# Simplified Method for Designing Piled Raft Foundation in Sandy Soils

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**ABSTRACT:** The main purpose of this study is to develop a simplified method for computing the load carried by piles, and settlement of piled raft based on the characteristics of an un-piled raft, pile group, and soil. These are important criteria for preliminary piled raft design. Based on the results obtained from finite element analysis, simplified formulas and curves are generated for different conditions of sand and different pile spacing. These formulae and curves contain the stiffness ratio and efficiency factor of the un-piled raft and pile groups. The results of the proposed method were validated using the Poulos–Davis–Randolph method.

**KEYWORDS:** Stiffness, Raft, Piles, Load sharing, Settlement.

## 1. INTRODUCTION

Many projects have been designed using piled raft foundations owing to the limited bearing capacity and excessive settlement of a shallow foundation. The conventional design of a pile foundation assumes that the total applied load is borne by the piles. In a piled raft foundation, the raft transfers part of the load to the subsoil. Therefore, piled raft provides greater cost saving than the conventional design. The important factors for designing the foundation are load-sharing of pile and raft and settlement. The analysis of a piled raft foundation is very complex, requiring a sophisticated program for designing it. It costs more and involves more computing time than the conventional method does. However, these obstacles can be overcome by using a simpler analysis method.

Piled raft foundations have been analyzed using several methods. Burland (1977) developed simplified process to estimate the design load of pile if the pile acts as settlement reducer, the model consists raft supported on single pile. Poulos (2002) conducted a simple method for estimating load sharing, and settlement, the piled raft, and the subsoil were considered as elastic. To reduce computer run time of analysis piled raft, Ta and Small (1997), and El-Mossallamy et al. (2006) developed approximation methods for the preliminary design. Lee et al. (2010) utilized a finite element method (FEM) to analyze piled raft and studied the relationship between the bearing behavior of a piled raft and bearing behavior of its components (piles, and raft). Omeman (2012) developed a simple method for determining loads that carried by pile and raft by using stiffness of pile and raft.

Previous research considered the raft as a rigid raft. The simplified method described in this paper considers differential settlement by accounting for average settlement, which controls the stiffness of the unpiled raft and pile group.

Owing to the complexity of three dimensional soil–structure interactions, these problems can be addressed by using 3D FEM. Twenty-seven models of piled raft, unpiled raft, and pile group were analyzed for different types of sands and pile spacing. A simplified method was developed based on FEM for predicting the settlement and the proportion of load that is carried by the piles. Efficiency factors were computed for the raft and pile after determining the stiffness values of the unpiled raft and pile groups by using the formulas and curves of the simplified method. Based on the efficiency factors, the load carried by the piles and raft, the stiffness of and average settlement of piled raft were calculated. Results obtained by the proposed simplified method were validated using the PDR (Poulos-Davis-Randolph) method.

## 2. LOAD SHARE MECHANISM

The piled raft foundation is a combination of the unpiled raft foundation and pile group foundation. The simplified method proposed in this paper is based on the stiffness values of the piled raft ($K_{pr}$), unpiled raft ($K_{ur}$), and pile group ($K_{pg}$) for a given settlement. The allowable settlement of a pile foundation is 25 mm, where the maximum allowable settlement of pile and raft are 25 mm and 50 mm respectively according ACI-318, and Bowels (1997). The load carried by the piled raft is the sum of the raft and pile loads, which is written as follows:

$$Q_{pr} = Q_r + Q_p \quad , \tag{1}$$

where $Q_{pr}$ is a load carried by a piled raft and $Q_r$ and $Q_p$ are loads carried by the raft and pile components, respectively, for piled rafts. The loads carried by the raft and pile ($Q_r$), and ($Q_p$), may differ from the individual loads on the unpiled raft ($Q_{ur}$) and pile group ($Q_{pg}$) for the same settlement. Omeman stated that the difference is due to an interaction between the raft and the pile, where the pile influences the stiffness of the raft, and the raft influences the stiffness of the piles (Omeman 2012). Consequently, to determine the piled raft load ($Q_{pr}$) based on the loads of an unpiled raft and a pile group, the effect of the interaction between the unpiled raft and the pile group has to be considered. Therefore, the above equation is changed into the following (Lee et al. 2010):

