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A Parametric Study on the Interaction factors of Pile-Raft System

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Abstract

Traditionally, the interaction factors including pile-soil-raft and pile-soil-pile in pile-raft system are often ignored to simplify the analysis that leads to unsafe and inadequate designs. In addition, the pile-raft system involves interaction with soil which makes it complex to analyze. The interaction depends on many geometrical and strength factors: including, modulus of elasticity of soil (E), Poisson's ratio (ν), spacing/diameter (s/d) ratio, length of piles, geometry of raft etc. To investigate the effect of these parameters in the design of pile raft system, we proposed interaction charts for pile-raft system. A series of 3D finite element analysis were performed and effect of parameters was studied. It has been found that there is a possible interaction between pile, soil, and raft that has effect on the design of pile-raft system. From the developed charts, the results clearly highlighted that the pile-soil-pile interaction decreases with increasing s/d ratio, and soils with high modulus of elasticity are more sensitive to variation of interaction factors between the piles of a pile-raft system. Furthermore, increasing the length of pile enhances the interaction between pile and soil while increase s/d decreases the interaction factor. It is concluded from the parametric study that the designers should consider the effect of interaction factors in the design of the pile-raft system.

Keywords: Interaction factors, Settlement, and finite element software.

1. Introduction

There is an increasing trend of using piled raft foundation system to transfer huge structure loads especially in case of high-rise buildings. In such foundation, the role of piles in reducing the settlement and differential settlement is very important and thus making design very economical. Sometimes, during the design stage of piles, under the design loads, they are subjected to yield. So, in such design cases, controlled settlements in piled raft foundation system becomes responsible in taking additional loads even though the pile load capacity exceeded. So, it becomes very critical to determine foundation settlement and hence it is utmost necessary for the designer to take into account the piles and raft role in combination as well as the interaction effect between their components.

The response of piled raft system is highly dependent on the interaction factors which exist between their components like pile to pile, pile to raft and pile to soil (Long 1993; Katzenbach et al. 2000). Iinteraction factor is defined as the additional settlement caused by loaded adjacent pile under load to the settlement of pile under its own load. The piled raft foundation design will become highly conservative if the imposed load carried by the system assumed to be only resisted by piles without considering the contribution of raft. On the other hand, if the interaction effect between piled raft components is not clearly identified in designing the load carrying capacity of piles and raft, then the design of such system may not be conservative. So, it is utmost necessary to consider the effect of interaction factors in the design process of piled raft foundation and should be clearly identified.

The load carrying mechanism of piled raft becomes highly complex due to the interaction effect as it develops when the stress and displacement zone of both raft and piles overlapps each other. (Katzenbach et al. 2000) categorized interaction effects between pile raft components into three as pile to raft, raft to pile and pile to pile. The interaction between pile to pile is also known as group piles effect. The interaction between pile to raft and raft to pile yield varying load response than those of pile groups and unpiled rafts. In case of pile rafts, the load carrying capacity of piles can be made larger than that of group piles because of raft to pile interaction (Long, 993).

According to Katzenbach et al. 2000, there is one positive and one negative effect of raft-pile interaction on piles loading response. The positive aspect is that due to the raft pressure, the confining stresses arise within the soil mass which ultimately increase the skin friction of pile. But this effect is highly dependent on the location of piles in the raft as well as the stress level. In case of high stresses due to the raft pressure, the soil below the raft may reach the ultimate capacity and remain at the failure leading to the plastic flows of soil and decrease in the available shear stress at the interface of soil-pile. on the other hand, one of the negative aspects is reduction in the relative displacement of surrounding soils and the piles which ultimately result in the reduction in the mobilization of the skin friction (Han and Ye 2006).

(Liu et al. 1985; Reul and Randolph 2003; de Sanctis and Mandolini 2006) carried out extensive studies on the effects of interaction factors on pile raft foundation response to loads. Based on the pile raft geometric configuration, Liu et al. (1985) carried out some field load tests and suggested the interaction factor between raft-pile-soil. There is some finite element analysis performed by Horikoshi and Randolph (1998) and they proposed that interaction between pile raft components is the function of stiffness of piles and raft and pile raft configuration. Similar to the settlements specified for the performance-based design of foundation, It is very important to take into account the settlement based interaction factors effect for varying load carrying mechanisms. The interaction factors can be clearly examined from the Fig 1 below.

In this study, various factors are investigated through finite element analysis program, Plaxis 3D that effect the interaction effect between pile raft components embedded in clayey soil, including stiffness of the soil, poison ratio of the soil, length of piles and spacing to diameter (s/d) ratio of piles. Various interaction effects explained as above are reviewed from the literature and the series of numerical analysis on piled raft models are conducted by varying the prescribed parameters to see that how the interaction effects vary. And finally, based on the results obtained, the detailed characteristics of interaction factors effects are discussed in detail.

