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Parametric Study for Prediction of Scour around Exposed Pile Group Consists of Two Circular Piles

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Abstract Engineers have spent more time and effort in understanding local scour phenomena, especially engineers involved in bridge foundation design. Estimating local scour depth, d_S values are important in order to avoid catastrophic failure of bridges and to get more economical design. Local scour around exposed piles using 3D computational fluid dynamic model was not studied extensively by researchers, where most of researchers concentrated on prediction of single pile scour and limited flow conditions. The main objective of this paper is to use the SSIIM model in predicting local scour around pile group consisting of two circular piles under different flow conditions and to produce more-reliable equations to predict pile group scour precisely. Results and the developed equations by SSIIM model show the influence of different parameters on the local scour around the pile group consisting of two piles. The results of the SSIIM model runs were analyzed in the light of pervious works and developed useful curves and equations to calculate the local scour around pile group consisting of two piles for different conditions.

Keywords Local Scour, SSIIM, Numerical model, k–ε Turbulence model, CFD, piles group

Introduction

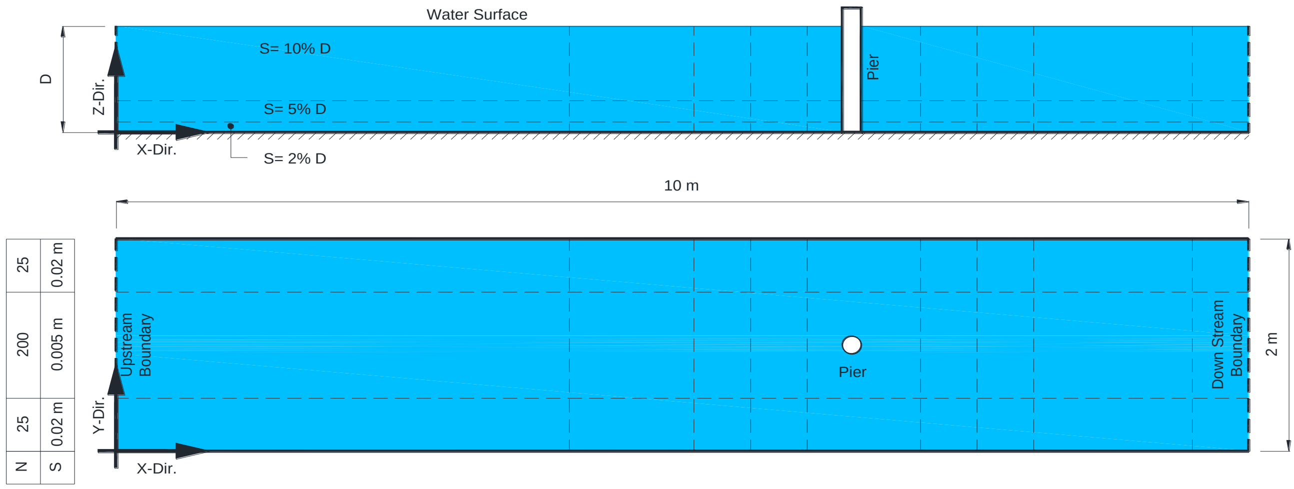
Transportation across rivers and water ways are mainly depending on bridges as it connects both banks of water ways through deck slab, abutments and piers inside the water way. Hence, it is very important to design those bridges for structural forces and hydraulic point of view in order to avoid any catastrophic failures in future. Due to limitation of the used hydraulic models in flume test and numerical models the bridge design may be overestimated which is resulting in additional costs, also this uncertainty may lead to under estimating the design of one or more pier which consequently leads to failure. Researches have calculated scour depth from flume test, these tests are costly and require effort and time form the researchers to get accurate conclusions. Cost reduction can be obtained by combining practical work and numerical modeling as proposed in the current research.

The main objective of the current paper was to predict local scour around bridge piers consists of two piles using a 3D computational fluid dynamic model (SSIIM) for clear water scour and live bed scour. It worth to say that the current model has been validated in another research by the author for clear water scour for rectangular piles [1] and for live bed scour by [2]. In this paper, SSIIM model was used to simulation. The same model has been usedby [3-10] to predict scour around bridge piers snuggle piles with different shapes. In addition to this paper a study by [11] and [12] have been done earlier to validate the SSIIM in prediction of local scour.

The 3D computational fluid dynamic model (SSIIM) was validated for prediction of scour development with time (scour rate) as it was compared with the results from experimental work. In this paper, the validated and calibrated models have been used to perform a parametric study in order to get influences of flow angle, spacing between piles, pile size, and flow condition for group consists of two on the scour depth values. The outcomes of the paperare useful in getting the angles of attack and spacing to be avoided while the design of pile group consists of two piles. In addition, the paper aims to predict scour based on large number of SSIIM model runs to increase the reliability of the developed predictor equations. In order to give more reliability to developed equations,the analysis of the obtained results have been conducted in the light of earlier published data.

Numerical Model Geometry, Properties, Verification and Calibration

In the current paper, the used numerical model was calibrated and verified by [2] based on the experimental results by [13] at Hydraulic Laboratory of Cairo University, Giza, Egypt. In the experimental study a large-scale rectangular flume was used, the length, width and depth of flume were 21.0m, 2.0m, and 0.9m respectively. The numerical model mesh has been prepared to fit the study purpose and the limitation of the SSIIM limitation as long as optimizing the calculation time. Finer grids were adopted where the piles exist and gradually the grids became coarser whenever it reaches the models end. Figure (1) represents schematic diagram for the used model more details for the area where piles exist is described in Figure (3). In order to get more reliability, the used model results were verified with previous equations.



Number of Grids (N)	4	11	10	50	200	50	10	14	1
Cell Size (S)	1.00 m	0.10 m	0.05 m	0.01 m	0.005 m	0.01 m	0.05 m	0.10 m	0.50 m

Figure 1: Numerical model grids layout [2]

Parametric Study

The parametric study program and the different parameters are described in this section; as illustrated in Figure (2)the geometrical parameters are pile size, b and spacing as long as the angle between piles. Circular piles with diameters of 50mm, 100mm, and 150mmwere used. Piles centerline spacing were 2b, 3b, and 4b.The Angel between the two piles was changing from 0° to 90° measured with respect to flow direction where zero angles is parallel to the flow. In order to select the number of angles, fixed increment of 15° was assumed, this increment was selected to be reasonably suitable and acceptable to recognize its influence. Finally, seven angles with values of 0°, 15°, 30°, 45°, 60°, 75° and 90° were examined. Also, the effect of each parameter on the local scour around pile group for different values of Froude number, F_r of 0.21, 0.28, and 0.32 were estimated.

