Investigating the Impact of Pile Group Arrangement on Local Scour around Bridge Pier Using Physical Model

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Abstract

Scour is a natural phenomenon resulting from stream flow impact on the bed material, which causes the movement of the sediment at the vicinity and around the supports of hydraulic structures. Scour around a single pile or pile group is very complex phenomena that have great consequences on the bridge structure stability. Higher values of scour depth may lead to structure failure and loss of human life. The scour characteristics are strongly depending on the pile arrangement, pile dimension and flow parameters, especially tail water depth. Consequently, the supposed pile characteristics are very crucial in predicting maximum scour depth and length during the design phase. This paper presents the experimental work conducted using physical model as a tool to investigate the effect of the pile arrangement on the resultant scour around pile group compared to the case of single pile. Experiments were carried out under steady clear-water scour conditions. Different pile diameters were tested under various pile group arrangements, and different flow depths. In total, 108 experiments were carried out. It was observed that local scour depth and length decrease with the decrease of the Froude number. The study results show that the normalized local scour depth (d_s/D) is highly affected by the normalized pile spacing ratio (G/D). New physically-based scour equations for practical design purposes were developed for predicting the maximum scour depth and length. Selected data from flume tests were employed to validate the theoretical development and refine the mathematical format of the formula. Parameters for the design equations were determined by combining lab data and field experience to offer a reasonable level of reliability and conservatism, taking into consideration that these relations are limited to the tested experimental data range.

Keywords: Bridge pier, Pile group, Scour around pile, Scour length, Scour depth

1. INTRODUCTION

Pile group bridge pier seems to be more familiar to engineers and researchers to be used due to its low cost compared to the other types. However, the scour mechanism for the pile group is much more complex than that for a single pile. Although local scour is one of the main reasons of failure during service condition, still design of local scour depths are more difficult to be predicted, which makes the estimation of scour depth one of the critical issues during the design phase. Bridge pier scour is an important issue in the safety evaluation of bridges. It is a very complex phenomenon as it is influenced by the many factors of flow, structure and sediment, particularly the complicated vortex and turbulence mechanisms around piers. Padmini and Asis (2009) studied the local scour around vertical piers focusing on its mechanism, prediction and reduction techniques.

The prediction of the local scour depth around single pile and pile group was the focus of different studies long time ago for example: Hannah (1978), investigated scour around two-pile, side-by-side, and tandem arrangement, for different pile spacing, Salim and Jones (1998), found that the scour depth decreases as the spacing between the piles increases. Ashtiani and Beheshti (2006) conducted an experimental study to evaluate the success of some of the commonly used formulas for scour-hole depth prediction.

In general, the scour phenomenon is extremely complex in nature and consequently experimental investigations of the scouring has been limited to the consideration of only certain aspects of the problem where other parameters are assumed to be constant. Many equations based on the experimental data have been developed to estimate the local scour depth around pile. Roberto, et al. (2013) evaluated the behavior of six bridge pier scour depth empirical formulae on the basis of an analytical method. The sensitivity of predicted scour depth was analyzed with respect to the approach flow depth, river bed slope and median sediment size. The local scour around bridge pier pile is affected mainly by the dimensions and arrangement of the pile. The effect of pile group arrangement on local scour was the main objective of the study carried out by Ahmed et al. (2011), using numerical model. Salim and Jones (1998) argued that scour depth decreases as the spacing between piles increases.

The scour depth and length are very important factors in the design phase as an input for the protection measures design. The research about single pile is well covered according to (Breusers and Raudkivi, 1991; Melville and Coleman, 2000). Junke Guo (2013) carried out an experimental investigation on the clear-water scour at singular circular piers in non-cohesive sediment mixtures, with the objective to provide a new pier scour equation based on the understanding of flow–structure–sediment interactions in the USA. Melville (2008) presented a comprehensive description of the process of local scour at bridge piers, where he argued that the observed scour depth at laboratory is reduced in the field. For pile group, little is known about scour (Salim and Jones, 1998; Coleman, 2005); more work is still needed to understand the scour process resulting from the existence of the pile group. Rui Lança et al. (2013) argued that Local scour at pile group is more complex and difficult to predict than that at single piers. Rui Lança et al. (2013) argued that more research efforts seem to be needed as the number of studies reported in the literature on scouring at pile groups is small.

Sheppard et al. (2004) investigated the local scour depth for circular pile under clear water conditions; they tested three pile diameters, three different uniform non-cohesivesediment diameters and a range of flow water depths and flow velocities. The approach flow water depth and Froude number (Fr) are the main flow parameters that affect the scour. The scour depth varies with respect to single pile and pile group arrangement, Ashtiani and Beheshti (2006), found that the scour-hole depth for some cases of pile group increases as much as two times more than its magnitude for the case of single pile. Sumer et al. (2005) executed an experimental work on scour around pile group under steady current with different configurations. Junke Guo (2013) concluded that pier scour results from flow–structure–sediment interactions, and the equilibrium scour depth is determined by the flow–structure and the flow–sediment interactions, where the flow–structure interaction results in a vertical stagnation flow, generating horseshoe vortices at the foot of the pier playing an important role in the formation of maximum equilibrium scour depth.

It is believed that the scour around a solid pier is due to impingement of a down-flow jet along the stagnation line together with a horseshoe vortex created ahead of the pier, Raudkivi (1986), where the velocity of down flow, the size and strength of a horseshoe vortex themselves depend on the size of the scour hole. The horseshoe vortices interact with the down flow, act as a catalyst, increase its strength and bring it towards the pier, Melville (1988).