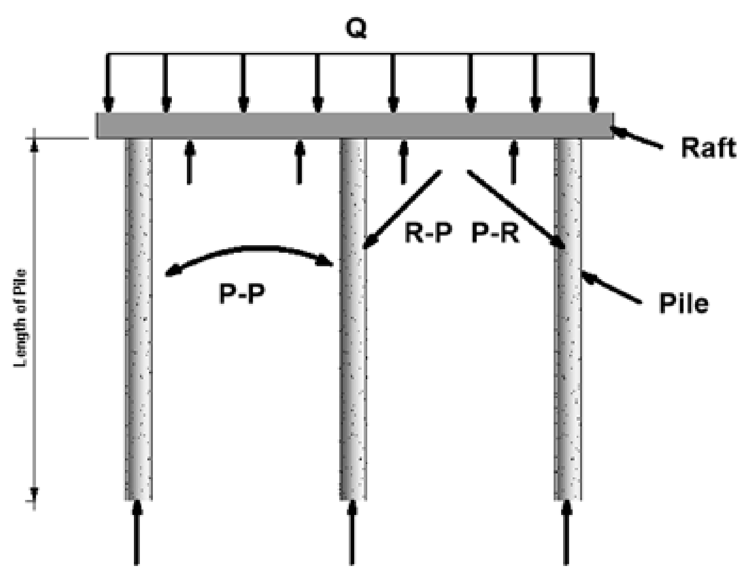

Fig. No. 1 Pile-Soil-Pile 1 and Pile-Soil-Raft Interaction

2. Methodology

In this research work, numerical analysis is carried out using Plaxis 3D. The soil, piles and raft are modeled accordingly and the parameters is assigned to each one. The soil used is a clayey soil having unsaturated unit weight of 18 KN/m3 and saturated unit weight of 20 KN/m3. The soil model is selected so far is the clayey soil because in such type of soils, the interaction effect dominates. These unit weights are selected based on the literature review which comes under the acceptable range. The other properties include angle of internal friction selection as 100. The poisson ratio are varied between 0.3 and 0.5. The cohesion for this soil is taken as 30 KN/m2. The soil model with respect to dimension is selected such that to limit the stress within the soil mass and avoid the boundary crossing by such effects. The stiffness of soil varied from 30MPa to 80MPa this is because, to utilize the full capacity of raft, the soil should be stiff. The soil is modeled as Mohar Columb model but for validation with Boussinesq equation, few models are analyzed with elastic properties so as to best fit the criteria of elasticity for analytical and equation. The models are analyzed under same pressure and varying s/d ratios, lengths of piles, stiffness of soil and poisson ratio of soil. The results obtained from the relevant models are plotted for pile-soil-pile interaction and pile-soil-raft interaction which can be seen from the relevant sections. The steps involve in creating and analyzing the model are best illustrated from the figure-2 below.

2.1 Model validation

In order to validate the elastic deformation property of PLAXIS 3D, the vertical stress distribution in a semi-infinite, homogeneous and isotropic soil mass under a uniform square pressure is studied through both numerical and analytical methods. The results of numerical model in PLAXIS 3D and Boussinesq equation are compared and some interpretations are made.

In PLAXIS, modeling is done in the same way as done for actual model in above case. Soil properties used are the same as above with the same analysis methods. Dimensions of model are 10x10 m with a load intensity of 100KN/m2. For analysis, a concrete cube of dimension 2 x 2 x 5 m is placed on the soil mass for load application and four points at different places are analyzed through both methods. In PLAXIS, this cube is divided into very fine elements which leads to fine meshing as compared to the rest of the model.

Similarly, Boussinesq equation shown below is used to calculate vertical stresses at those stress points.

Vertical Stress = Q x IN,

Where Q = intensity of load over rectangular area

IN = Influence factor,

To compare the results, we have developed table 1 and a bar chart shown in figure 3. The vertical stress calculated through PLAXIS 3D and Boussinesq are well agreement as shown by percentage error ranging from 0.06 % to 3.35%.

2.2 Pile-Soil-Pile Interaction

Importance of interaction factor in analysis and design of pile-raft foundation is clear from the above discussion. Poulos and Davis [1], determined this factor by using below formula:

$$\alpha = \frac{\Delta W}{W}$$

Where, ΔW is the additional settlement due to adjacent loaded pile and W is the original settlement due to under its own load.