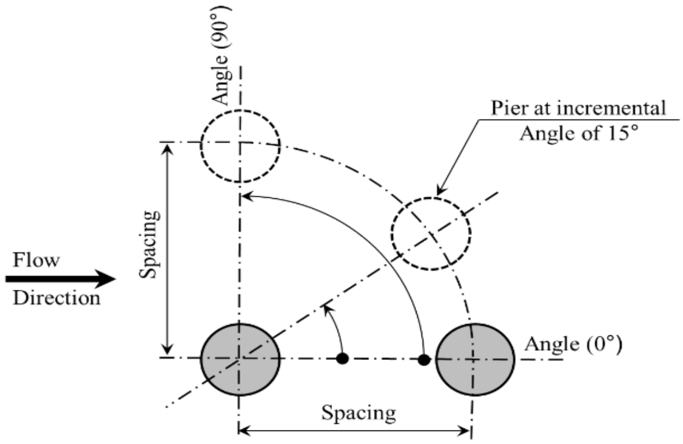


Figure 2: Geometrical parameters

Numerical calculations were conducted at the computer lab of Civil Engineering department at Faculty of Engineering, Shobra, Cairo, Egypt. The total number of runs was 189 runs. Numerical models geometries have been prepared using meshing subroutine developed using Visual basic application; the subroutine was used to automatically generate irregular mesh at locations where circular piles exist. the developed subroutine calculate precisely piles locations, place it in the correct position in SSIIM geometry file "Koordina" and updates SSIIM control file in order to block water flow in piles area. Figure (3) represents sample mesh shape as modeled in SSIIM for circular piles shape, where the red line identifies piles locations.

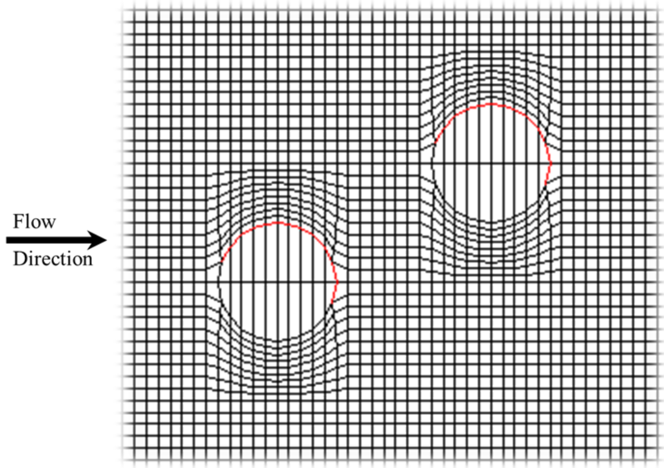


Figure 3: SSIIM mesh for Circular piles shapes

Results and Discussion

The relative local scour values, d_S/b as predicted by the SSIIM model for circular piles shape are presented in Table (1).The results shows a general trend for the influences of each flow depth to pile size ratio, Y/b and piles spacing to pile size ratio, S/b on the local scour depth d_S around pile group consists two circular piles.

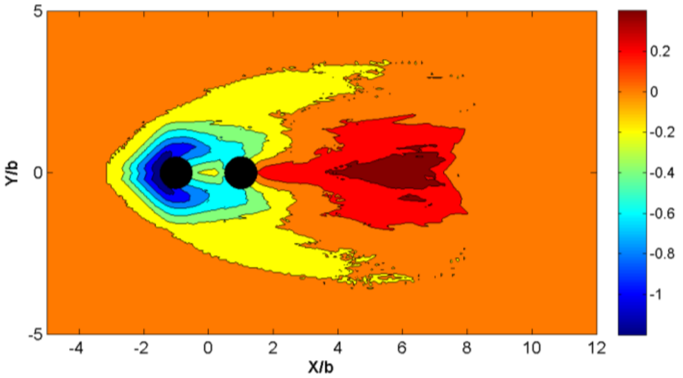
Table 1: Summary of Relative Scour (d_S/b) Results for Circular Piles Shape

	Y/b	**4**			**2**			**1.33**		
	S/b	**2**	**3**	**4**	**2**	**3**	**4**	**2**	**3**	**4**
Fr = 0.21	0	1.451	1.448	1.427	1.185	1.196	1.191	0.987	0.993	1.006
	15	1.549	1.566	1.546	1.221	1.228	1.197	0.999	1.004	1.013
	30	1.598	1.532	1.608	1.238	1.272	1.219	1.020	1.028	1.100
	45	1.791	1.690	1.706	1.342	1.343	1.346	1.088	1.131	1.148
	60	1.846	1.794	1.735	1.408	1.387	1.342	1.180	1.131	1.103
	75	1.879	1.780	1.660	1.466	1.354	1.322	1.197	1.104	1.120

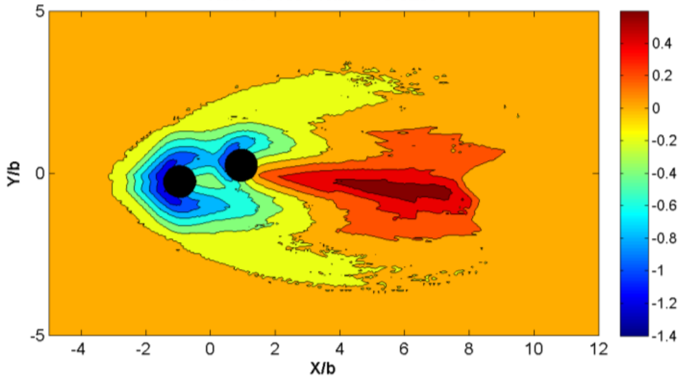
	Y/b	4			2			1.33		
	S/b	2	3	4	2	3	4	2	3	4
	90	1.965	1.752	1.631	1.451	1.346	1.322	1.177	1.107	1.093
Fr = 0.28	0	1.763	1.789	1.730	1.482	1.494	1.491	1.255	1.273	1.227
	15	1.794	1.757	1.746	1.543	1.498	1.496	1.294	1.221	1.265
	30	1.746	1.746	1.780	1.502	1.493	1.481	1.304	1.278	1.314
	45	1.891	1.859	1.782	1.517	1.626	1.595	1.342	1.415	1.426
	60	2.041	2.034	1.913	1.712	1.625	1.593	1.463	1.446	1.448
	75	2.017	2.037	1.951	1.702	1.622	1.572	1.475	1.418	1.387
	90	2.217	1.953	1.801	1.747	1.626	1.553	1.453	1.387	1.382
Fr = 0.32	0	1.882	1.965	1.998	1.644	1.668	1.644	1.460	1.471	1.425
	15	1.954	1.954	1.970	1.677	1.650	1.653	1.478	1.451	1.414
	30	1.966	1.893	2.002	1.671	1.629	1.621	1.406	1.423	1.420
	45	2.013	1.918	1.978	1.671	1.717	1.733	1.457	1.485	1.479
	60	2.111	2.044	1.990	1.880	1.714	1.692	1.583	1.531	1.498
	75	2.150	2.130	1.995	1.892	1.694	1.655	1.562	1.499	1.446
	90	2.357	2.048	1.951	1.794	1.673	1.649	1.554	1.458	1.438