2. STUDY OBJECTIVES

Although there is a lot of work done to study the complex phenomena of scour around bridge piers and pile group, still more work is needed to get more practical and applicable equations for estimating the developed scour due to construction of hydraulic structures such as bridge. Therefore, the aim of this study is to investigate the impact of the pile group arrangement on the occasioning local scour depth and length. Also, the correlation between the different parameters on the scour parameters needs to be determined using the tool of physical modelling

3. EXPERIMENTAL SETUP AND PROCEDURES

The experimental program was carried out in the 16 m long rectangular flume with horizontal slope hosted at Hydraulics Research Institute (HRI); the flume was of 0.7 m depth and 0.7 m width. The first 11 m of the flume bed is fixed and the total length of the mobile bed is 5 m; the flow rate was controlled by the approaching water depth. The model test program was based on clear water scour condition, where the flow depth in the flume is adjusted by the flab tail gate at the downstream end of the flume and two point gauges fixed on a movable bridge on the flume to measure the flow depth and the scour parameters. The same water level was maintained throughout the experiment by adjusting the tail gate. The d_{50} (0.49 mm) of the bed material was constant for all the test series, the impact of the sediment size is neglected in this study as the effect on the local scour depth occurs only with D/d_{50} <50 based on (Raudkivi and Ettema, 1983; Melville and Chiew, 1999). For all tests, D/d_{50} varies between 50 and 100 which agree with the recommendations of Melville and Sutherland (1988) that D/d_{50} should be more than 25.

108 tests were carried out representing four pile arrangements (Figure 1), the first case is a single pile, the second one is side by side pile group (2*1), the third case is tandem position (1*2) and (1*3) and the last was three piles in triangular arrangement. Three pile diameters of 25.4, 38.1, and 50.8 mm were tested under different normalized spacing ratio (G/D) that varied between zero for single pile case up to 3, where (G) is the pile spacing and (D) is the pile diameter. In this study, experiments were stopped at

the end of each test, where the water is slowly drained to determine the contours of scour hole around the pile and the scour length and width by employing the point gauges. To start a new test, the bed is levelled again to the original status.

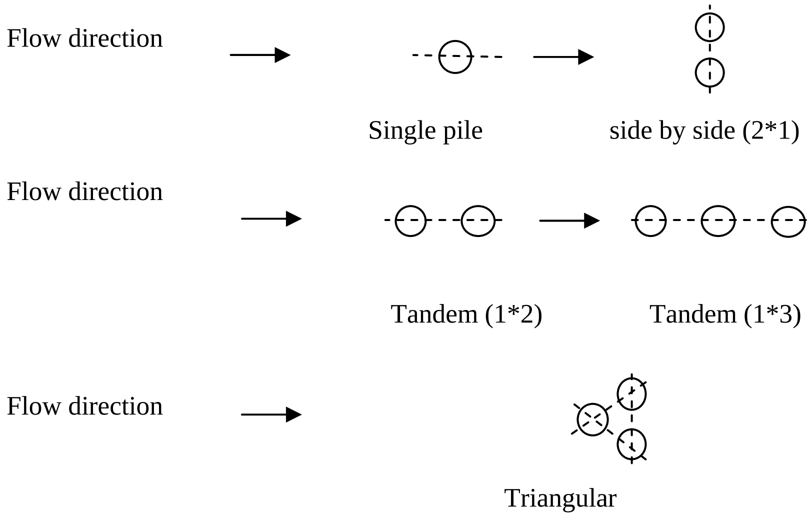


Figure 1: Pile Arrangement

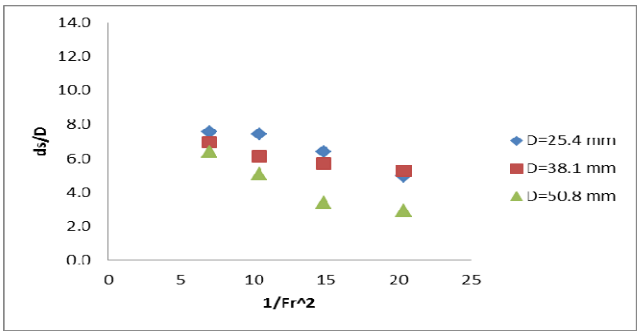
4. EXPERIMENTAL RESULTS

The bridge pier scour parameters resulting from obstructing the flow and the resulting vortices were investigated in this experimental program; three pile arrangements were tested through 108 experiments. This was done for three pile diameters and three pile spacing ratio from 0 to 3. The governing parameters representing the effect of pile diameter and pile arrangement on the developed scour depth and length are represented as the normalized scour depth and normalized pile spacing ratio for the different flow conditions represented by $1/Fr^2$.

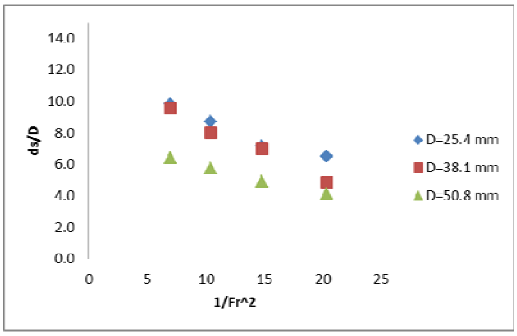
4.1. Effect of Pile Characteristics on the Local Scour Depth

4.1.1 Effect of pile diameter

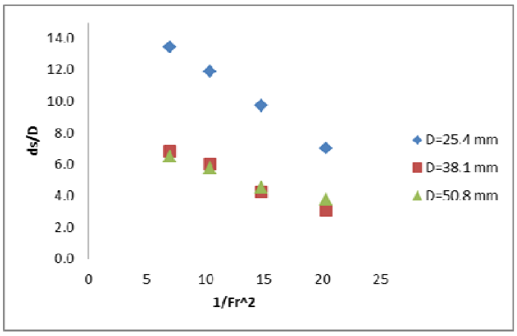
Figure (2) illustrates the impact of the different pile diameter on the developed local scour depth, in general local scour depth decreases with increasing ($1/Fr^2$) for all investigated pile diameters. It was found that maximum scour depth occurs always with smaller diameter for the different pile arrangements under different flow conditions, with the maximum value in the case of tandem (1*2) and G/D= 3 as in Figure (2-b). The minimum scour depth occurred in the case of single pile and D=50.8 mm, Figure (2-a). It could be concluded that increasing the pile diameter reduces the scour depth values.