Settlement of pile and adjacent pile are calculated by using finite element software PLAXIS 3D. For this soil is modeled in PLAXIS 3D software and assigned properties of soil are listed in table 2. Clayey soil is selected because soil structure interaction is active due to its deformation properties. Properties of pile used are listed in table 3.

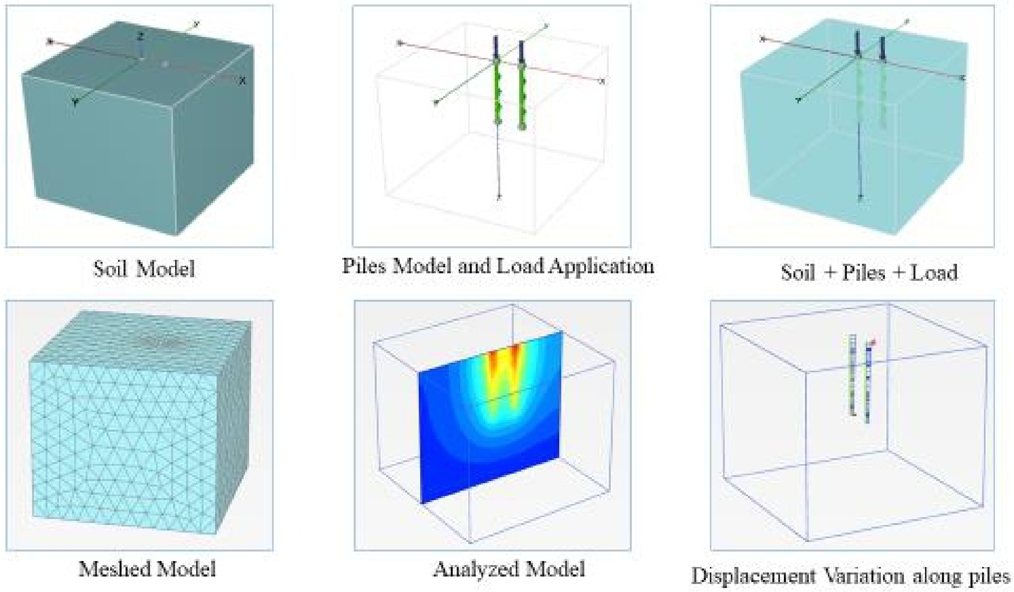

Fig. 1 Model construction for analysis in Plaxis 3D

Table. 1 Vertical stress comparison through Boussinesq Eq. and PLAXIS 3D

Total vertical stress including overburden pressure (KN/m^2)			%Difference
Location	Boussinesq Eq.	PLAXIS 3D	
Point-1	106	103.8	2.08
Point-2	107.16	106.7	0.43
Point-3	68.7	71	-3.35
Point-4	106.56	106.5	0.06

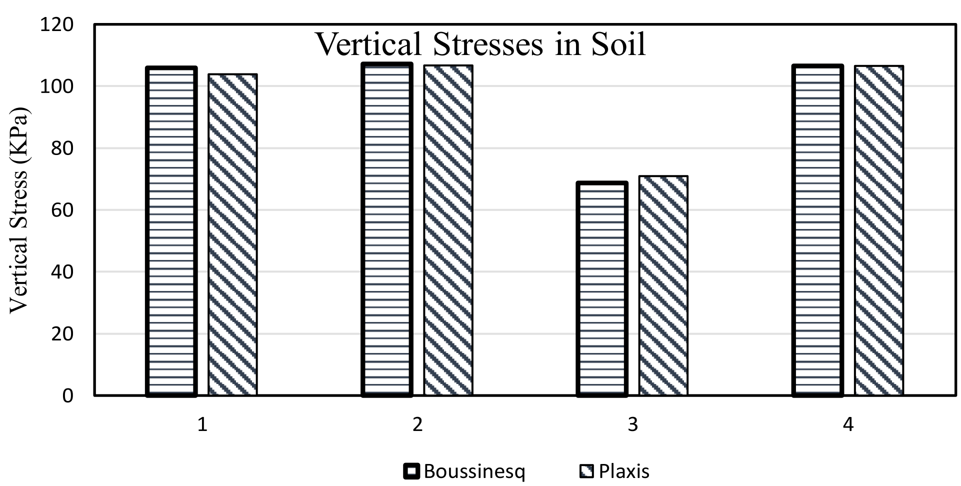

Fig. 3 Comparison of vertical stress obtained through PLAXIS 3D and Boussinesq Equation

As already discussed, pile-soil-pile interaction depends on many factors such as modulus of elasticity of soil, length of pile, Poisson's ratio and spacing between piles. So, in this study soil modulus of elasticity is varied from 30 MPa to 80 MPa and different charts are developed for varying spacing. Similarly, length of piles is varied from 10m to 40m with an increment of 5 m and graphs are developed for different modulus of elasticity, which shows the length variation along X-axis and Interaction factor along Y-axis. Study on Poisson's ratio is also carried out for 0.3 and 0.5 with varying modulus of elasticity.

