scour [Cheremisinoff, Cheng 1987]. The present study focuses on investigating local scour experimentally. Such scour is affected by many parameters, primarily the flow, fluid, sediment and pier and abutment characteristics [Ansari *et al.* 2002]. This type of scour can be classified into two scour regimes, namely clear-water and live-bed based on the capacity of the approach flow to transport sediment around bridge foundations [Chiew, Melville 1987].

The basic mechanism that is responsible for the development of this type of scour is the formation of down-flow at the upstream face and the subsequent horseshoe vortices system at the base [Muzzammil *et al.* 2004]. A scour hole starts to develop when the transporting rate of sediment away from the local region is greater than the transporting rate into the region. While scour depth continues to increase, the strength of the vortices gradually decreases, thus, lessening the transporting rate until equilibrium is re-established which stops the scouring process (Fig. 1). Scour of pier and abutment may be expected to be comparable in some aspects due to the resemblance between an abutment and its mirror image in the channel wall with a pier. However, abutment flow patterns may differ due to the impact of the channel boundary, flood plain, and a lateral flow component [Kwan, Melville 1994]. Overestimation of scouring depth can result in uneconomical bridge design. Engineers sometimes experiences great difficulty in straightening pier wells that may get tilted whilst sinking to larger depths. Thus, knowledge of the expected maximum depth of scour for design discharge is necessary to develop a proper design.

The flume consists of three sections as follows. The first section: involves an inlet tank (length = 0.2 m, depth = 1.17 m) at the upstream side. The second section includes the working section with a rectangular weir having 0.61 m in width and 0.35 m in height, and three screens to prohibit the entering of undesirable particles and debris, as well as a sediment basin (length = 0.4 m, depth = 0.3 m) located at the section end. A layer of sand with 10 cm thickness was spread in the middle of the working section. The third section includes a reservoir of 0.75 × 0.61 × 1.17 m (length, width and depth, respectively) used to supply water by a centrifugal pump connected with an electric motor have a maximum capacity of 8.5 $m^3 \cdot s^{-1}$. A regulating valve used to control the water flow and a point gauge (±0.1 mm reading accuracy) moves by a pair of parallel rails used for depth measurements in the flume.

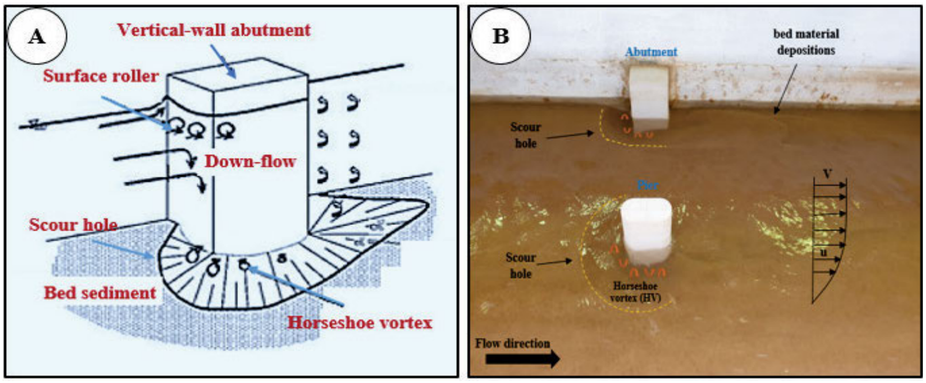

Fig. 1. The system of horseshoe vortex (HV): A) around bridge abutment, B) during the run; source: own elaboration

One of attempts to understand the mechanism of pier-abutment scour interference was made by Nyarko and Ettema [2011] who conducted a series of laboratory experiments in non-cohesive boundary using two shapes of an abutment (spill-through and wing-wall). They found that pier existence did not cause a significant increase in abutment scour, though it might cause reduction of abutment scour when a pier became close to a spill slope toe of the spill-through abutment. As for pier, scour measured when pier depth close to an abutment exceeded the depth measured for an isolated pier. Another attempt was made by Memar *et al.* [2016] who investigated the impact of scour interference for two cases, first for a single pier with an abutment and the second for two tandem piers with an abutment using three different distances (x). The results showed that in the first case, impact of pier on abutment scour was either decreasing or was negligible. The second case showed that piers increased an abutment scour depth. Maatooq [2008] aimed to show that scour depended on the distance interaction between pier and abutment and the distance coefficient was used as multiplicative factor with a formula developed previously by the same researcher to predict scour around a bridge pier only. Despite these efforts, the effect of spacing between pier and abutment on scouring is still vague until today and needs more attention and studies, whether experimental or numerical.

MATERIALS AND METHODS

MATERIALS

The experimental flume. All experiments were carried out by utilising flume manufactured of fiberglass reinforced plastic material with steel reinforcement of 5.64 × 0.61 × 0.4 m length, width and depth, respectively (Fig. 2, 3).

The experimental models. Physical models made from plastic material and having smooth surface without any roughness have used for all experiments. For pier, an oblong and lenticular shape components of similar dimensions were utilised (width = 3.5 cm, length = 7 cm and height = 20 cm), while taking into consideration that the flume width is more than 8 times the pier size for clear-water conditions [Shen *et al.* 1969]. Likewise, a vertical-wall abutment of 5 cm in length, 7 cm in width and 20 cm in height. Figures 4, 5 and 6 show the plastic models with details.

The bed materials. Mechanical sieve analysis was conducted in order to classify the bed material characteristics used during the experiments. The test exhibited that the sand bed material consists of cohesionless sand with a median particle sediment size (d_{50} = 0.3 mm) and a geometric standard deviation (σ_g = 1.32), where ($\sigma_g = \sqrt{d_{84} : d_{16}}$) used for sediment gradation (i.e. to characterise level of uniformity distribution particle size). It is generally acceptable that the sediment probably considered as uniform if σ_g < 1.4 and non-uniform else [Zhang, Nakagawa 2008]. Figure 7 clarify the grain size distribution curve.