a) Single Pile

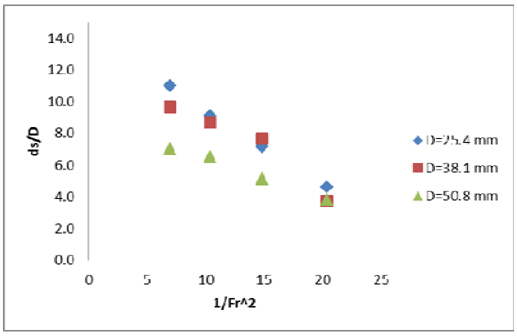


G/D=2

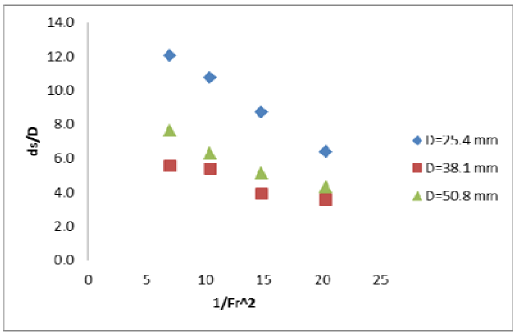


G/D=3

b) Tandem Arrangement (1*2)

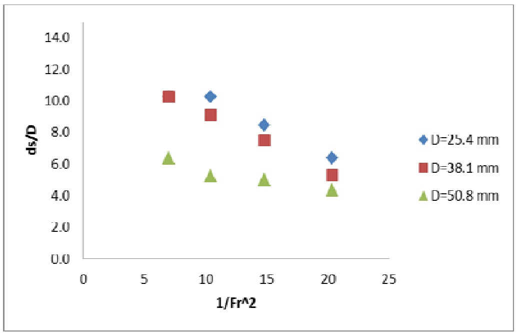


G/D=2

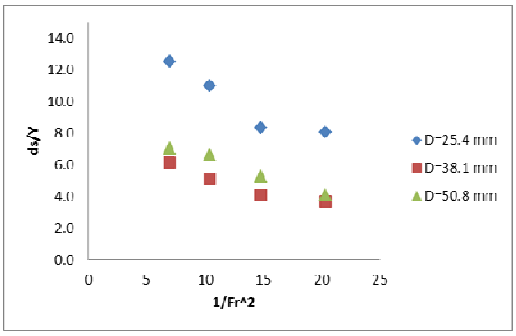


G/D=3

c) Tandem Arrangement (1*3)

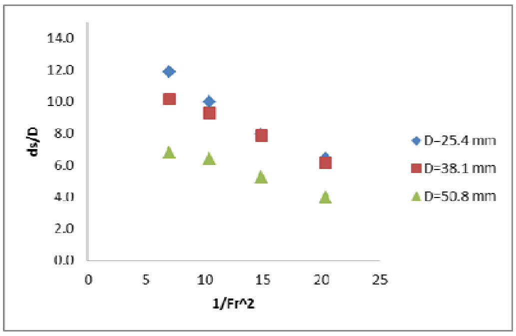


G/D=2

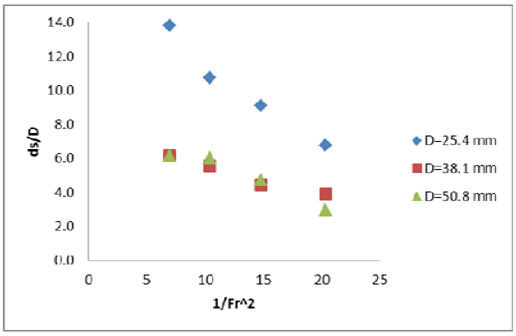


G/D=3

d) Side by Side Arrangement (2*1)



G/D=2



G/D=3

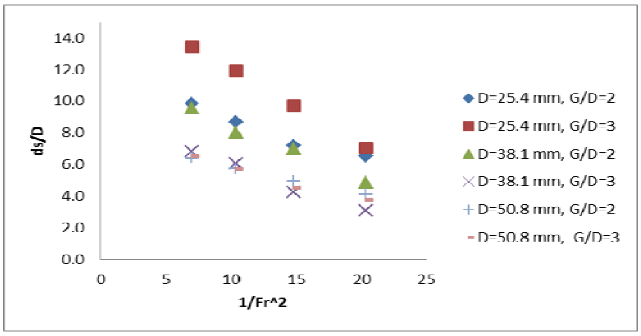
e) Triangular Arrangement

Figure 2: Effect of Pile Diameter on Local Scour Depth

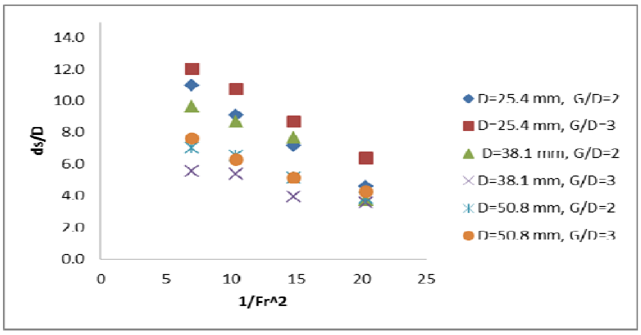
4.1.2 Effect of pile spacing ratio

An important key issue in the pile group design is the pile spacing ratio; it affects very much the developed local scour depth around bridge piers as could be seen in Figure (3). It could be stated that local scour depth decreases with increasing the ($1/Fr^2$) value for all G/D values. It is clear from Figures

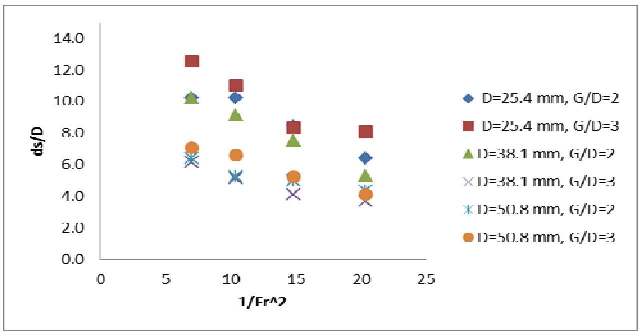
(3a, b, c, d) that scour depth increases with increasing the pile spacing ratio for the same pile diameter. From the results analysis, it was found that for the different flow conditions, the maximum scour occurs with smaller pile diameter and pile spacing ratio of G/D=3 for the different pile arrangement. The minimum developed scour depth was found to be in the case of G/D=3 and pile diameter of 38.1mm for all pile arrangement. Figures (3-a, b, c, d) illustrate that increasing pile diameter with increasing the spacing ration, the scour depth decreases except with smaller diameter.