To check variation of interaction factor with s/d (spacing between piles to pile diameter ratio) for different modulus of elasticity of soil, soil is modeled in software shown in figure 4 and its properties are listed in table 2. As discussed, previous pile-soil-pile interaction depends on modulus of elasticity and s/d. So, analysis is done by increasing s/d ratio for different modulus of elasticity of soil. Figure 6 shows the variation of interaction factors with s/d ratio for different modulus of elasticity of soil. It can be seen clearly from the charts that increase in s/d causes a decrease in interaction between piles showing inverse relationship. Reason for the decrease in interaction between piles is less overlapping area of pressure of two piles which we call pressure bulb. Figure 5 shows the pressure bulb of piles and their interference which leads to influence their load carrying capacity through interaction and hence increase settlement of piles. Also piles with spacing of 4m having more overlapping area than piles with 7m and hence their interaction factor is more so their settlement will be more. Similarly soil with high modulus of elasticity have more interaction affect compared to low soil modulus of elasticity.

Also, interaction factors depend upon the length of pile, because these pressure bulbs are influenced by the length of piles. For this length of piles are varied from 10 m to 40 m with an increment of 5 m while pile spacing was kept constant at 2 m. Pile and soil properties selected for this study is shown in table 2 and 3. Length of piles are varied with different modulus of elasticity of soil i.e., 30 MPa and 60 MPa and results are shown in figure 7. It is concluded from the graph that by increasing pile length, interaction factors between piles increases at constant spacing and the reason is overlapping of pressure bulbs up to much length.

Table 2. Model Soil Properties

Type of soil	**Clayey soil**
Material model	Mohr Coulomb
Unsaturated unit weight	18 [kN/m^3]
Saturated unit weight	20 [kN/m^3]
Modulus of elasticity	30-80 MPa [varying]
Angle of internal friction	10 ^{o}
Poisson’s ratio	0.3 and 0.5
Cohesion	30 [kN/m^2]
Dimension	(50x50x50) m

Table 3. Model Pile Properties

Modulus of elasticity	3.000×10^6 kN/m^2
Diameter	1.000 m
Length of Pile	Varying
Spacing between piles	Varying

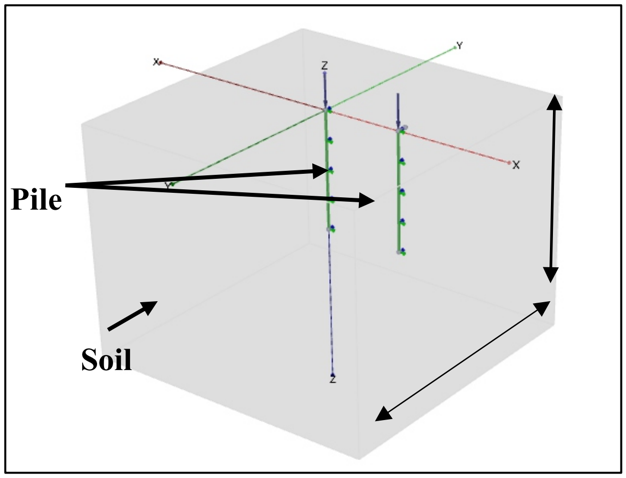

Fig. 4 Soil Model in PLAXIS 3D software

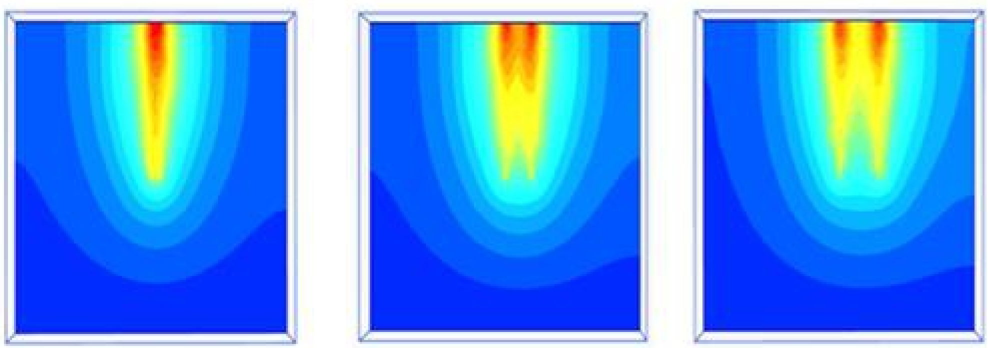

Fig. 5 (a) shows overlap of pressure bulb when piles are at distance of 2m (b) shows overlap of pressure bulb when spacing is 6m (c) shows overlap of pressure bulb when spacing is 9m between piles