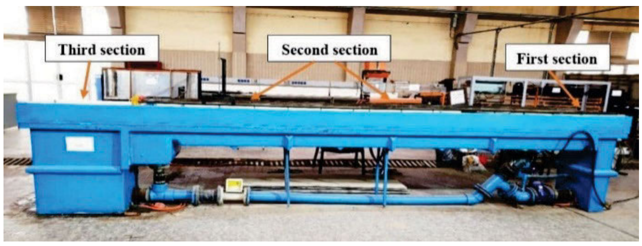

Fig. 2. The main sections of the used experimental flume; source: own elaboration

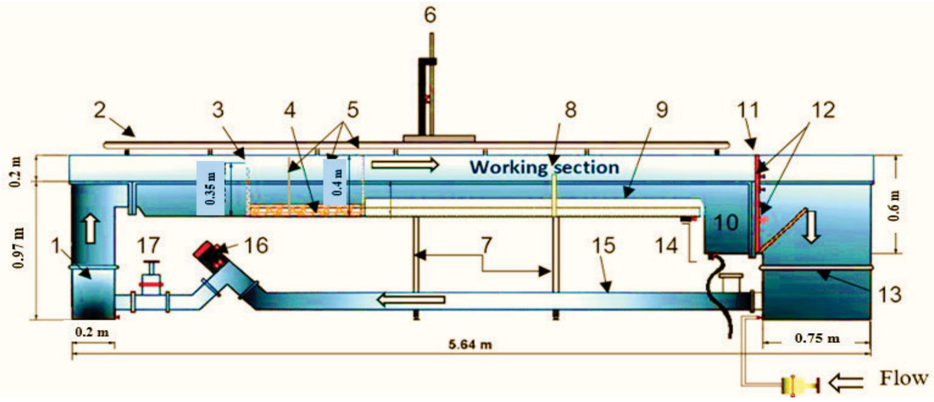

Fig. 3. Laboratory flume drawing with details; *1* = inlet tank, *2* = rail, *3* = weir, *4* = gravel, *5* = screens, *6* = point gauge, *7* = two support, *8* = model, *9* = bed sediment, *10* = sediment basin, *11* = tailgate, *12* = valves to control the tailgate, *13* = reservoir tank, *14* = drain, *15* = pipe 10 cm diameter, *16* = centrifugal pump, *17* = regulating valve; source: own elaboration

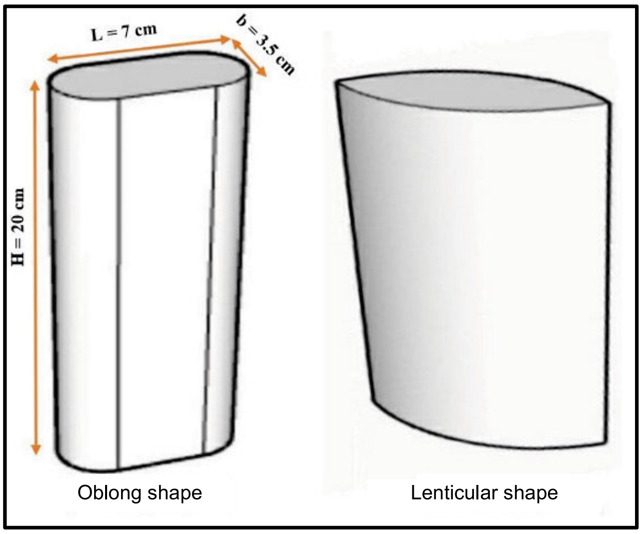

Fig. 4. Sketches for the pier shapes; source: own elaboration

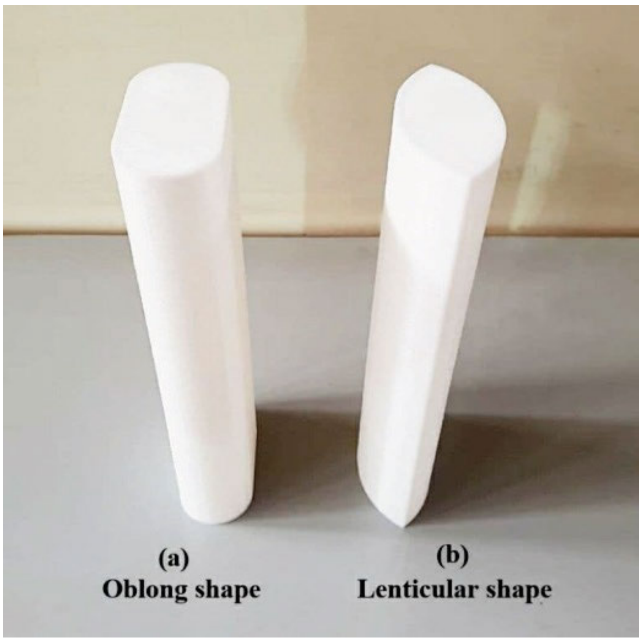

Fig. 5. Pier models with constant length to width ratio (L:b = 2); source: own elaboration

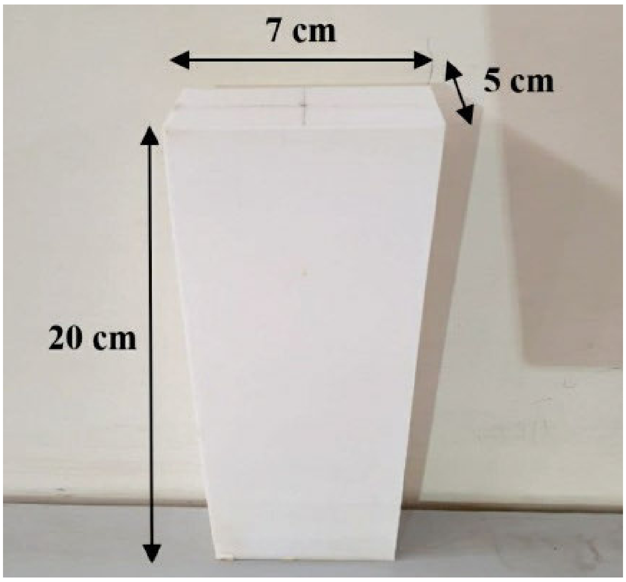

Fig. 6. Physical model of vertical-wall abutment; source: own elaboration

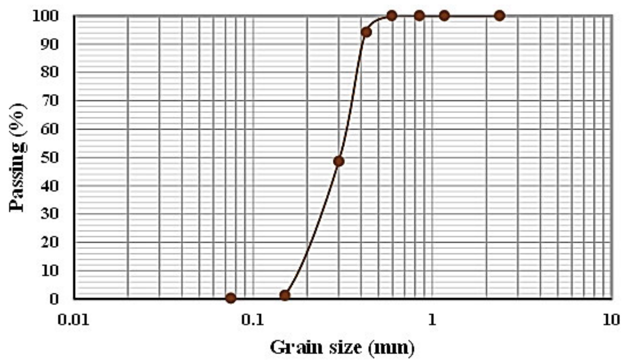

Fig. 7. Grain size distribution curve for bed sediment; source: own study

METHODS

Dimensional analysis for local scour around pier and abutment was used by authors. This analysis is a mathematical technique which plays an influential role in explaining the relationship between various physical quantities, as well as help to comprehension the physical mechanism of the scouring process. By using this techniques, the maximum depth of scour (d_{Smax}) around pier and abutment under clear-water conditions can be described as a function given in Equation (1).