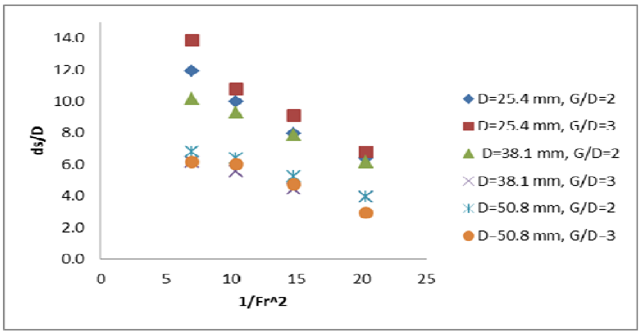
a) Tandem (1*2)



b) Tandem (1*3)



c) Side by Side (2*1)



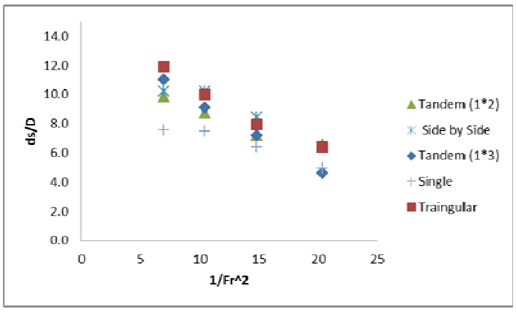
d) Triangular

Figure 3: Effect of Pile Spacing Ratio on Local Scour Depth

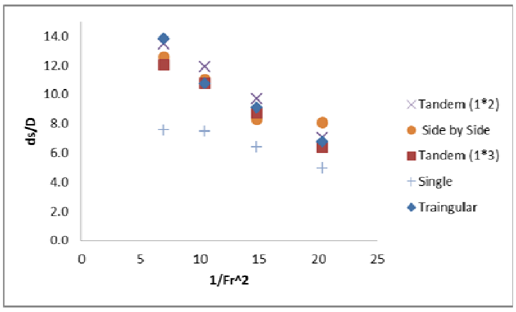
4.1.3 Effect of pile arrangement

Figure (4) illustrates the great impact of pile group arrangement on the resulting local scour depth around the bridge pile or pile group. The impact of the pile arrangement is mainly depends on the pile diameter. It was found that under different pile arrangement, maximum local scour occurs when G/D=3 and tandem (1*2), Figure (4-a), while the minimum developed local scour depth occurs in the case of single pile and with increasing the pile diameter up to 50.8 mm (Figure 4-c).

In general, the scour depth values for all arrangement are greater in case of smaller diameter. Figure (4-a) shows clearly that single pile produce the minimum local scour depth, while the maximum local scour depth occurs in the case of tandem (1*2) and G/D=3. For D=38.1 mm, as in Figure (4-b), the minimum local scour depth occurs with tandem (1*3) and G/D=3, while the maximum values occurs in the case of side by side and G/D=2. With D=50.8 mm, the tandem pile arrangement also causes higher values of local scour depth with G/D=3, while the minimum scour depth occurs with single pile (Figure 4-c).