Influence of Changing Angle between Piles

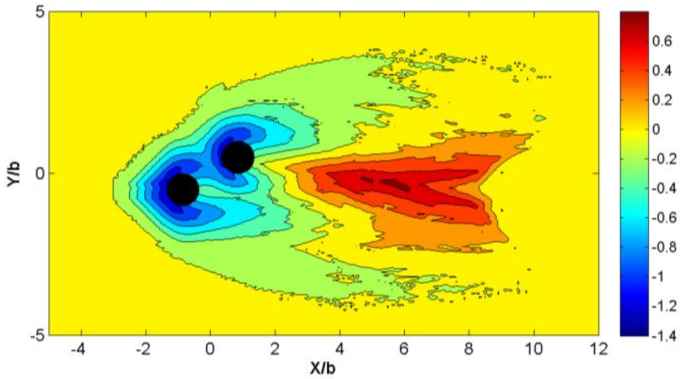
The colored contour plan in Figure (4-a) to Figure (4-g) represents the relative scour (ds//b) at end of SSIIM run, for constant Y/b = 2, S/b = 2 and Froude number of 0.21 and variable angle. Horizontal and vertical axis were plotted with respect to the pile size, the color scale shown at right of the plan helps in recognizing the relative scour values, where blue color indicates the scour hole, and red color indicates the sediment deposition.