$$d_{S\max} = f\{B, S_o,\ b, L, x, \alpha, y,\ v,\ v_c, \rho,\ \rho_s, g, d_{50}, \mu, \sigma_g\} \tag{1}$$

Definitions of all the parameters are listed in Table 1. By using Buckingham's π-theorem method and applying the hypothesis to eliminate terms with constant values: (1) constant sediment size and relative density, (2) steady viscosity, (3) constant pier and abutment dimensions (width and length) with alignment to the flow direction, (4) constant flume width and fixed horizontal slope (S_o = 0) without any inclination. Therefore, the factional relationship can be simplified and written as follows:

Table 1. The parameters affecting scour depth in (MLT) system

Symbol	Definition	Dimension
$d_{S\max}$	maximum scour depth	L
B	width of flume	L
S_0	flume bed slope	–
b	pier or abutment width	L
L	pier or abutment length	L
x	spacing between pier and abutment (from face to face)	L
	angle of attack for pier and abutment	–
y	flow depth	L
v	mean flow velocity	$L{\cdot}T^{-1}$
v_c	critical mean velocity	$L{\cdot}T^{-1}$
ρ	fluid density	$M{\cdot}L^{-3}$
ρ_s	sediment density	$M{\cdot}L^{-3}$
g	gravitational acceleration	$L{\cdot}T^{-2}$
d_{50}	median particle grain size	L
μ	dynamic viscosity of fluid	$M{\cdot}L^{-1}{\cdot}T^{-1}$
σ_g	geometric standard deviation	$L{\cdot}T^{-2}$
Fr	Froude number	–

Source: own elaboration.

$$f_4\left\{\frac{d_{S\max}}{y}, \frac{x}{y}, \frac{v}{v_c}, \mathrm{Fr}\right\} = 0 \tag{2}$$

$$\frac{d_{S\max}}{y} = f_5\left\{\frac{x}{y}, \frac{v}{v_c}, \mathrm{Fr}\right\} \tag{3}$$

Equation (3) and its variables will be used in laboratory experiments.

RESULTS AND DISCUSSION

Studying and analysing the results obtained from the laboratory data are substantial steps in designing safe bridges and to decrease the impact of the scour phenomenon around their foundations. The experiments are classified according to their objectives in Table 2. All the laboratory work was carried out under clear-water conditions and steady subcritical flow, and the obtained results are listed in Table 3.

Table 2. Summary of the laboratory experiments

Run	Description
Oblong pier with abutment	
1–4	to test the flow intensity and Froude number
5–8	to test the flow depth effect on scour depth
9–16	to test the effect of reducing spacing (from 23.5 to 16.0 cm) on scour depth at different velocities and flow depths
17–24	to test the effect of reducing spacing (from 16.0 to 9.0 cm) on scour depth at different velocities and flow depths
Lenticular pier with abutment	
25–28	to test the flow intensity and Froude number
29–32	to test the flow depth effect on scour depth
33–40	to test the effect of reducing spacing (from 23.5 to 16.0 cm) at different velocities and flow depths
41–48	to test the effect of reducing spacing (from 16 to 9 cm) at different velocities and flow depths

Source: own study.

Table 3. The experimental results

Run	x (cm)	y (cm)	Q $(m^3{\cdot}s^{-1}){\cdot}10^{-3}$	v $(m{\cdot}s^{-1})$	v_c $(m{\cdot}s^{-1})$	Fr	$v{:}v_c$	$x{:}y$	Pier ds (cm)	$ds{:}y$	Abutment ds (cm)	$ds{:}y$
Oblong pier with vertical-wall abutment												
1	23.5	3.5	2.979	0.139	0.223	0.237	0.623	6.714	2.90	0.83	2.55	0.73
2	23.5	3.5	3.404	0.159	0.223	0.271	0.713	6.714	3.50	1.00	2.90	0.83
3	23.5	3.5	3.527	0.165	0.223	0.281	0.740	6.714	3.75	1.07	3.30	0.94
4	23.5	3.5	3.773	0.176	0.223	0.300	0.789	6.714	4.15	1.19	3.80	1.09
5	23.5	3.0	3.773	0.206	0.217	0.379	0.949	7.833	4.50	1.50	4.15	1.38
6	23.5	4.0	3.773	0.154	0.227	0.245	0.678	5.875	3.35	0.84	3.00	0.75
7	23.5	4.5	3.773	0.137	0.231	0.206	0.593	5.222	2.65	0.59	2.60	0.58
8	23.5	5.0	3.773	0.123	0.235	0.175	0.523	4.700	2.40	0.48	2.05	0.41