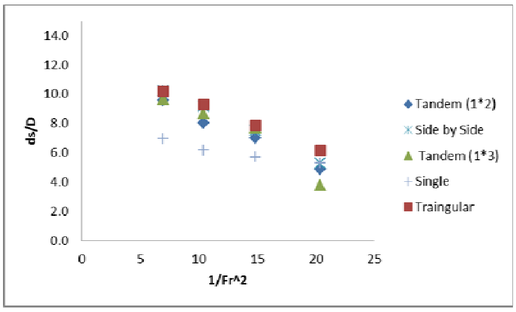


G/D=2

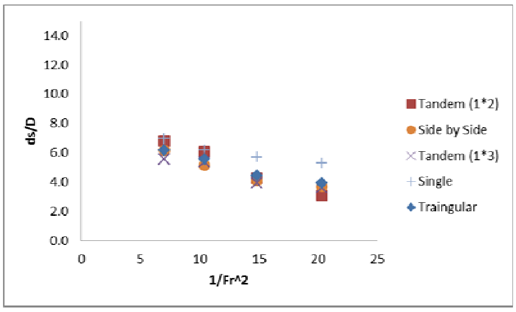


G/D=3

a) Case of D=25.4 mm

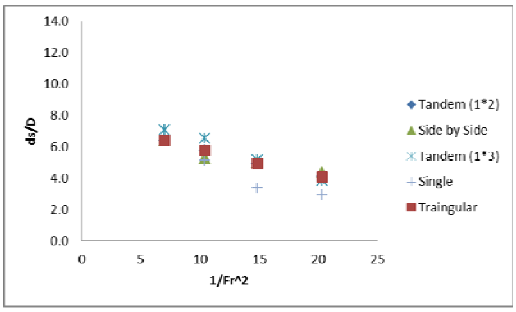


G/D=2

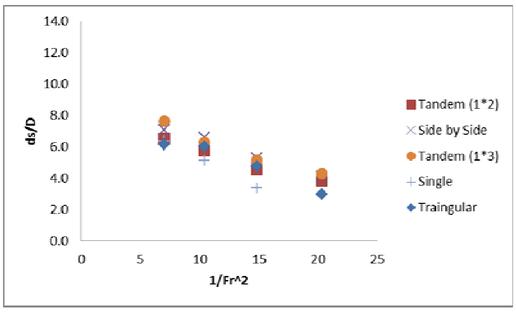


G/D=3

b) Case of D=38.1 mm



G/D=2



G/D=3

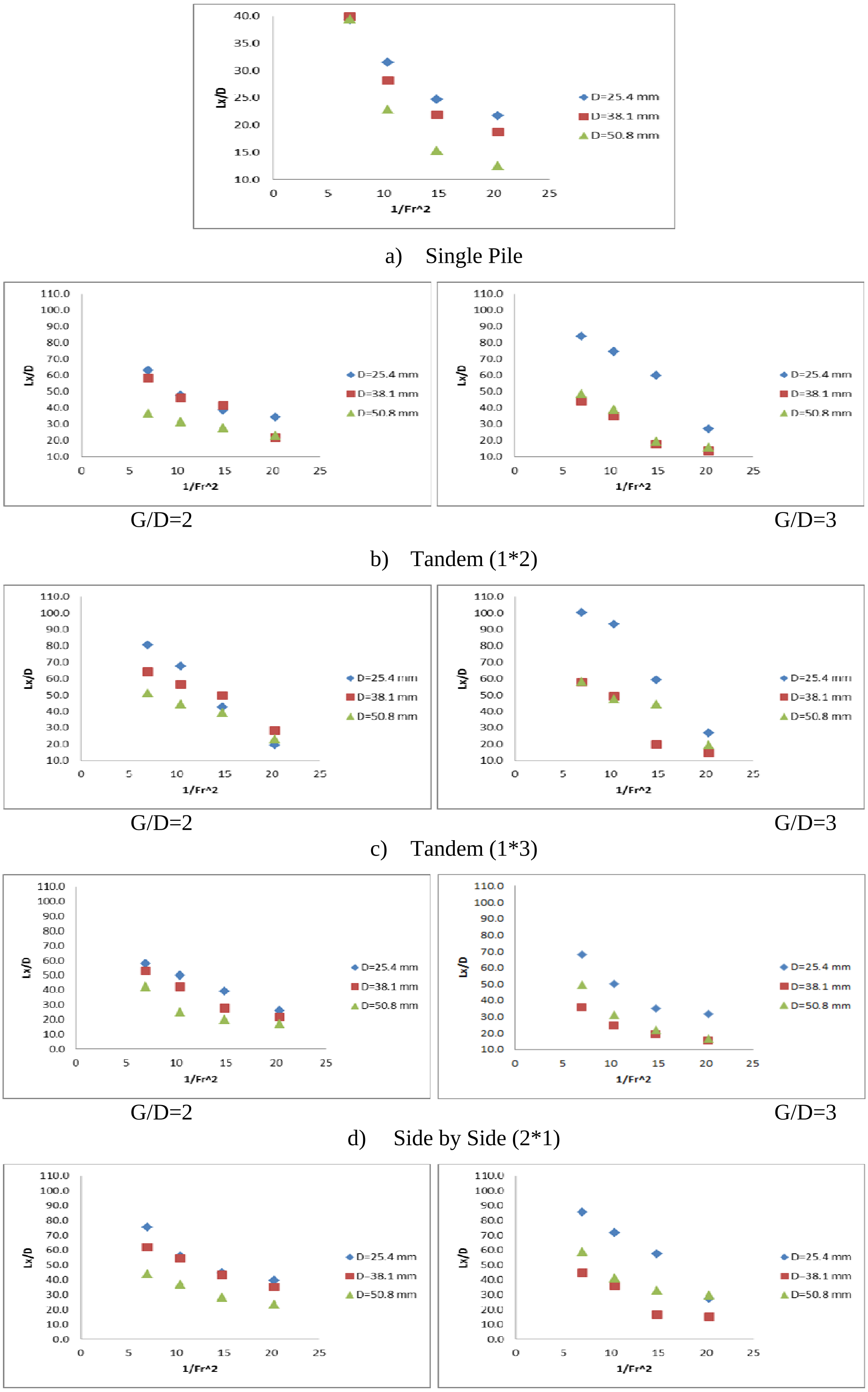
c) Case of D=50.8 mm

Figure 4: Effect of Pile Group Arrangement on Local Scour Depth

4.2. Effect of Pile Characteristics on Local Scour Length

4.2.1. Effect of pile diameter

From the results analysis, it was found that for different pile diameters, the scour length decreases with increasing the value of ($1/Fr^2$) under different pile arrangement. From Figure (5), it is clear that with increasing pile diameter for each arrangement, the scour length decreases. Maximum scour length occurs with smaller pile diameter. The maximum value was found to be in case of Tandem arrangement (1*3) and G/D=3, Figure (5-c). While the minimum scour length was found to occur with single pile and D=50.8mm, Figure (5-a).



a) Single Pile

G/D=2 G/D=3

b) Tandem (1*2)

G/D=2 G/D=3

c) Tandem (1*3)

G/D=2 G/D=3

d) Side by Side (2*1)

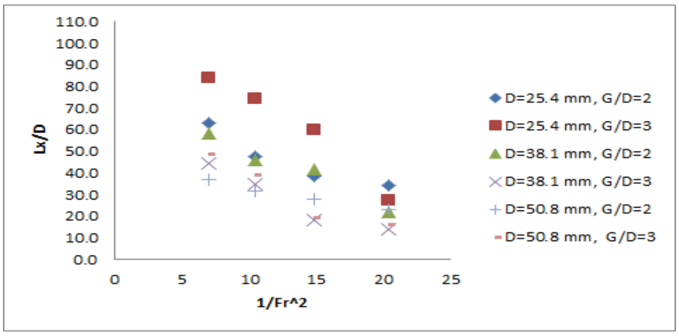
G/D=2 G/D=3

e) Triangular

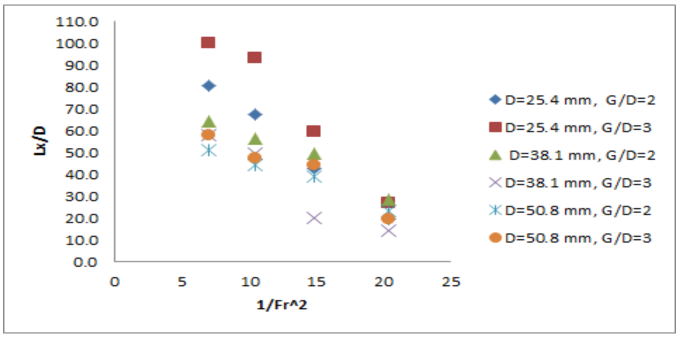
Figure 5: Effect of Pile Diameter on Scour Length