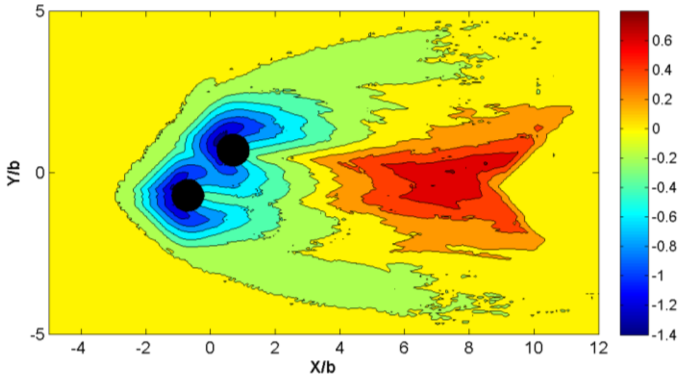
a) Angle = 0°



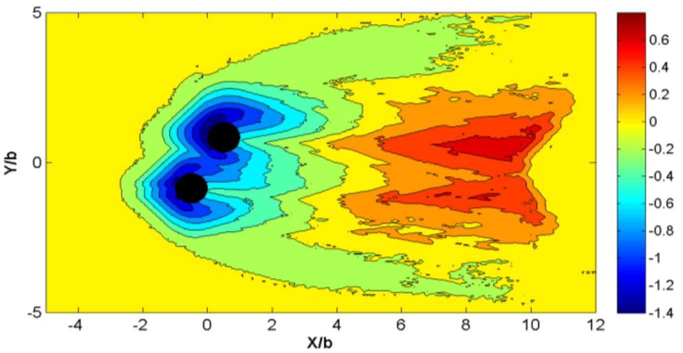
b) Angle = 15°



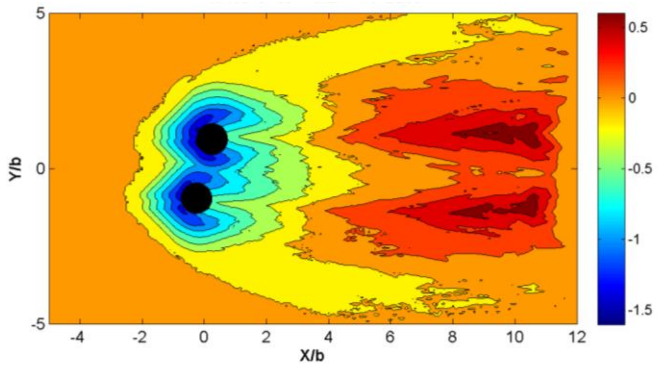
c) Angle = 30°



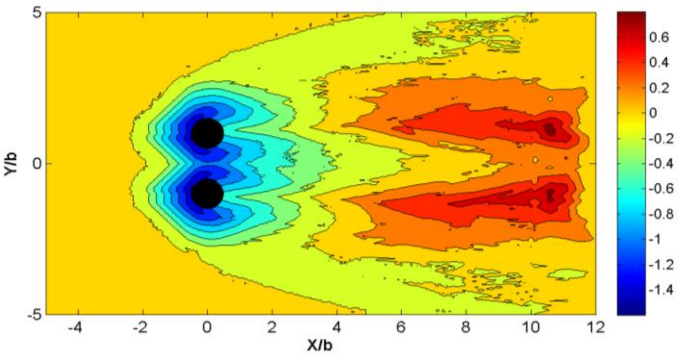
d) Angle = 45°



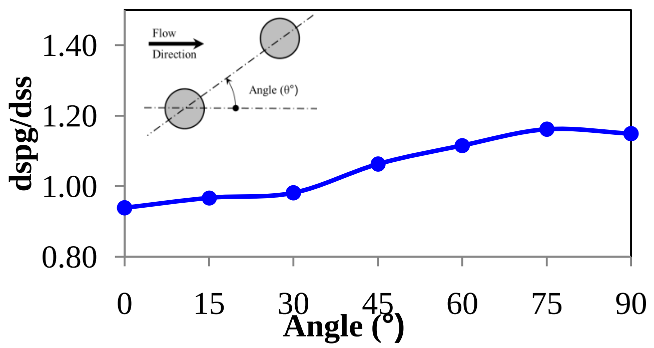
e) Angle = 60°



f) Angle = 75°



g) Angle = 90°



h) Variation of dspg/dss with Angle

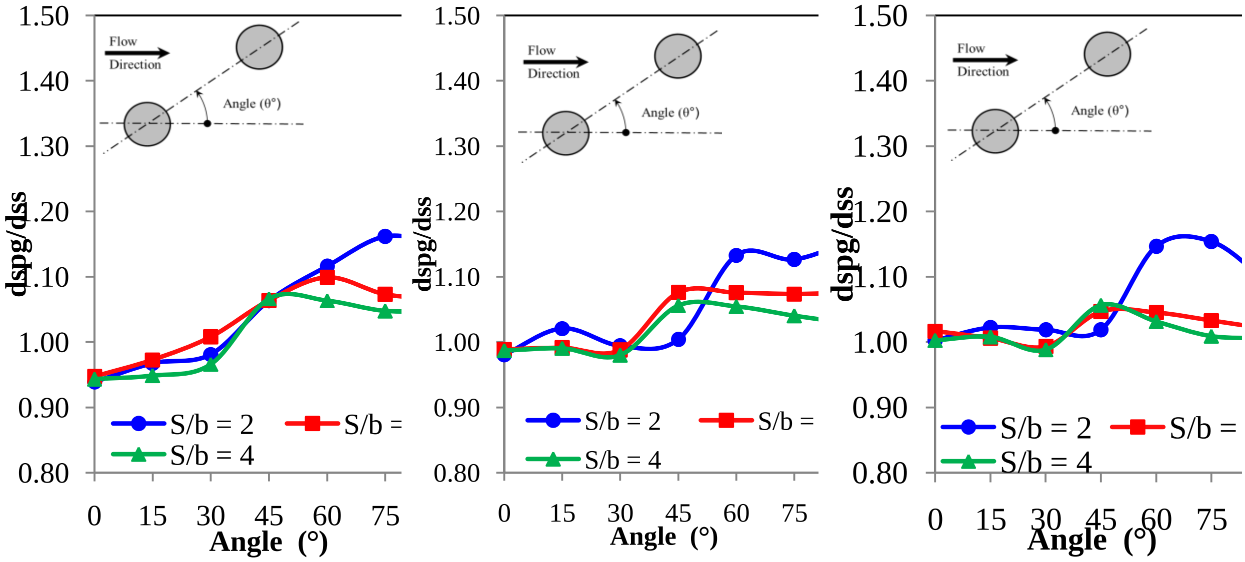
Figure 4: Scour Contours for Y/b= 2, S/b = 2 and Fr=0.21

The maximum relative scour at angle of zero was (ds/b = 1.185) which is very close to the maximum scour obtained from the experimental results by [13] of single pile (ds/b = 1.20), and it is slightly increase to 1.221 and 1.238 for angles 15° and 30° respectively. For angles of 45° and 60°, the maximum relative scour depth were (ds/b = 1.342) and (ds/b = 1.408) respectively, the maximum scour depth for the two cases occurs at the second pile which mean that the effect of the flow shedding disappeared and stronger horse shoe vortex at the front of the downstream pile exist. The formation of this horseshoe vortex is due to the normal flow in addition to the accelerated flow at the two sides of the front pile. Finally for angles 75° and 90°, the maximum relative scour for the two cases is greater than previous angles, the relative scour values are (ds/b = 1.466) and (ds/b = 1.451) for the two angles respectively. The main reason behind this is diminishing shedding and the existence of strong compressed horseshoe vortex in the area between the two piles, [14], and [15].

Figure (4-h) illustrates the effect of changing the angle between piles on the normalized scour depth (dspg/dss) where (dss) and (dspg) is the scour depths for single pile and piles group respectively. The chart conclude: firstly, smaller scour depths were obtained at smaller angles (0° to 30°) due to flow shedding by the upstream pile and the group tends to work as single pile. Secondly, scour increases when the angle between piles ranging between 30° to 75° due weakness on the shedding effect and due to exposing the downstream pile to the flow and the wake vortex created by the upstream pile. Finally, the scour depth for the presented case does not exceed 1.15 of the single pile scour.

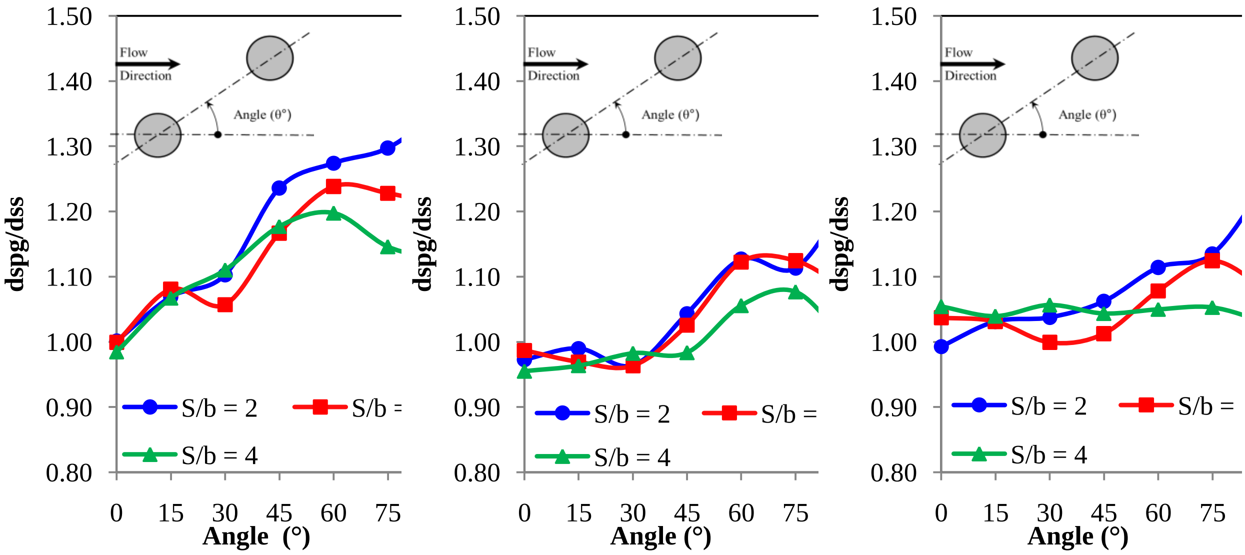
Figure (5) combines the normalized maximum scour for spacing ratio (S/b = 2 to 4) at constant water depth to pile size ratio (Y/b=2) for different Froude numbers. It is concluded from figure (5-a) that at Fr=0.21, the effect of pile spacing is insignificant for smaller angles however it increase by the increase of the angles between piles and the effect of front pile shedding is found in all piles spacing for small angles. It is also concluded that at higher angles the scour values increases by decreasing spacing between piles for the same angles which is logical and compatible with the results obtained by [15]. The maximum normalized scour depths obtained that were found at angle of 90 are 1.15, 1.07, and 1.05 for spacing ratio (S/b) of 2, 3 and 4 respectively. Similar conclusions are found when changing the Froude number as shown in Figure (5-b) and Figure (5-c) but with greater scour depth due to the change of flow conditions.

Similar behavior was noted for different water depth to pile size ratio presented in figure (6) and figure (7) for lower Froude numbers, but for higher Froude Number the values of the normalized scour are almost the same for all angle at different spacing. It is also noted that the values of the pile group scour depth does not exceed 1.35 of the single pile scour depth for lower Froude numbers and smaller spacing, whereas it reaches the single pile scour depth for the large spacing and higher Froude numbers.