cont. Tab. 3

Run	*x* (cm)	*y* (cm)	*Q* $(m^3 \cdot s^{-1}) \cdot 10^{-3}$	*v* $(m \cdot s^{-1})$	v_c $(m \cdot s^{-1})$	Fr	$v:v_c$	*x*:*y*	Pier *ds* (cm)	*ds*:*y*	Abutment *ds* (cm)	*ds*:*y*
9	16.0	3.5	2.979	0.139	0.223	0.237	0.623	4.571	3.15	0.90	2.10	0.60
10	16.0	3.5	3.404	0.159	0.223	0.271	0.713	4.571	3.95	1.13	2.55	0.73
11	16.0	3.5	3.527	0.165	0.223	0.281	0.740	4.571	4.20	1.20	2.90	0.83
12	16.0	3.5	3.773	0.176	0.223	0.300	0.789	4.571	4.55	1.30	3.30	0.94
13	16.0	3.0	3.773	0.206	0.217	0.379	0.949	5.333	4.70	1.57	3.60	1.20
14	16.0	4.0	3.773	0.154	0.227	0.245	0.678	4.000	3.75	0.94	2.60	0.65
15	16.0	4.5	3.773	0.137	0.231	0.206	0.593	3.555	3.10	0.69	2.30	0.51
16	16.0	5.0	3.773	0.123	0.235	0.175	0.523	3.200	2.25	0.45	1.80	0.36
17	9.0	3.5	2.979	0.139	0.223	0.237	0.623	2.571	3.45	0.99	1.80	0.51
18	9.0	3.5	3.404	0.159	0.223	0.271	0.713	2.571	4.15	1.19	2.30	0.66
19	9.0	3.5	3.527	0.165	0.223	0.281	0.740	2.571	4.30	1.23	2.60	0.74
20	9.0	3.5	3.773	0.176	0.223	0.300	0.789	2.571	4.65	1.33	3.10	0.89
21	9.0	3.0	3.773	0.206	0.217	0.379	0.949	3.000	4.90	1.63	3.40	1.13
22	9.0	4.0	3.773	0.154	0.227	0.245	0.678	2.250	3.95	0.99	2.20	0.55
23	9.0	4.5	3.773	0.137	0.231	0.206	0.593	2.000	3.20	0.71	1.90	0.42
24	9.0	5.0	3.773	0.123	0.235	0.175	0.523	1.800	2.45	0.49	1.50	0.30
Lenticular pier with vertical-wall abutment												
25	23.5	3.5	2,979	0.139	0.223	0.237	0.623	6.714	2.30	0.66	2.40	0.69
26	23.5	3.5	3.404	0.159	0.223	0.271	0.713	6.714	3.10	0.89	2.85	0.81
27	23.5	3.5	3.527	0.165	0.223	0.281	0.740	6.714	3.40	0.97	3.10	0.89
28	23.5	3.5	3.773	0.176	0.223	0.300	0.789	6.714	3.70	1.06	3.65	1.04
29	23.5	3.0	3.773	0.206	0.217	0.379	0.949	7.833	4.20	1.40	4.10	1.37
30	23.5	4.0	3.773	0.154	0.227	0.245	0.678	5.875	3.10	0.78	3.05	0.76
31	23.5	4.5	3.773	0.137	0.231	0.206	0.593	5.222	2.50	0.56	2.65	0.59
32	23.5	5.0	3.773	0.123	0.235	0.175	0.523	4.700	2.05	0.41	2.00	0.40
33	16.0	3.5	2.979	0.139	0.223	0.237	0.623	4.571	2.50	0.71	2.05	0.59
34	16.0	3.5	3.404	0.159	0.223	0.271	0.713	4.571	3.45	0.99	2.40	0.69
35	16.0	3.5	3.527	0.165	0.223	0.281	0.740	4.571	3.80	1.09	2.60	0.74
36	16.0	3.5	3.773	0.176	0.223	0.300	0.789	4.571	4.05	1.16	3.10	0.89
37	16.0	3.0	3.773	0.206	0.217	0.379	0.949	5.333	4.45	1.48	3.70	1.23
38	16.0	4.0	3.773	0.154	0.227	0.245	0.678	4.00	3.35	0.84	2.75	0.69
39	16.0	4.5	3.773	0.137	0.231	0.206	0.593	3.555	2.40	0.53	2.40	0.53
40	16.0	5.0	3.773	0.123	0.235	0.175	0.523	3.200	2.15	0.43	1.90	0.38
41	9.0	3.5	2.979	0.139	0.223	0.237	0.623	2.571	2.90	0.83	1.95	0.56
42	9.0	3.5	3.404	0.159	0.223	0.271	0.713	2.571	3.60	1.03	2.20	0.63
43	9.0	3.5	3.527	0.165	0.223	0.281	0.740	2.571	3.85	1.1	2.40	0.69
44	9.0	3.5	3.773	0.176	0.223	0.300	0.789	2.571	4.15	1.19	2.95	0.84
45	9.0	3.0	3.773	0.206	0.217	0.379	0.949	3.00	4.50	1.5	3.50	1.17
46	9.0	4.0	3.773	0.154	0.227	0.245	0.678	2.250	3.50	0.88	2.30	0.58
47	9.0	4.5	3.773	0.137	0.231	0.206	0.593	2.00	2.65	0.59	2.10	0.47
48	9.0	5.0	3.773	0.123	0.235	0.175	0.523	1.80	2.30	0.46	1.80	0.36

Explanations: parameters' symbols as in Tab. 1.
Source: own study.

Effect of flow intensity ($v:v_c$) on the local scour ($ds:y$). Flow intensity refers to the ratio of the approaching flow mean velocity (v) to the critical mean velocity (v_c) [Chang *et al.* 2004]. In order to illustrate the impact of flow intensity on the scouring process around pier and abutment, sets of experiments were performed at four different velocities for each pier shape, whereas the other parameters kept constant. The results acquired showed that scour depth increased almost linearly with the increase in the flow intensity for velocities beneath the threshold value as shown in Figure 8. This is consistent with MELVILLE and COLEMAN [2000] who noticed that for uniform graded sediment and under clear-water conditions, scouring depth increased linearly with velocity to a maximum value at the threshold velocity.

Moreover, the increase in the flow intensity leads to an increase in volume and width of the scour hole. This probably ascribes to the increase in separation zone in the downstream side of pier and abutment so more vortices (eddies) will be created which in result causes more scour, and according to RICHARDSON and DAVIS [2001] "The greater the velocity, the deeper the scour depth". Figure 9 presents some selected experiments to show the significant effect of flow intensity on the local scour.

Effect of Froude number (Fr) on the local scour (*ds:y*). Froude number has severe effect on scour depth. According to experiments results, any increase in Froude number will lead to an increase in scour depth at constant values of other parameters, as presented in Figure 10.

The results reconcile with the law of Froude number ($\mathrm{Fr} = v/\sqrt{gy}$) which evidently shows that the increasing in Fr is directly proportional to the increase in flow velocity at constant flow depth and as a result of the increase in the scour depth geometry. Many researchers have addressed the impact of Fr on the scouring process in their studies, around pier, abutment, spur-dike or groynes. For example, JAIN and FISCHER [1979] investigated the impact of a high Froude number on the scouring

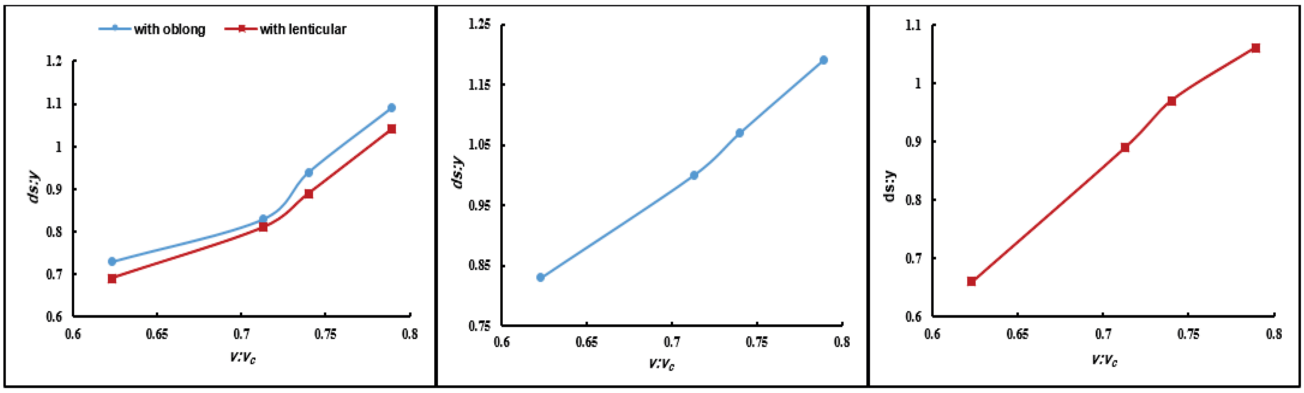

Fig. 8. The effect of flow intensity (v:v_c) on the scour depth ratio (*ds*:*y*): a) vertical-wall abutment, b) oblong pier, c) lenticular pier; where v = mean flow velocity, v_c = critical velocity, *ds* = local scour depth around pier and abutment, *y* = flow depth; source: own study