4.2.2. Effect of pile spacing ratio

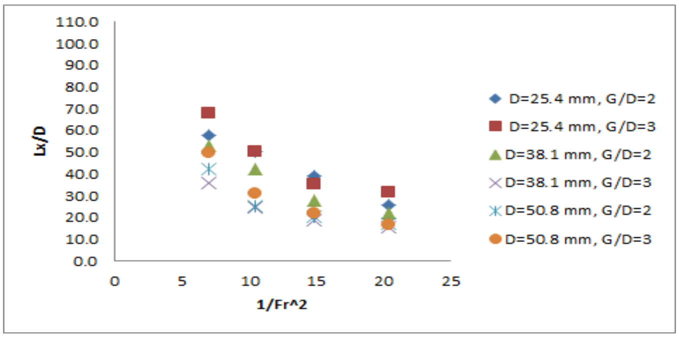
The pile spacing ratio has an excessive effect on the scour length with different pile arrangements, scour length in general decreases with the increase of $1/Fr^2$ values. From elaborating Figure (6), it is clear that the maximum scour length occurs with D=25.4 mm and G/D=3 for the different tested arrangements, while the minimum scour length occurs with D=38.1 mm and G/D=3. Generally it could be concluded that, for the different tested arrangements increasing the pile spacing ratio increases the scour length.



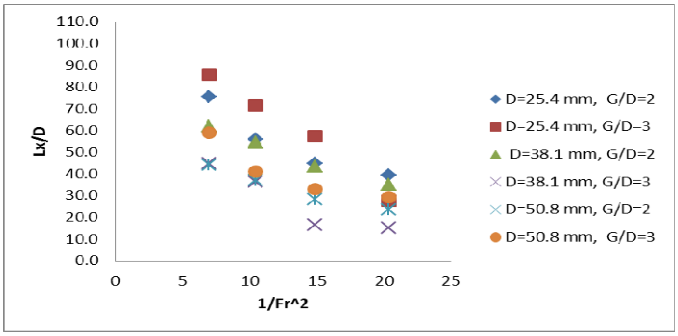
a) Tandem (1*2)



b) Tandem (1*3)



c) Side by Side (2*1)

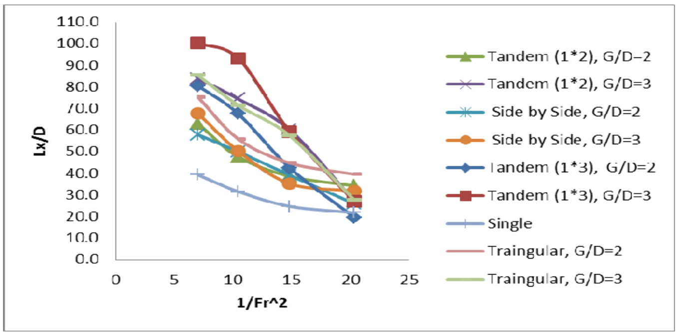


d) Triangular

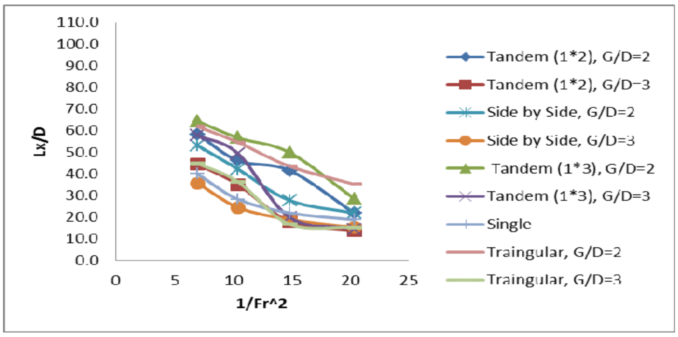
Figure 6: Effect of Pile Spacing Ratio on Scour Length

4.2.3. Effect of pile arrangement

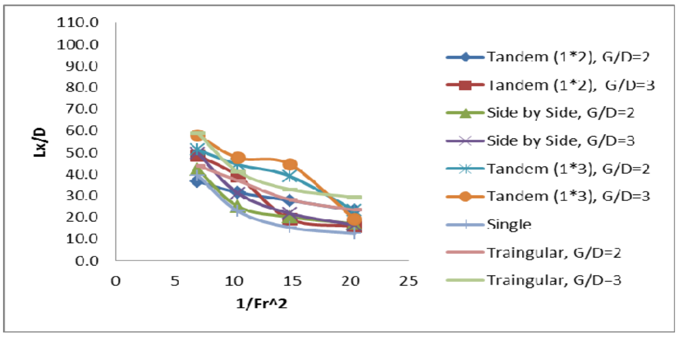
The pile arrangement has a valuable impact on local scour depth for the bridge pier pile group. It was found also from the experimental program that a significant impact on the resulting scour length has been recorded. Figure (7) presents the experiment results, where it was found that scour length decreases with increasing the ($1/Fr^2$) values for the different arrangements of all tested pile diameters. Maximum scour length results from the tandem arrangement with different spacing ratios and with the different pile diameters. The maximum value occurs in the case of D=25.4 mm, Figure (7-a). Almost, for all pile diameters, the minimum scour length occurs in the case of single pile, with a minimum value corresponding to D=50.8 mm, Figure (7-c).