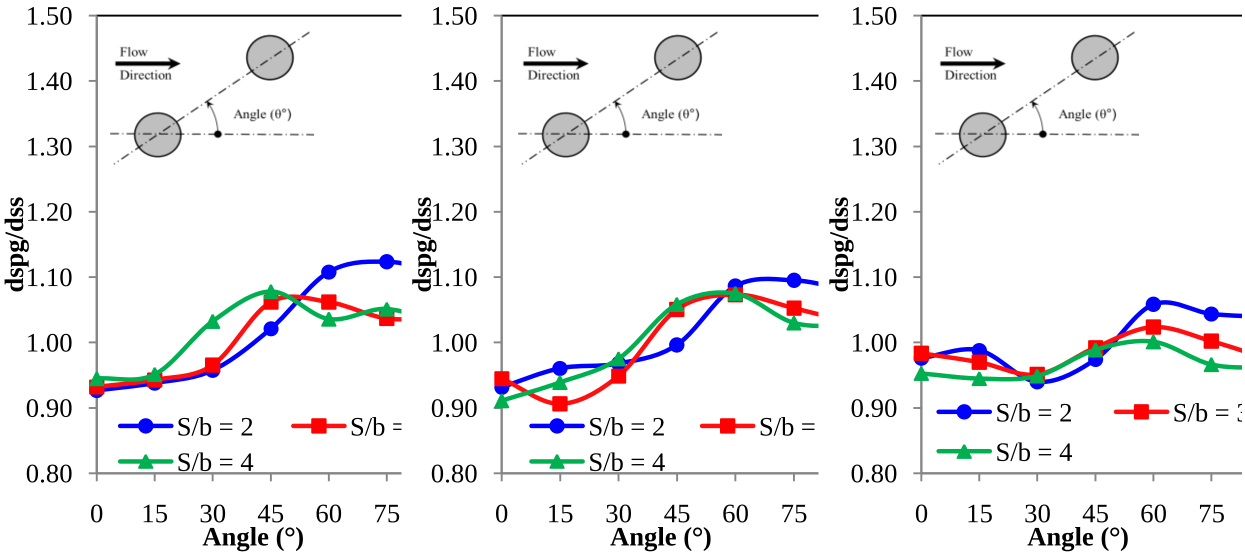
a) Fr=0.21   b) Fr=0.28   c) Fr=0.32

Figure 5: Variation of dspg/dss with Angle at Y/b=2



a) Fr=0.21   b) Fr=0.28   c) Fr=0.32

Figure 6: Variation of dspg/dss with Angle at Y/b=4

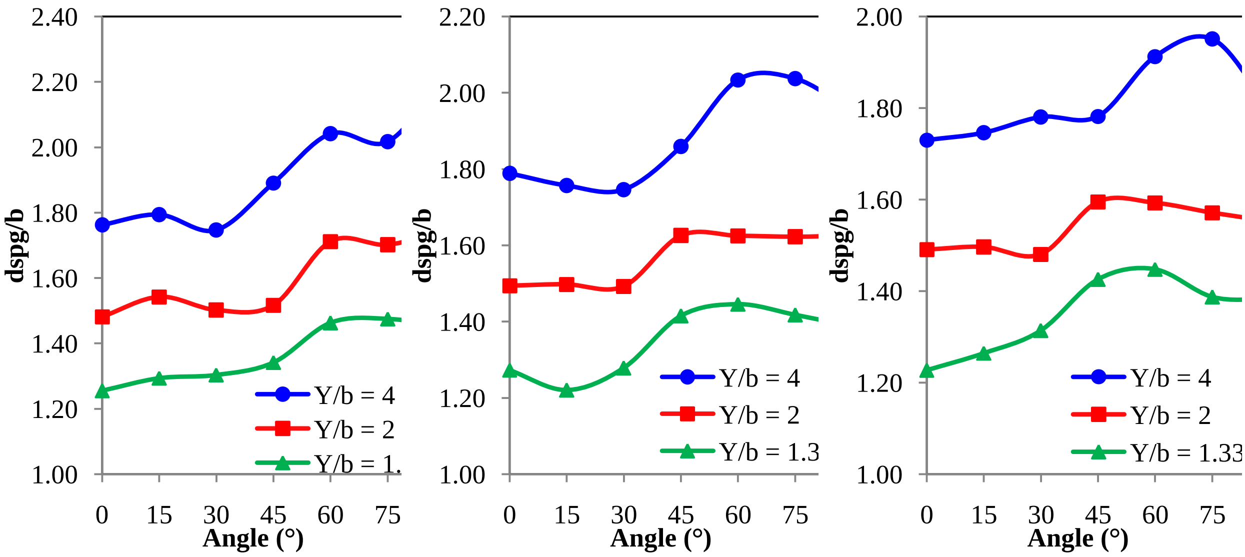


a) Fr=0.21 b) Fr=0.28 c) Fr=0.32

Figure 7: Variation of dspg/dss with Angle at Y/b=1.33

Influence of Pile Size at Constant Spacing and Froude Number:

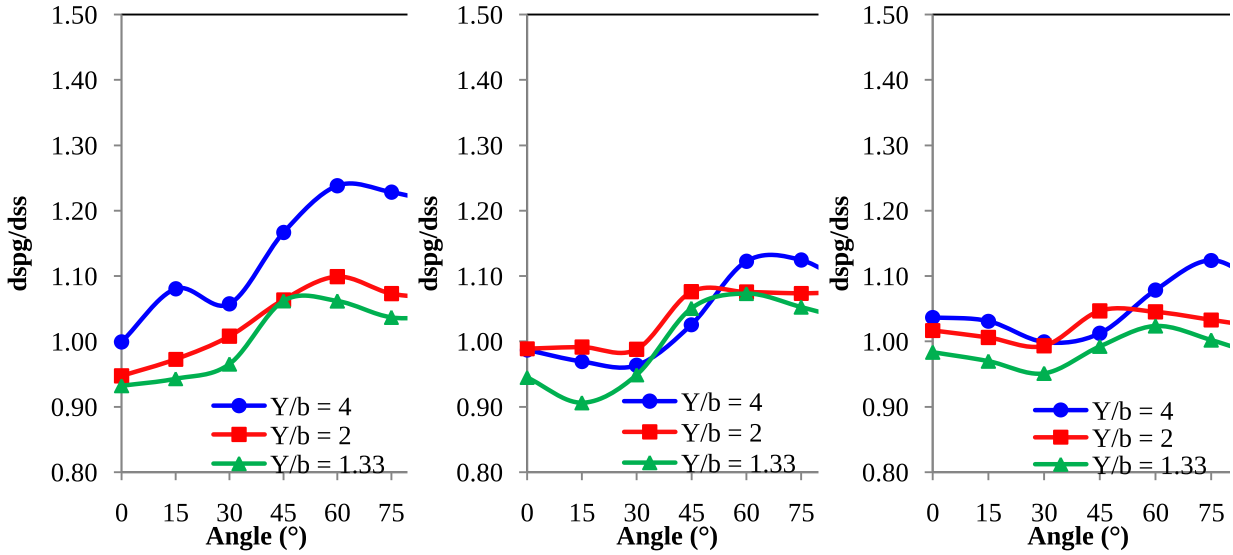
Influence of changing pile size is discussed in this section; theX-axis represents the angle between piles whereas the Y-Axis represented by two methods. In the first method, the Y-Axis represents the pile-group scour depth to pile size (dspg/b) as shown in Figure (8), the relative scour depths are directly proportional with the increase of water depth to pile size ratio (Y/b), this means that the pile size is highly contribute in final scour value as expected.