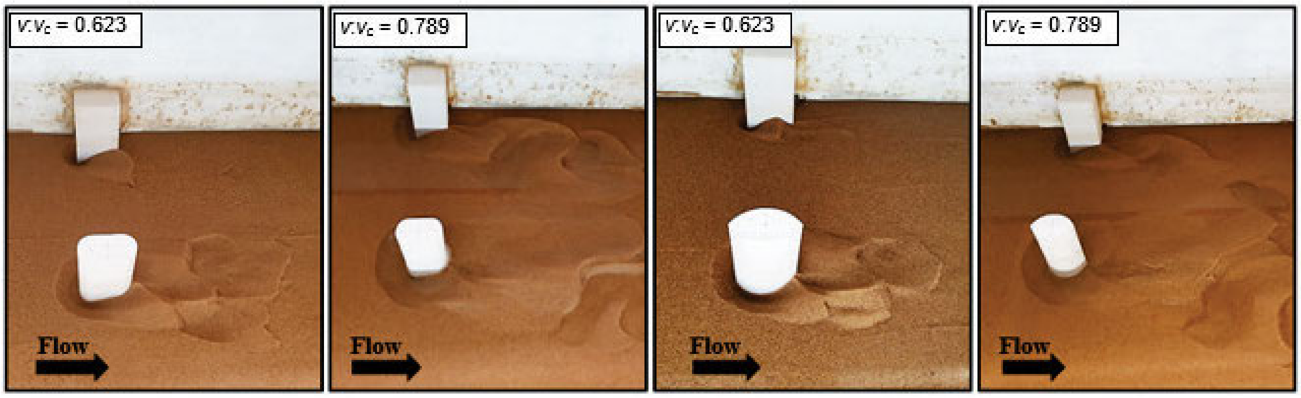

Fig. 9. The impact of flow intensity (v:v_c) on development of scour depth (*ds*:*y*) when increasing flow intensity (from 0.623 to 0.789): a) oblong pier, b) lenticular pier; where v, v_c, *ds*, and *y* as in Fig. 8; source: own study

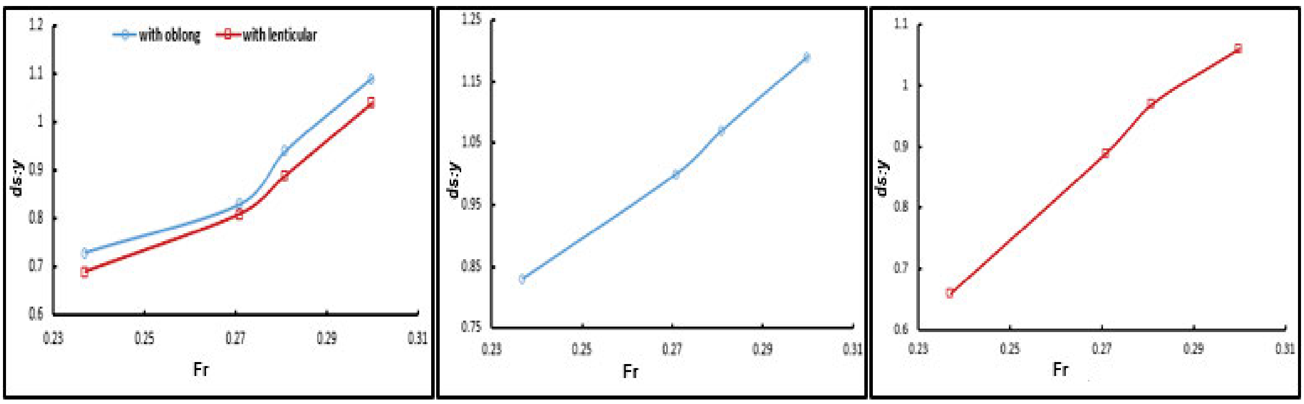

Fig. 10. The effect of Froude number (Fr) on scour depth ratio (*ds*:*y*): a) vertical-wall abutment, b) oblong pier, c) lenticular pier; where *ds* and *y* as in Fig. 8; source: own study

depth around a circular pier and found that the scour depth increased with the increase in Fr (or the velocity; as the depth of flow remained constant for all tests), as well ABOZEID *et al.* [2007], KHWAIRAKPAM *et al.* [2012], AL-KHATEEB *et al.* [2016] and others, despite the differences in these studies, all confirmed that Froude number has a significant influence on scour development and consider as one of the important parameters affecting scour dimensions.

Figure 11 shows the impact of increasing Froude number (from 0.237 to 0.3). On the one hand, it can be noticed that when Fr = 0.237 fewer sediments are distributed with a small camber around the scour hole. On the other hand, when Fr = 0.3 the scour can occur in a wider and larger region, and sediments accumulate with higher camber around the sides of the scour hole. Then sediments start to gradually decrease and vanish downstream of pier and abutment.

Effect of flow depth (*y*) on the local scour (*ds*). Flow depth does make a considerable difference in the value of scour depth, laboratory experiments were carried out under the constant maximum flow discharge to clarify this case.