a) Case of D=25.4 mm



b) Case of D=38.1 mm



c) Case of D=50.8 mm

Figure 7: Effect of Pile Arrangement on Scour Length

5. MATHEMATICAL RELATIONS

A dimensional analysis was performed based on regression methods techniques employing the collected experimental data to develop a practical relation describing the influence of the pile characteristics and group arrangements on the resultant maximum local scour depth around bridge piers pile (whether single or group) taking into consideration the different flow conditions. The basis for this study was the local pier scour equation recommended by the Federal Highway Administration (FHwA), Circular HEC–18 (Richardson and Davis, 2001), which hasthe following formulation:

$$S/h = 2.0 K_1 K_2 K_3 K_4 (b/h)^{0.65} (Fr)^{0.43} \quad (1)$$

Where S= scour depth (m); h= flow depth directly upstream of the pier (m); b= pier diameter (m); K_1= shape factor; K_2= correction factor for angle of attack; K_3= correction factor for bed form ; K_4= correction factor for size of bed material; Fr= Froude number.

From the literature and the experimental work done, the maximum local scour depth was found to be a function of different parameters representing the flow and pile characteristics; in the current process, an additional term was included to account for the different pile arrangements impact on the subsequent scour. In this study, the maximum scour depth, d_s is a dependent variable and can be expressed as:

$$d_s = f\,(D, d_{50}, G, n, m, Fr) \qquad (2)$$

Where:

d_s	= local scour depth (m)	
D	= pile diameter (m)	
d_{50}	= bed material nominal diameter (mm)	
G	= pile spacing (m)	
n	= number of pile rows (-)	
m	= number of pile columns (-)	
Fr	= Froude number (-)	

The following mathematical function has been found to fit the local scour data in the clear-water scour conditions under the outlined conditions. The maximum relative scour depth was correlated to the other independent parameters. The presented equation defines the normalized scour depth (d_s/D) as a function of the other parameter, as illustrated below:

$$\frac{d_s}{D} = EXP\left(-1.112\left(\frac{D}{d_{50}}\right)^{\frac{1}{4}} + 0.11\left(\frac{G}{D}\right)^{\frac{1}{4}} + 0.144\left(\frac{m}{n}\right)^{\frac{1}{4}} + 0.298\frac{D}{Y} - 0.044\frac{1}{Fr^2} + 5.14\right) \qquad (3)$$

With R^2 = 0.856

The same principle was applied to predict the maximum scour length corresponding to the maximum scour depth under the different flow condition, and the developed equation is written as:

$$\frac{Lx}{D} = EXP\left(-1.052\left(\frac{D}{d_{50}}\right)^{\frac{1}{4}} + 0.794\left(\frac{G}{D}\right)^{\frac{1}{4}} - 0.564\left(\frac{m}{n}\right)^{\frac{1}{4}} + 0.3\frac{D}{Y} - 0.071\frac{1}{Fr^2} + 7.1\right) \qquad (4)$$

With R^2 = 0.856

The developed regressed equations were validated, where the correlation between observed and simulated values is presented in Figures 8 and 9.

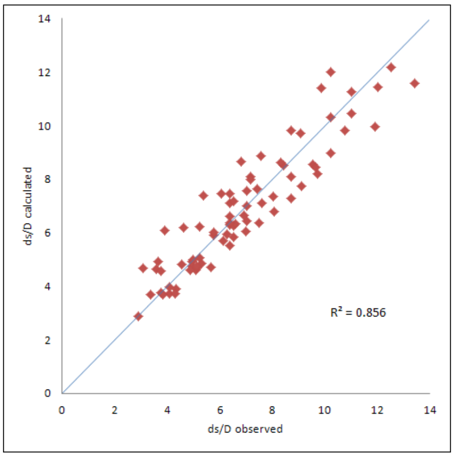


Figure 8: Validation of Scour Depth Equation

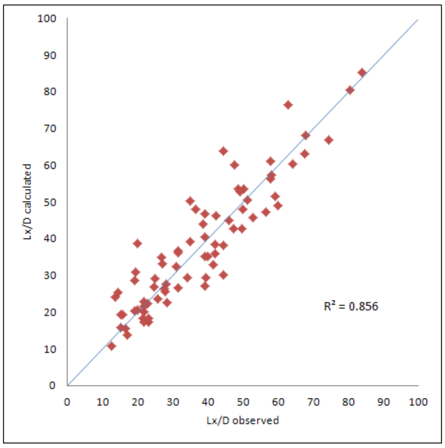


Figure 9: Validation of Scour Length Equation

5.1. Comparison Between Developed and Existing Local Scour Depth Formula

The developed empirical relation was compared to different existing local scour depth formula, where these equations have been used to estimate the maximum local scour depth compared to the new developed equation. Below is a description of the comparable equations.

HEC-CSU EQUATION 2001

The CSU local scour equation, which is described in HEC-18, resulted from a series of studies is expressed by equation (5) as follows:

$$\frac{y_s}{b} = 2K_1K_2K_3K_4\left[\left(\frac{h}{b}\right)^{0.35} Fr^{0.43}\right] \quad (5)$$

Where:

Fr = Froude number (F = V/(gh) $^{0.5}$).

y_s= local scour depth (m)

b= pier width (m)

h= approaching water depth (m)

K_1 = Correction factor for pier shape (K_1 = 1 for circular piers).

K_2 = Correction factor for angle of attack of approach flow (K_2 = 1 for direct approach flow).

K_3 = Correction factor for bed form (K_3 = 1.1 for clear-water scour).

K_4 = Correction factor for armoring (K_4 = 1 for sand bed material).