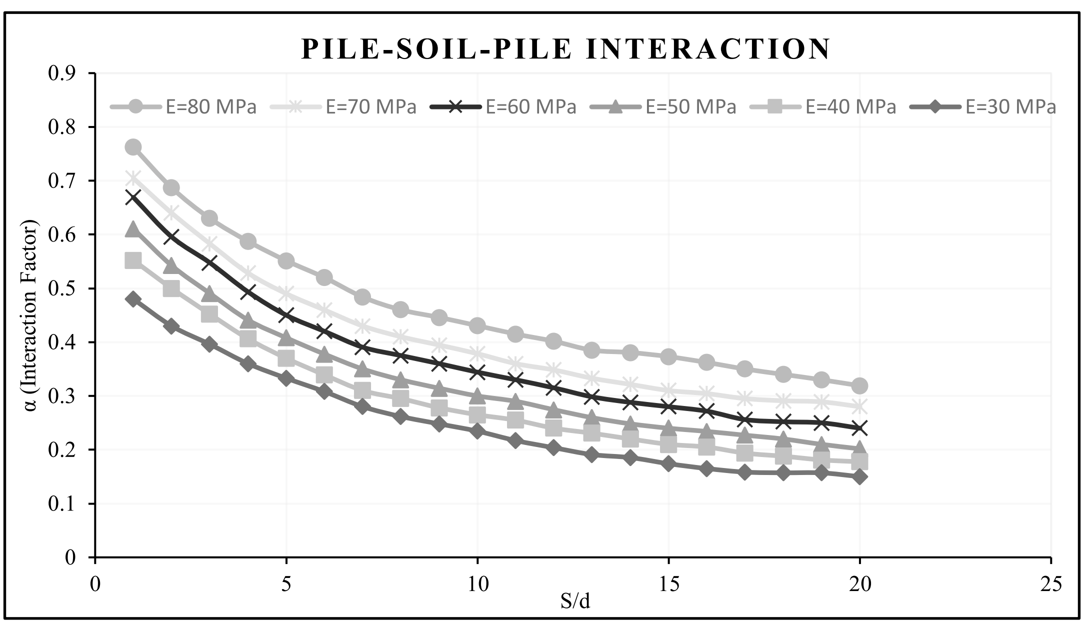

Fig. 6. Comparison of Interaction factor for varying E, and s/d

Poisson's ratio of soil is the most important factor that show the behavior how it compresses or elongate. Pile-soil-pile interaction factor depends also on Poisson's ratio of soil as it plays important role in load transfer among pile-raft components. For this study Poisson's ratio is varied between 0.3 and 0.5 for different s/d ratio and soil modulus of elasticity as shown in figure 8 and 9. It is concluded from figure 8 that interaction between piles decreases with increase spacing between piles but soil with more Poisson's ratio have less interaction between piles. Figure 9 shows same behavior but for another modulus of elasticity. By comparing figure 8 and 9, it can be concluded that soil with greater stiffness have more interaction compare to less stiff soil. When Interaction between piles is more it mean it will have more settlement so high Poisson's ratio mean more percentage of lateral displacement than vertical displacement (Settlement). So high Poisson's ratio will have less vertical settlement and hence less interaction factor as shown in below graphs.