It is observed that, there is an inverse relationship between scour depth and flow depth, in which a scour depth increases due to decreasing flow depth as illustrated in Figure 12. These results are due to absence of the re-circulating motions near the free surface at high flow depths, so it reduces the horseshoe vortices ability to pick up and entrain sediments. Through his investigations about the scour around spur-dikes, ELAWADY *et al.* [2001] detected that lower flow depths created wider area of scour

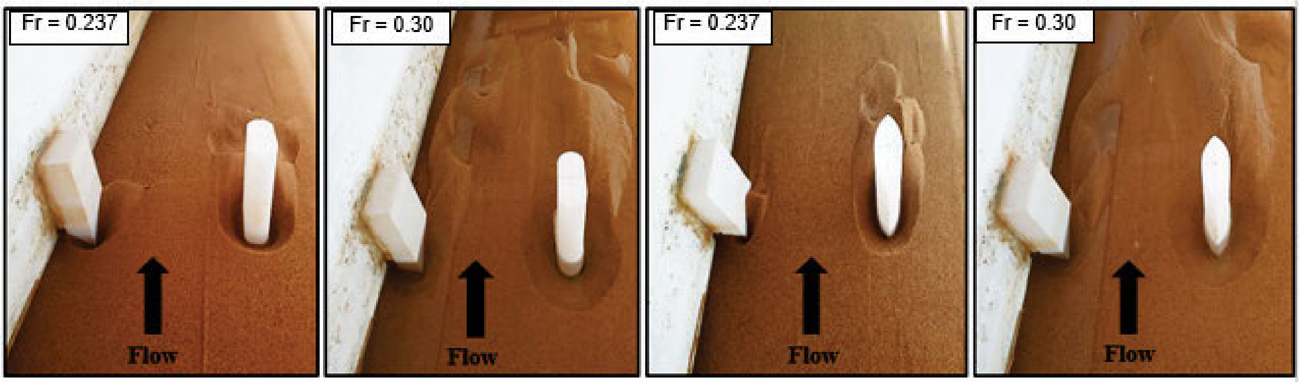

Fig. 11. The impact of Froude number (Fr) on the scour depth development (*ds:y*) when increasing Froude number (from 0.237 to 0.30): a) oblong pier, b) lenticular pier; where *ds* and *y* as in Fig. 8; source: own study

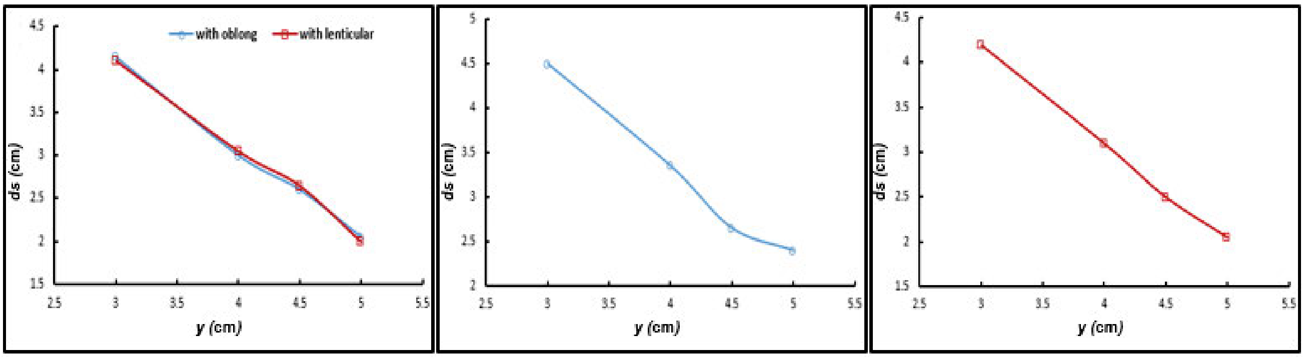

Fig. 12. The effect of flow depth (*y*) on scour depth development (*ds*): a) vertical-wall abutment, b) oblong pier, c) lenticular pier; where *ds* and *y* as in Fig. 8; source: own study

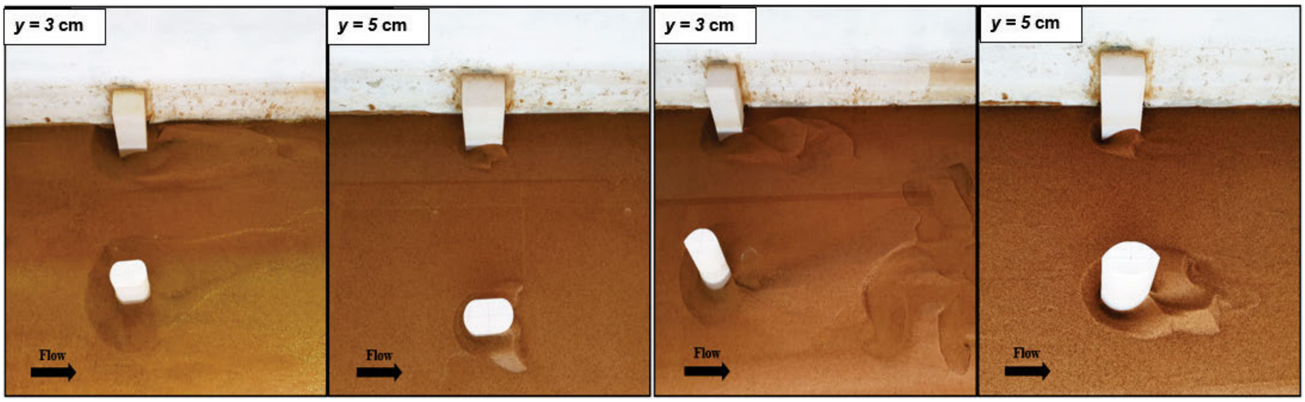

Fig. 13. The effect of flow depth (*y*) on the scour depth development (*ds*): a) oblong pier, b) lenticular pier; y as in Fig. 8; source: own study

compare to greater depths. This effect also applies to pier and abutment as shown clearly in Figure 13. Moreover, ALABI [2006] indicates that the flow depth has an influence on the depth of local scour when the horseshoe vortex is affected by the bow wave (i.e. when the two rollers interfere with each other), but as flow depth continues to decrease, the bow wave will dominant and resulting in horseshoe vortex less capable of moving bed sediment.

Effect of spacing between pier and abutment (*x:y*) on the local scour (*ds:y*). To obtain more knowledge about the behaviour of local scour when increasing or decreasing spacing between pier and abutment. Two sets of experiments were conducted at three different distances (23.5, 16.0, 9.0 cm) under the same flow conditions and the results were plotted in Figure 14.

It is concluded that maximum scour tends to increase for a pier and decrease for an abutment when we reduce spacing between them as follows: under the maximum value of Froude number (Fr = 0.3), spacing is reduced from 23.5 to 16.0 cm, scour depth increases for oblong and lenticular by a percentage of 9.60 and 9.46%, respectively, while the percentage for the abutment scour range decreases about 13.2 and 15.1%. Moreover, the increase measured is about 12.0% for oblong and 12.2% for an lenticular piece when the spacing is reduced from 23.5 to 9.0 cm. On the other hand, scour decreases between 18.4 and 19.2% for the abutment.