a) S/b = 2 b) S/b = 3 c) S/b = 4

Figure 8: Variation of dspg/b with Angle at constant Fr=0.28

In the second method, Y-Axis represents pile group scour depth to single pile scour depth ratio, (dspg/dss), Figure (9) have been drawn for different Froude Numbers. Figure (9-a) concludes that the normalized scour values for (Y/b= 4) are reasonably greater than other Y/b ratios, which is an indication that for clear water scour conditions the scour depths for deep flow are greater than shallower one at the same angle. However, for live bed scour conditions as indicated in Figure (9-b) and Figure (9-c), the normalized scour depth values are not changed a lot.

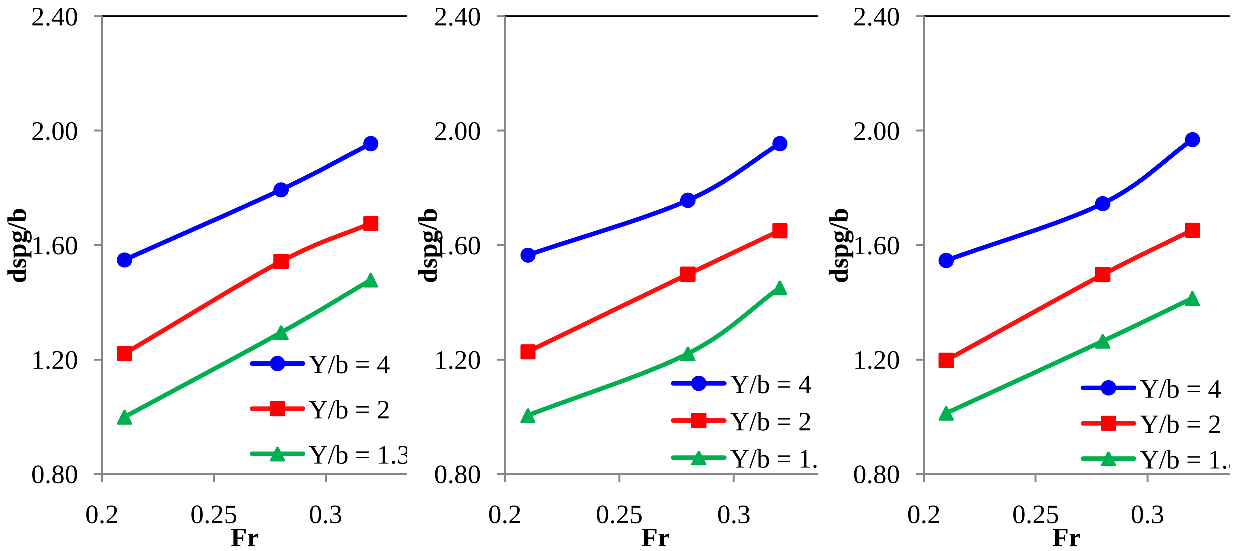


a) S/b = 3, and Fr = 0.21 b) S/b = 3, and Fr = 0.28 c) S/b = 3, and Fr = 0.32

Figure 9: Variation of dspg/dss with Angle for different Fr

Influence of Pile Size at Constant Spacing and Angles

Influence of changing pile size at different Froude numbers is presented in Figure (10), the charts are drawn for a constant angle of 45° at different (S/b). The obtained results of the model show that the relative scour depth (dspg/b) increases with each Froude number, Fr and the water depth to pile size ratio, Y/b, at constant pile spacing and angle.



a) S/b = 2 b) S/b = 3 c) S/b = 4

Figure 10: Variation of dspg/b with Fr at angle = 45°

In order to understand the influences of the spacing at constant angles, charts at different spacing are combined together for each angle as illustrated in Figure (11). it can be concluded from these figures that the value of scour are not significantly changed by changing the spacing for the same pile size and Froude number for smaller angles (0° ≤ angle ≤ 30°), this is applicable for the all pile sizes. The effect of spacing becomes significant when the angle is more than 45° as there are a clear shift in the curves at S/b=2 and 3.