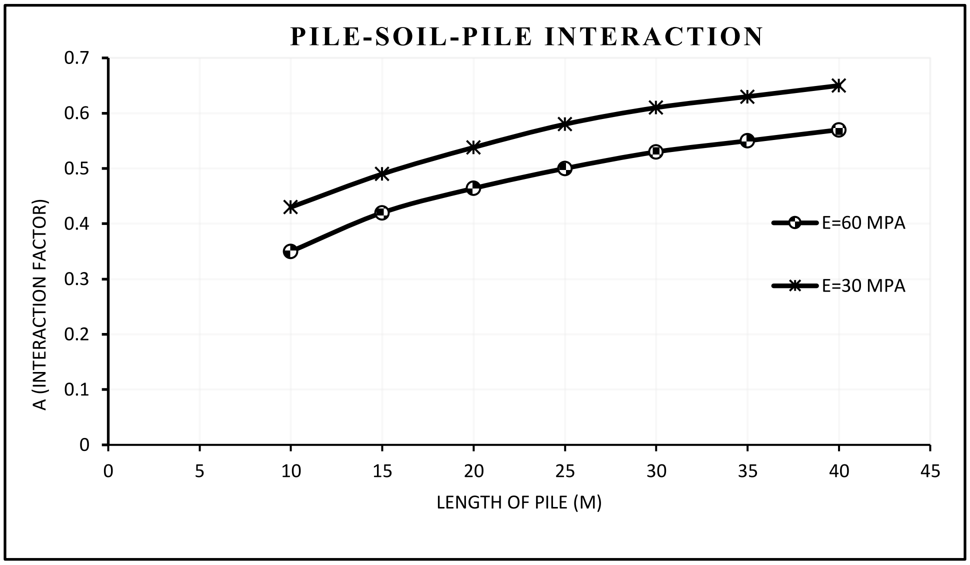

Fig. 7 Comparison of Interaction factor for varying length and E

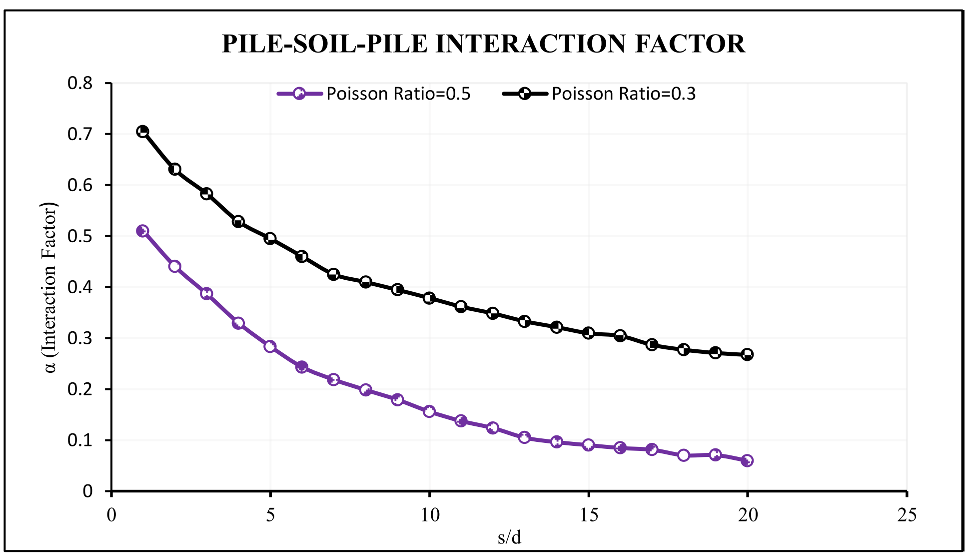

Fig. 8 Variation of s/d for Poisson's ratio of 0.3 and 0.5 at E= 70 MPa

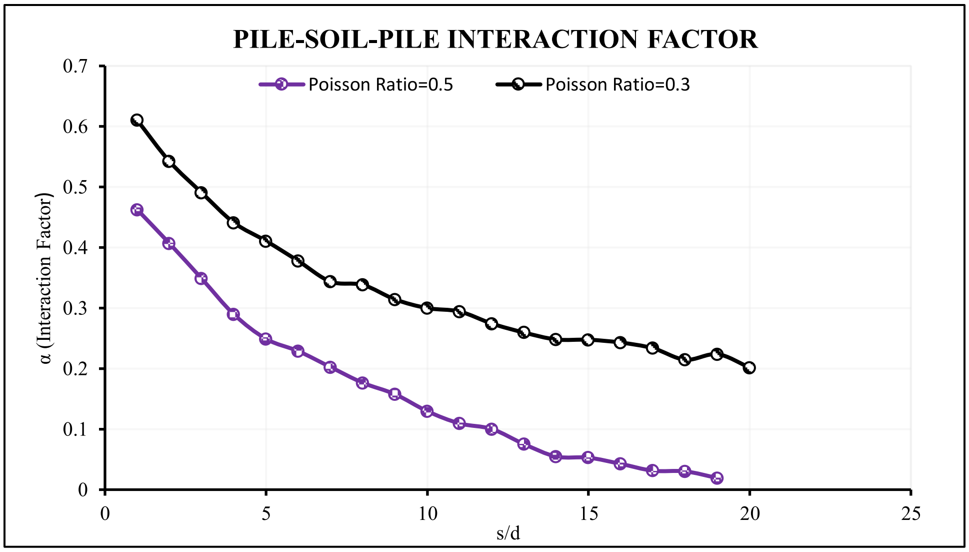

Fig. 9 Variation of s/d for Poisson's ratio of 0.3 and 0.5 at E= 50 MPa

2.3 Pile-Soil-Raft Interaction Factors

Pile-soil-raft interaction exist among pile-raft components which is defined as increase in settlement of raft caused by pile under raft. Randolph developed an equation for finding out this interaction which is based on increase in settlement of circular raft due to pile below that raft. Randolph equation is shown below for finding interaction factor:

$$\alpha_{rp} = 1 - \frac{ln\left(\frac{r_r}{r_p}\right)}{ln\left(\frac{2r_m}{r_p}\right)}$$

Where rr is diameter of raft, rp is the diameter of pile, rm= 2.5ρ (1-ύ), ρ is the degree of homogeneity of beneath soil, ύ is the Poisson's ratio of soil.