Equation (5) is rewritten in the form of equation (6) for circular piers under clear-water scour conditions as follows:

$$\frac{y_s}{b^{0.65}h^{0.35}} = 2.2K_4Fr^{0.43} \quad (6)$$

SHEPPARD-MELVILLE EQUATION 2011

The Sheppard-Melville equation for clear-water scour is described by ettema as in Equation (7) as follows:

$$\frac{y_s}{b} = 2.5\,tanh\left[\left(\frac{h}{b}\right)^{0.4}\right] \quad (7)$$

where: b = pier diameter; y_s = the maximum potential scour depth; h = approaching flow depth

Figure (10) presents the estimated normalized scour depth under different flow conditions using the two different previous equations compared to the measured scour depth in the case of side by side arrangement and G/D=2. Figure (11) represents another comparison for single pile and D=50.8 mm. It is clear from the figures that the calculated scour depth using the new developed equation doesn't match with the calculated values using the equations of Sheppard 2011and CSU 2001. This may be due to the difference in data range used in the experimental work for developing of these equations, the experimental conditions and the parameters included in the derivation of such equations. This difference in the calculated depth using the three different equations is in an agreement with previous studies and the literature about the scour around bridge piers and pile group phenomena, where it was found that some of the developed equations are underestimating and others are overestimating. From Figures 10 and 11, it is clear that the new equation produce results that are correlated in different cases with Sheppard equation.

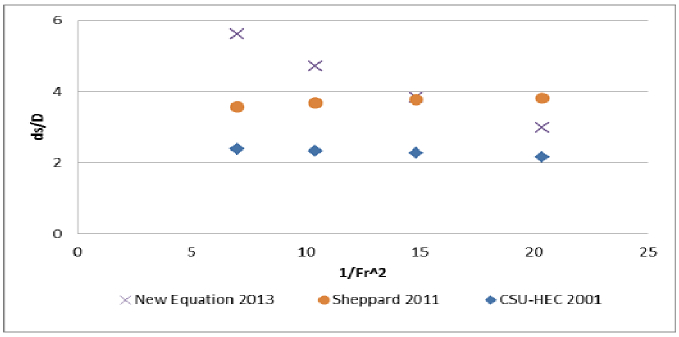


Figure 10: Validation of the New Scour Depth Equation with Previous Equations, Case of Side by side, G/D=2, D=50.8 mm

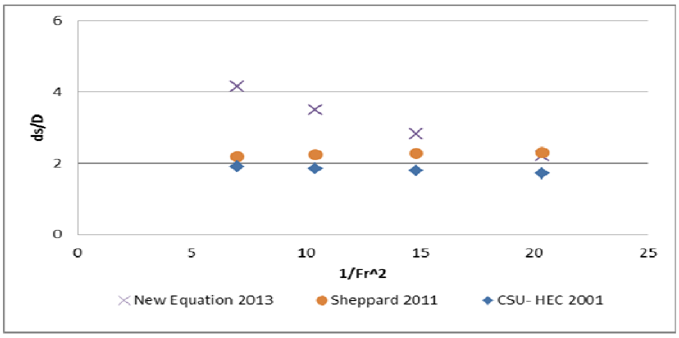


Figure 11: Validation of the New Scour Depth Equation with Previous Equations, Case of Single Pile and D=50.8 mm

6. CONCLUSIONS AND RECOMMENDATIONS

6.1. Conclusion

This paper presents an experimental work employing physical model techniques to assess the impact of the bridge pier pile group arrangements on the local scour parameters. The study results show the high impact of the pile spacing ratio on the developed local scour depth and the corresponding scour length. It was also found that the pile diameter affects greatly the resulting local scour. Empirical relations were developed for stable scour hole in dimensionless method using regression analysis, which could help in predicting the relative maximum scour parameters. The results also showed a significant conformity between estimated and observed data which recommends an acceptable level of accuracy of the proposed equations within the data limitation. From the study results and analysis, the following conclusions may be driven out:

- Flow conditions, represented by Froude number (Fr = 0.222 to 0.379) have a tremendous effect on the developed scour parameters; the scour depth and length decreases with the decrease of the Froude number.
- Increasing the pile diameter reduces the local scour depth and scour length values.
- Increasing the spacing ratio increases the local scour depth and scour length for the different pile arrangements, for the same pile diameter.
- Increasing pile diameter with increasing the spacing ratio reduces the scour depth except with smaller pile diameter.
- The scour depth values are higher in the case of small pile diameter with different pile arrangements.
- Single pile results in minimum scour length.

- The minimum scour depth occurs in the case of single pile and pile diameter of 50.8 mm, while maximum scour depth happens in the case of G/D=3 and tandem (1*2) for all tested pile diameters.
- The maximum scour length occurs in the case of tandem arrangement for different spacing ratio and for the all tested pile diameter.
- The developed regressed relation between the scour parameters and the independent variables shows high correlation and it shows high level of confidence, with correlation coefficient, R^2 =0.856.
- The new predicted scour depth equation was validated using the experimental data.

6.2. Recommendations

From the study results and conclusion, it is recommended to test the developed practical relation in the prototype; the following recommendations can be given for future research work:

- Investigate the sediment size and flow angle effects on the local scour parameters.
- The triangular pile arrangement still needs more work to include different piles orientation and to develop a special relation for this pile arrangement.
- Further studies are needed to expand the applicability of the new equation.

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7. NOTATIONS

D	pile diameter (m)
d_s	local scour depth (m)
L_x	local scour length (m)
d_{50}	bed material nominal diameter (mm)
G	pile spacing (m)
G/D	pile spacing Ratio (-)
d_s/D	normalized local scour depth (-)
d_s/Lx	normalized local scour length (-)
n	number of pile rows (-)
m	number of pile columns (-)
Fr	Froude number, $V/(gh)^{0.5}$ (-)
V	mean velocity of flow directly upstream of the pier (m/s)
g	acceleration gravity (m/s^2)
h	flow depth directly upstream of the pier (m)
Y	tail water depth (m)
y_s	local scour depth (m)
S	local scour depth (m)
b	pier width (m)
K1	correction factor for pier nose shape
K2	correction factor for angle of attack
K3	correction factor for bed condition
K4	correction factor for bed armouring and bed material
R^2	correlation coefficient

8. ACKNOWLEDGEMENT

This research was done in the premises of the Hydraulics Research Institute (HRI) Delta Barrages, Egypt. The author would like to thank the management team of the institute. The author is also grateful for the HRI technician staff for their great efforts in executing and operating the physical model used for this study.

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