This is due to the interference between the horseshoe vortex at pier and abutment. From laboratory observations, when a pier location becomes closer to the abutment, the scour holes interfere together and this is clearly visible, especially at the smallest spacing (i.e. at x = 9.0 cm) under high velocities where the scour holes region for pier and abutment merge together to resemble one wide region. Additionally, particles rolling cause filling of sediment particles for the abutment scour hole which reduces the scour depth. Figure 15 shows the impact of reduced spacing from 23.5 cm to 9.0 cm.

Development of a new formula. For development of the non-dimensional formula (i.e. Eq. (3)), which presents an expression for the maximum depth of scour at bridge, pier and abutment, the computer package IBM SPSS Statistics 21 was used to analysis three formula for abutment, and oblong and lenticular pier through a non-linear regression analysis, and the developed equations are:

$$ds/y = c_1\left(\frac{x}{y}\right)^{c_2}\left(\frac{v}{v_c}\right)^{c_3}\mathrm{Fr}^{c_4} \tag{4}$$

for oblong pier: c_1 = 36.033, c_2 = –0.18, c_3 = –1.842, c_4 = 2.961. So, the equation becomes

$$ds/y = 36.033\left(\frac{x}{y}\right)^{-0.18}\left(\frac{v}{v_c}\right)^{-1.842}\mathrm{Fr}^{2.961} \tag{5}$$

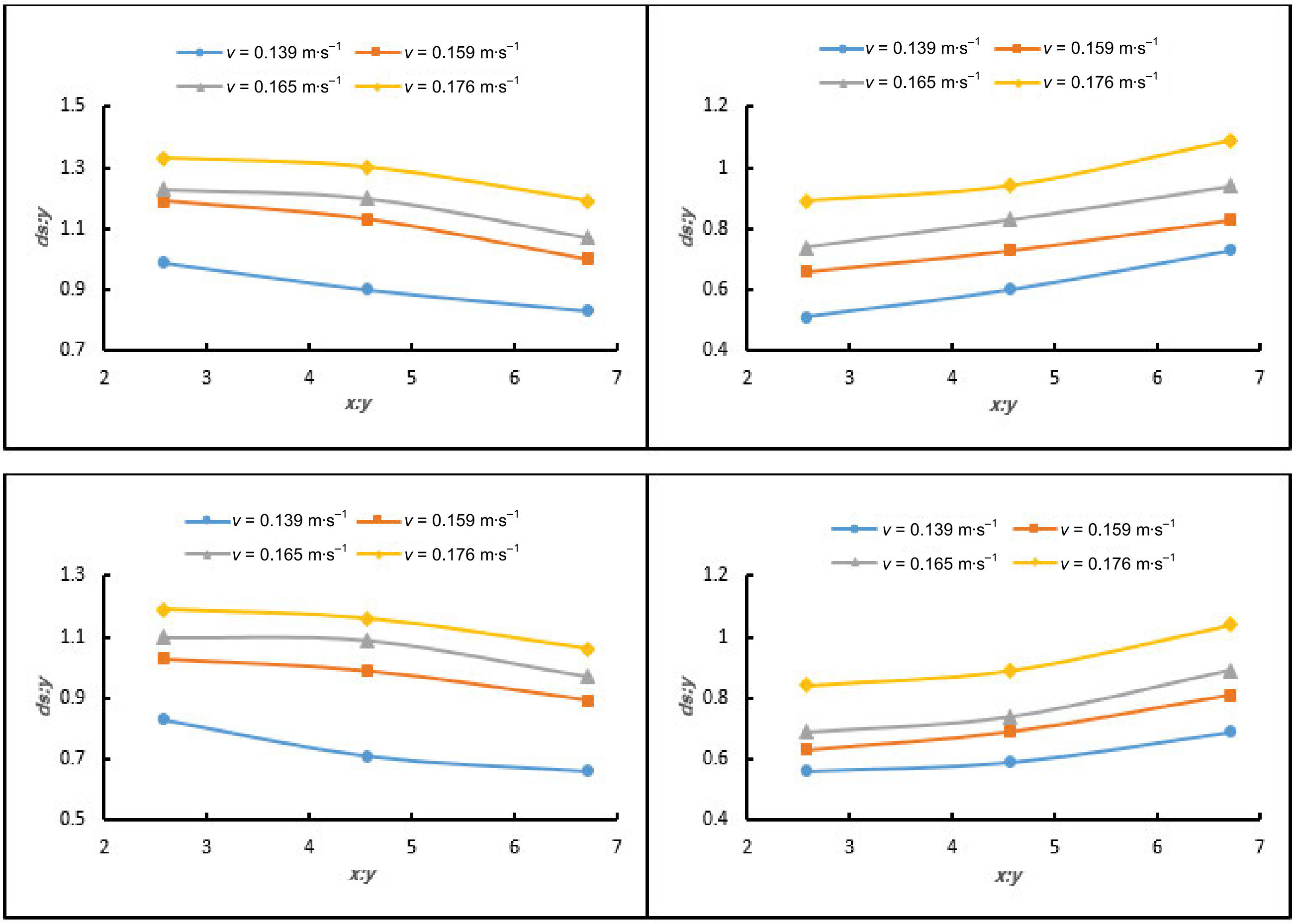

Fig. 14. The effect of spacing ratio (*x:y*) between different shapes of pier and abutment on development of scour depth ratio (*ds:y*) at different flow velocities: a) oblong pier with vertical-wall abutment, b) lenticular pier with vertical-wall abutment; x = spacing between pier and abutment (face to face), *ds*, *y*, and *v* as in Fig. 8; source: own study

for lenticular pier: $c_1 = 13.014$, $c_2 = -0.18$, $c_3 = -0.358$, $c_4 = 1.901$

$$ds/y = 13.014\left(\frac{x}{y}\right)^{-0.18}\left(\frac{v}{v_c}\right)^{-0.358}\mathrm{Fr}^{1.901} \tag{6}$$

for abutment: $c_1 = 1.438$, $c_2 = 0.295$, $c_3 = 0.859$, $c_4 = 0.602$

$$ds/y = 1.438\left(\frac{x}{y}\right)^{0.295}\left(\frac{v}{v_c}\right)^{0.859}\mathrm{Fr}^{0.602} \tag{7}$$

The determination coefficients (R^2) were 0.967, 0.969, and 0.977 for oblong, lenticular and abutment, respectively. Each equation was derived by using 80% of its experimental results, while the accuracy was tested by using 20% of the residual data. After substituting the residual data in Equations (5), (6), and (7), the results were compared with the experimental results to display predicted convergence of the observed records. A statistical comparison of the equations shown in Figure 16, and the determination coefficients values (R^2) were 0.9692, 0.9737, and 0.9779 for the equations of oblong, lenticular and abutment, respectively.