Randolph developed the above equation for constant soil modulus of elasticity that's why he published another equation to find out interaction by incorporating stiffness of soil at the pile top, pile tip and also along the pile length.

$$\alpha_{rp} = 1 - \frac{ln\left(\frac{r_r}{r_p}\right)}{ln\left(\frac{r_m}{r_p}\right)}$$

$$r_m = 0.25 + L\zeta[2.5\rho(1-\nu) - 0.25]$$

$$\zeta = {}^{E_{sl}}/_{E_{sb}}, \rho = {}^{E_{sav}}/_{E_{sl}}$$

Here rr is radius of raft which is equal to area of raft divided by number of piles which is shown in below figure 7.

Where Esl is the soil modulus of elasticity at tip level, Esb is soil modulus of elasticity below tip level at hard stratum, Esav is soil modulus of elasticity along the pile length which is shown in figure 7, and L = length of pile.

Pile-soil-raft interaction depend upon many factors such as length of piles, diameter of piles, spacing between piles, number of piles, modulus of elasticity of soil, and area of raft. For this parametric study is done by varying length of piles, diameter of piles and number of piles at constant area of raft. Properties of soil, pile and raft, used in simulation model, are given in table 4. Interaction factors are calculated at varies length and with varying spacing/diameter and graphs are developed.

Fgure 11 shows varying interaction factor with s/d for different length of piles. It is concluded from the above figure that increasing the s/d ratio will cause a decrease in the interaction factor between pile and raft. Also piles with more length have high interaction factor than with small length.

Figure 12 shows variation of interaction factor with varying s/d ratio for different length keeping number of piles is 16. It is concluded that with increasing spacing between piles, interaction factors between pile and raft are decreasing. But interaction factor for 40 m pile is more than 35 m, which shows that piles with more length have high interactions between raft and piles.

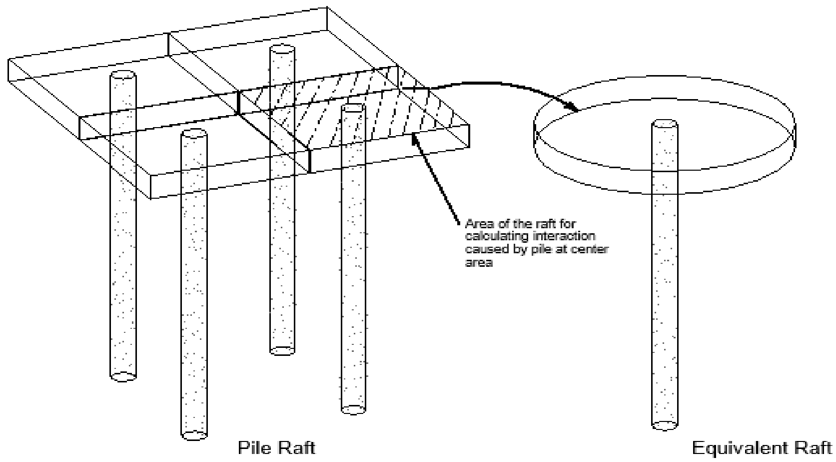

Fig. 10 Equivalent raft Concept.

Table 4. Material Properties

Modulus of elasticity of soil at head (E_{sl})	50 MPa
Modulus of elasticity of soil at tip (E_{sb})	50 MPa
Modulus of elasticity of soil along the length of pile (E_{sav})	50 MPa
Poisson's ration of soil	0.45
Degree of homogeneity	1
Length of raft	20 m
Width of raft	20 m