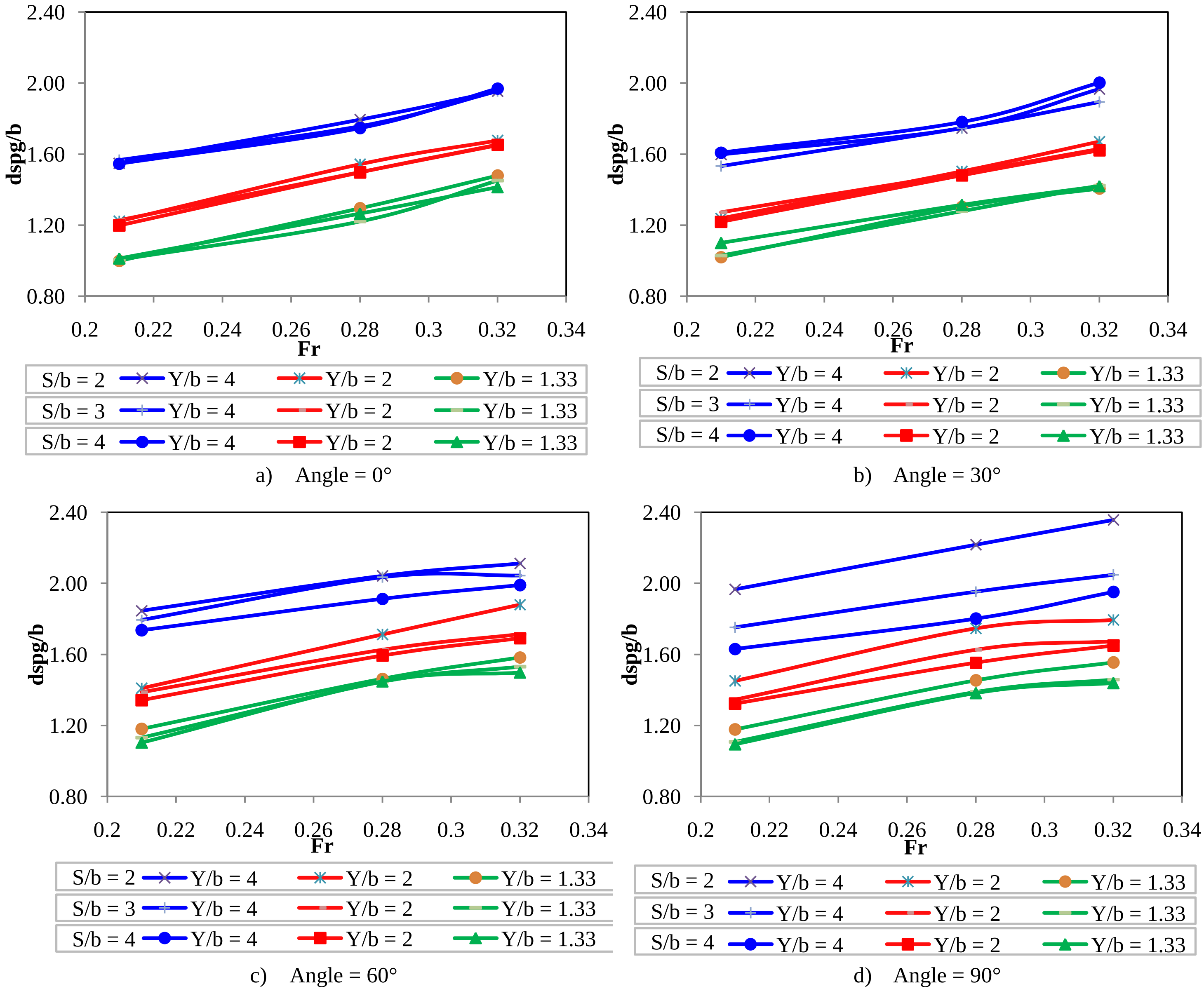


Figure 11: Variation of dspg/b with Fr for different S/b

Prediction of Scour Depth using Developed Equations

Equation (1) was developed for the prediction of the maximum scour depth of circular piles group. This equation was developed by power regression of the normalized scour depth (dspg/b) observed from the SSIIM models with Froude number, angle, spacing to pile ratio (S/b) and the flow depth to pile size ratio (Y/b). These developed equations are as follows:

$$\frac{dspg}{b} = \left[2.554 + 0.0035(\theta) - 0.0544\left(\frac{S}{b}\right)\right] F_r^{\,0.565} \left(\frac{Y}{b}\right)^{0.31} \quad \text{Eq. (1)}$$

With correlation coefficient R= 0.968 and R^2 = 0.937

Where: dspg Maximum Scour Depth of pile group

b	Pile Diameter
θ	Angles between Piles
S	Pile spacing
Y	Water depth

In addition to the equation above, the scour depth for the analyzed group is a function of S/b at constant Y/b and Froude number.Figure (12) illustrates the relation between S/b in horizontal axis and dspg/dss for different Y/b for constant angle and Froude number, horizontal line have been added to the chart to represent single pile scour at (dspg/dss=1). It seems from the chart that the value of normalized scour depth is decreasing by increasing the distance between piles, Equation (2) to Equation (4) represents the best-fit equation for the three depths to pier size ratio, and the R-Squared values are 0.9965, 0.9359 and 0.9314 respectively

At Y/b = 4 $$\frac{d_{spg}}{d_{ss}} = -0.335 \ln\left(\frac{s}{b}\right) + 1.5854 \quad \text{Eq. (2)}$$

At Y/b = 2 $$\frac{d_{spg}}{d_{ss}} = -0.15 \ln\left(\frac{s}{b}\right) + 1.247 \quad \text{Eq. (3)}$$

At Y/b = 1.33 $$\frac{d_{spg}}{d_{ss}} = -0.117 \ln\left(\frac{s}{b}\right) + 1.1809 \quad \text{Eq. (4)}$$

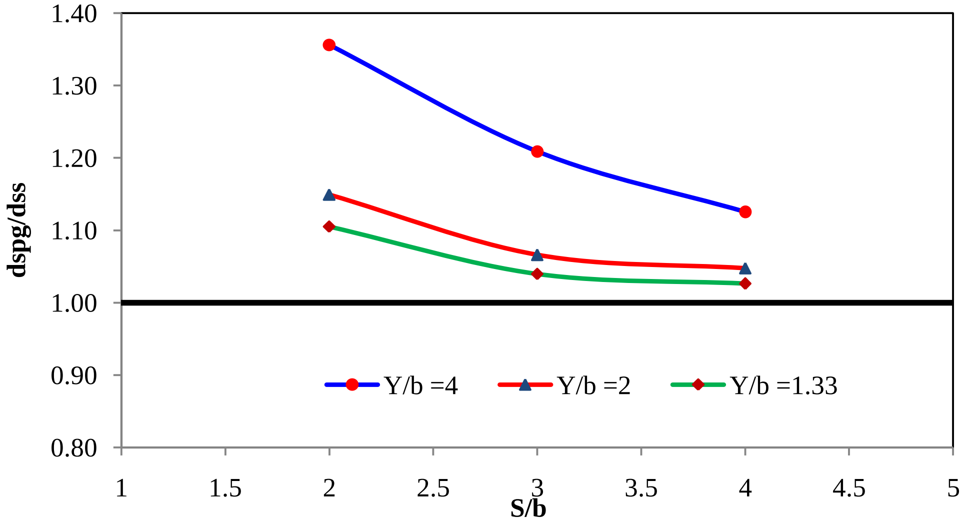


Figure 12: Relation between S/b and dspg/dss at Fr= 0.21

The three equations above are presented Figure (13), all equations have been extrapolated in order to get the spacing where piles behave as separate piles, it was found that the spacing varies for different (Y/b) where (S/b) are 5.3, 5.1, and 4.6 respectively. Values from [14] and [16] have been added to the curves to check equations applicability. Results observed by Hanna (1978) was at (Y/b) = 2 which is in line with Equation (3), results for [16] was based on(Y/b) = 3.1 which is between the Equation (2) and Equation (3) as presented in the figure.