CONCLUSIONS

The present study is concentrated on characterising the diversity in local scour behaviour under different conditions where the impact of various variables, particularly spacing, on controlling

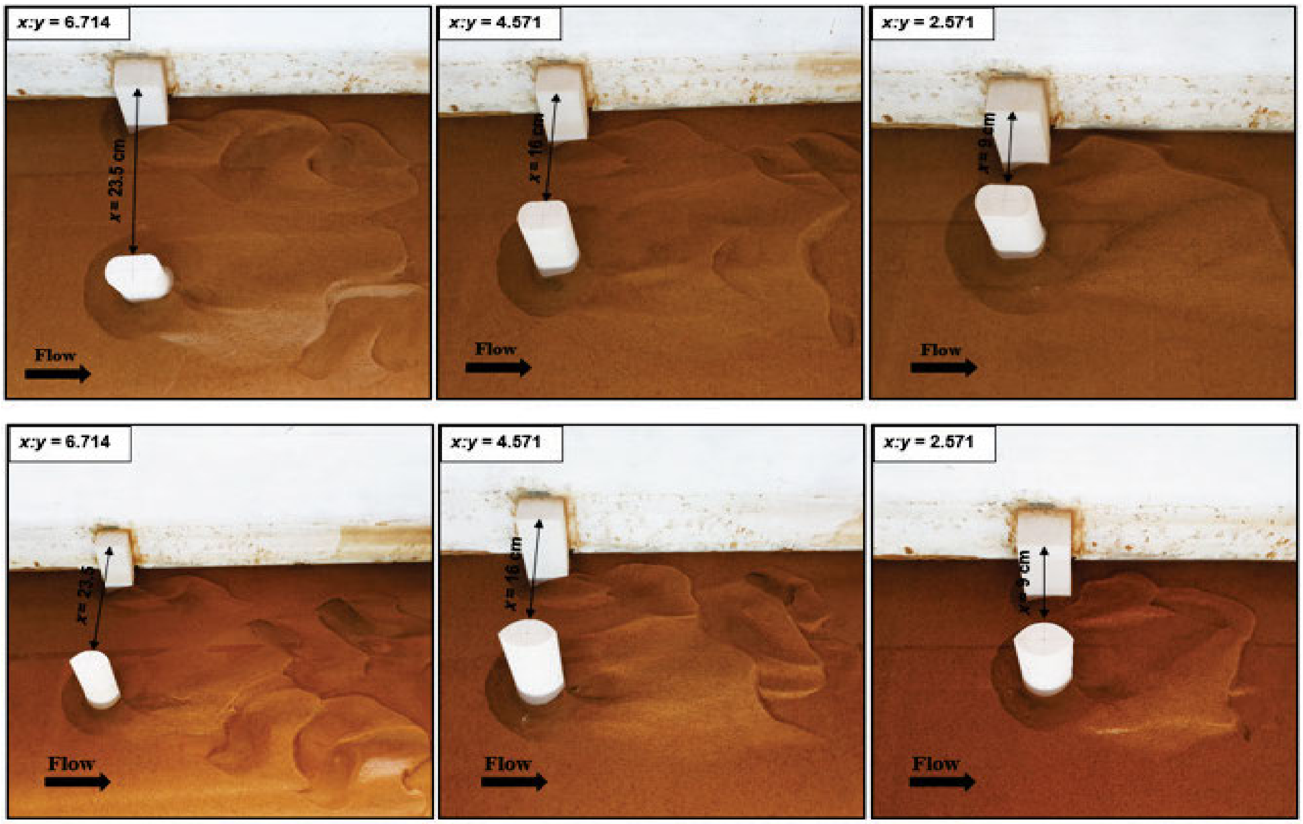

Fig. 15. The impact of spacing ratio (*x:y*) between different shapes of pier and abutment on scour depth ratio (*ds:y*): a) oblong pier, b) lenticular pier; *y* as in Fig. 8, *x* as in Fig. 14; source: own study

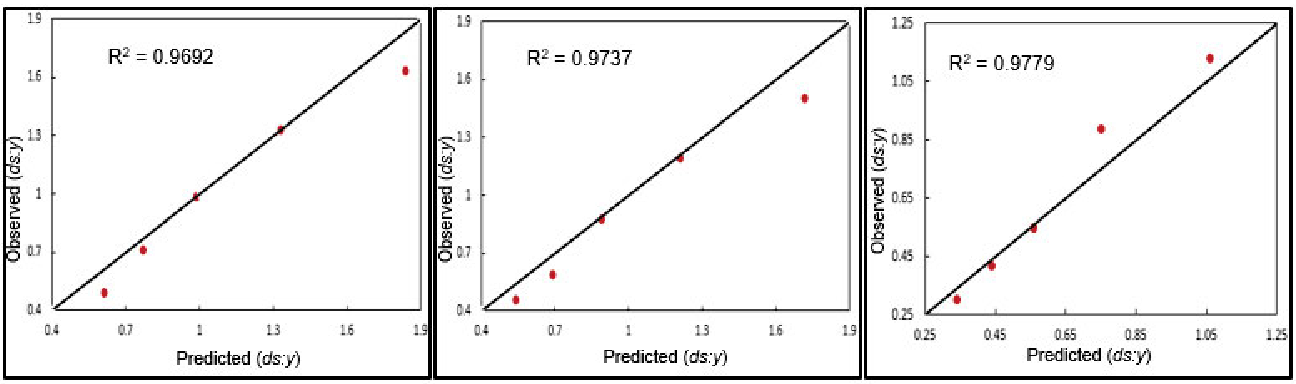

Fig. 16. Validation of Equations (5), (6) and (7) as derived from SPSS Statistics 21 with experimental data: a) oblong pier, b) lenticular pier, c) vertical wall abutment; source: own study

scour around pier and abutment was investigated. The conclusions from the study show that the maximum depth of scour was noticed with increasing flow intensity and Froude number (Fr). Moreover, the increase in flow depth was accompanied by decrease in the dimensions of the scour hole. The spacing between pier and abutment (x) has disparate effect on the scouring process. Due to the interference between the horseshoe vortex of the two structures, scour increased by 9.6% and 12% for oblong pier, whereas 9.46% and 12.2% for the lenticular one when spacing was reduced from 23.5 cm to 16 cm and then from 23.5 to 9 cm, respectively. Furthermore, abutment scour decreased by 13.2% to 15.1% with spacing reduced from 23.5 cm to 16.0 cm, and 18.4% to 19.2% when spacing was reduced from 23.5 cm to 9 cm. Additionally, the maximum scour depth caused by an oblong shape was more than for the lenticular shape by about 10.8% under the same conditions of maximum Froude number (Fr) and spacing x = 23.5 cm.

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