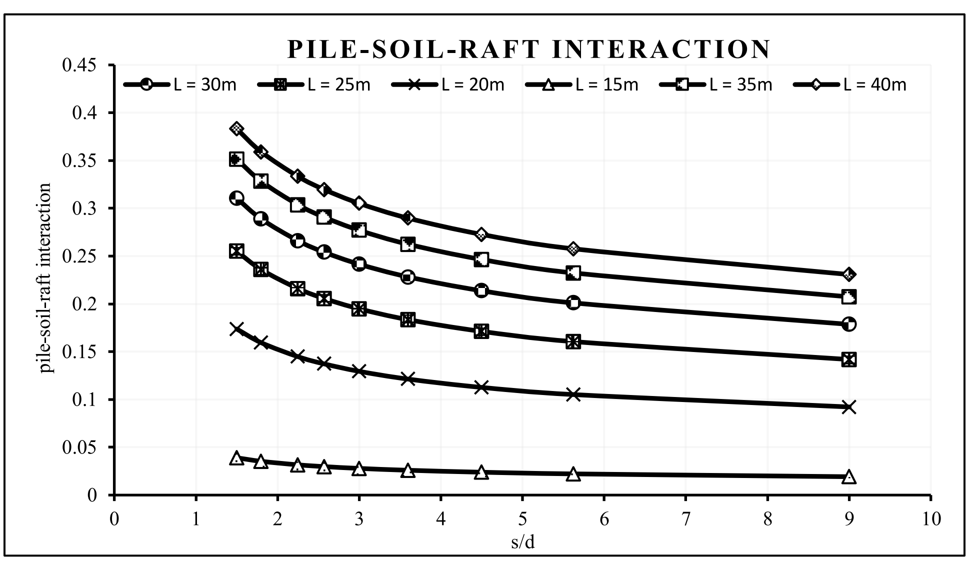

Fig. 11 Interaction factor rp with s/d for different length

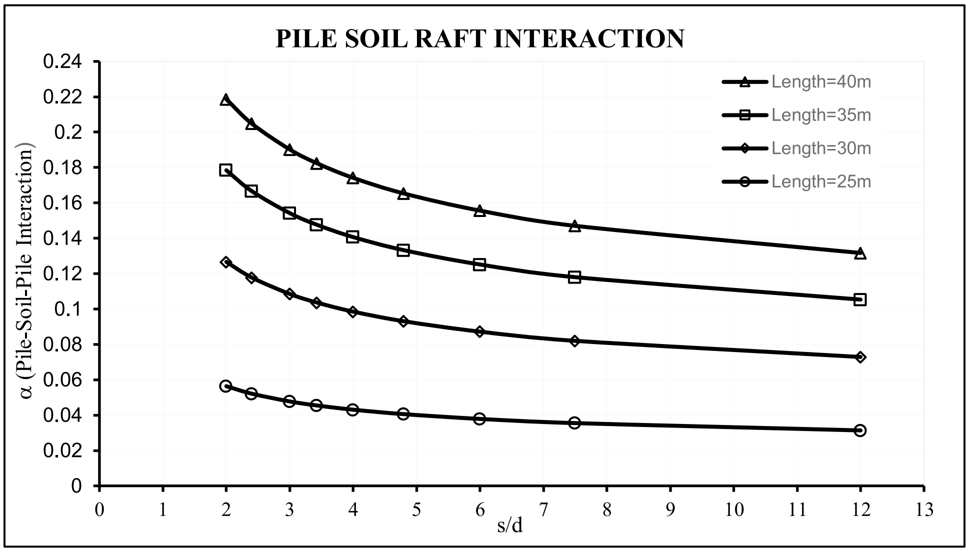

Fig. 12 Variation of Interaction factor with s/d for different length

3. Conclusion

It is concluded that interaction factors among pile-raft components are greatly affected by various parameters. Spacing/ diameter ratio has inverse relation with interaction factor between piles as pile-soil-pile interaction factor decreases with increasing spacing/diameter ratio, which means that neighboring piles have less effect on the pile settlement. Also, length of pile has direct influence on interaction factors between piles (pile-soil-pile) as piles with more length will have more pressure bulb overlap, thus greatly increasing settlement of each other. Similarly, Poisson's ratio has inverse relation and it shows that soil with small Poisson's ratio will have more interaction factor because of more percentage of vertical settlement. It can also be concluded that pile-soil-pile interaction is greater from pile-soil-raft interaction. It is recommended to select soil properties carefully for analysis and design of pile-raft foundation system. Most importantly, ignoring any interaction factor will cause inaccuracy of results and will lead to unsafe design.

Author's Contribution

Irfan Jamil proposed the concept of this research work and relevant problem statement have been addressed here. He has also contributed thoroughly in writing this paper and proof review of the paper. Irshad Ahmad, who has facilitated us during this research work both technically and theoretically. He also provided us with the data required for computational purposes and gave the final technical review to the manuscript before submission. Muhammad Shoaib Khan, contributed to this research work by carrying out numerical analysis through proposed software. Shahid Ali Khan has formatted this paper and helped us in the writing manuscript. Hamza Alam assisted us in the validation of the proposed study.

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