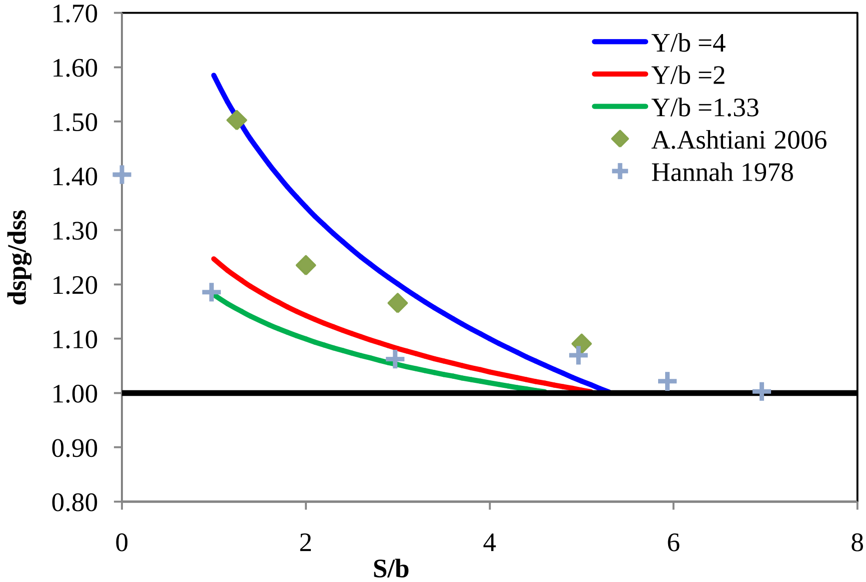


Figure 13: Relation between S/b and dspg/dss at Fr= 0.21

From practical point of view, it is very difficult to use the three equations as it represents on sole value of (Y/b) for each equation, hence Equation (5) is proposed in order to calculate dspg/dss for different (Y/b) value at constant angle of 90° and Froude number of 0.21. R-Squared value is 0.945, which indicates excellent correlation between the calculated values and observed values.

$$\frac{d_{spg}}{d_{ss}} = -0.0834\left(\frac{Y}{b}\right)^{0.974} \ln\left(\frac{s}{b}\right) + 1.067\left(\frac{Y}{b}\right)^{0.276} \qquad \text{Eq. (5)}$$

It is clear from the proposed equation that in the value of dspg/dss is a function of normalized spacing and normalized water depth which is not the same as proposed by [17], as it depends on the normalized spacing for the same flow conditions. Equation developed by [17] is stated hereunder after adjusting it to the studied angle, where the two terms in the equation are for the relative scour at each pile.

$$\frac{d_{spg}}{d_{ss}} = max\left[1.25\left(\frac{s}{b}\right)^{-0.1} or \;\; 1.195\left(\frac{s}{b}\right)^{-0.1}\right] \qquad \text{Eq. (6)}$$

Figure (14) represents comparison between the observed values from [14], [16], [17], [18] and the calculated normalized scour depth. It is clear from the chart that the equation predicts the scour depths with accuracy of ±10% as most of the calculated values are distributed around the equality line except for three values which might have a different experimental setup.

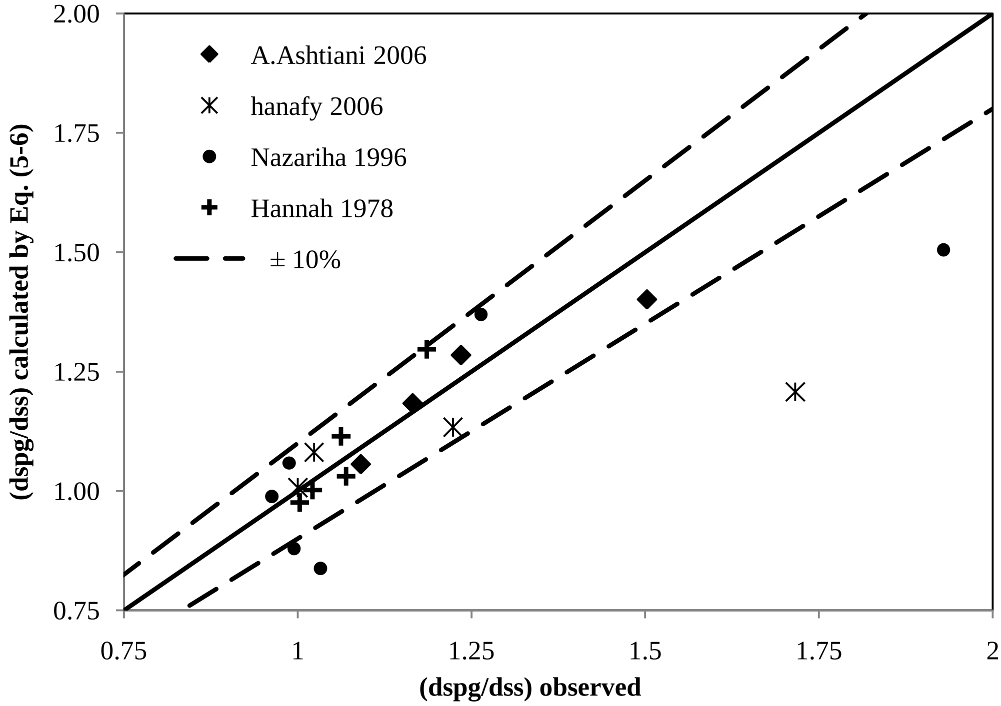


Figure 14: Relation between S/b and dspg/dss at Fr= 0.21

Conclusions

From the above discussion, the following conclusions can be drawn:

1. It is concluded from the study that the maximum normalized scour depths for combination of two piles does not exceed 1.35 of single pile scour depth for circular shapes.
2. The flow angle of attack has a recognized influence on group scour depth at lower Froude numbers; however, its effect is reduced for greater Froude numbers. For example, the obtained normalized scour depth at Froude number of 0.21 changing from (dspg/dss=1) to (dspg//dss=1.21) at constant S/b=3 and y/b=4 while the mean normalized scour depth at Froude of 0.32 is at (dspg/dss=1.05).
3. The absolute scour depths are directly affected by the pile size as the scour depth increases by increasing the pile size for any piles group at constant spacing and Froude Number. For instance, the obtained scour depths for circular piles were 0.088, 0.148 and 0.217 for pile sizes of 50mm. 100mm

and 150mm respectively at constant spacing ratio of (S/b=2) and Froude number of 0.28. Notwithstanding, when correlate the scour depth to the single pile scour it give almost the same ratio.

4. The maximum normalized scour depths are not significantly changed by changing the spacing for the same pile size and Froude number for smaller angles. For instance, at Froude number of 0.32 and angle of 30°, the normalized scour depths (dspg/dss) were 1.038, 0.999 and 1.056 for spacing of 2D, 3D and 4D respectively for circular piles of diameter 100mm.
5. The developed equations to predict maximum normalized scour for any angle under different flow conditions (Eq. 1) for circular have a very good correlation R= 0.968.
6. The developed equations to calculate the normalized group scour depth at angle 90° at different spacing (Eq. 2 through 4) concludes that the value of group scour depth is depending on the normalized spacing, the correlation of the three equation R^2= 0.9965, 0.9359 and 0.9314 respectively.
7. The three equations indicated have been combined in one equation (Eq. 5) which give a very good agreement with the observed values by Hanna (1978), M.Nazariha (1996), Ataie-AshtianiA. et al. (2006), Hanafy (2006), he R-Squared values is 0.945 which indicates excellent correlation between the calculated values and observed values.

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