$$Q_{pr} = \alpha_{ur} Q_{ur} + \alpha_{pg} Q_{pg}, \tag{2}$$

where $Q_{ur}$ and $Q_{pg}$ are loads of the unpiled raft and pile group, respectively, which cause a settlement of 25 mm. $\alpha_{ur}$ and $\alpha_{pg}$ are load efficiency factors for the raft and piles, respectively. Therefore, $\alpha_{ur}$ and $\alpha_{pg}$ represent the ratios of load capacities for the raft and piles that are combined into a piled raft to those of the unpiled raft and pile group ($\alpha_{ur} = Q_r/Q_{ur}$ and $\alpha_{pg} = Q_p/Q_{pg}$). The stiffness is defined as a ratio of the loads to the settlement, according to equation (2); the stiffness of the piled raft can be determined from equation (3) for the level of settlement shown in equation (3) (Omeman 2012).

$$K_{pr} = \alpha_{ur} K_{ur} + \alpha_{pg} K_{pg}, \tag{3}$$

where $K_{pr}$ is the stiffness of the piled raft and $K_{ur}$ and $K_{pg}$ are the stiffness of the unpiled raft and pile group, respectively. There are two conditions to equal the settlement of piles and raft. The first case is that when the stiffness of piles and raft are similar, the second case is that when pile and raft are connected together and worked as a unit (piled raft). In the latter case, the stiffness of the component of the piled raft, $K_p$, $K_r$, (pile group, and raft) are different. Based on the stiffness of pile and raft, the settlement of pile and raft is as; $\delta_p = Q_p/K_p$, and $\delta_r = Q_r/K_r$ respectively. $Q_p$, and $Q_r$ are as; $Q_p = (Pile\%)Q_{pr}$, and $Q_r = (Raft\%)Q_{pr}$. Therefore, when the ratio of the load carried by the pile to the stiffness of the pile equals to the ratio of the load carried by the raft to the stiffness of the raft, the settlement of the pile $\delta_p$ would be equal to the settlement of the raft $\delta_r$. Based on equations (1) and (3), $\alpha_{ur}$ and $\alpha_{pg}$ can be computed using equations (4) and (5), respectively (Omeman 2012).

$$\alpha_{ur} = (Raft\%)K_{pr}/K_{ur} \tag{4}$$

$$\alpha_{pg} = (Pile\%)\ K_{pr}/K_{pg} \tag{5}$$

where "Raft%", and "Pile%" are the percentages of load that are carried by the raft and pile, respectively.

## 3. STUDY CONDITIONS

To develop the simplified method for predicting the load carried by the piles and raft, twenty-seven models that involved a piled raft, unpiled raft, and pile group were conducted using different values of pile spacing (*3D*, *5D*, and *7D*) and sandy soil conditions. The piled raft and its components were subjected to a uniform vertical load varying from 200 kPa to 800 kPa. The pile diameter ($D$) was kept constant at 0.5 m, the raft was considered to be 1 m in thickness, and pile length $L$ was also kept constant at 15 m. Table 1 lists the dimensions of the square piled raft and the number of piles. The raft sizes of the piled raft and un-piled raft were identical for each spacing value of the piles. The length of the pile in the pile raft and the embedment length of the pile groups were kept equal.

Table 1 Geometric Properties of Piled Raft, un-piled raft, and pile group models

| Items | | Piled raft | Un-piled raft | Pile group |
|---|---|---|---|---|
| **Pile number** | | 9 | ------ | 9 |
| **Size of raft/cap (m)** | ***3D*** | 5×5 | 5×5 | 5×5 |
| | ***5D*** | 7×7 | 7×7 | 7×7 |
| | ***7D*** | 9×9 | 9×9 | 9×9 |
| | ***9D*** | 11×11 | 11×11 | 11×11 |

## 4. FINITE ELEMENT MODELLING

Loads that carried by pile and raft were considered, and the load-settlement behaviours of the piled raft, un-piled raft, and pile group were investigated by carrying out 3D finite element analyses (FEA). Figure 1 shows a typical 3D FE mesh used in this parametric analysis. A relatively finer mesh used near the piles and underneath the raft. A coarser mesh was used farther from the pile and the raft. Sand, piles, and the raft were represented by first-order solid finite hexahedral elements (8-node bricks).

The dimensions of the system (soil, piles, and raft) were considered as follows: the horizontal dimensions ($x$, and $y$ direction) is six times the breadth of the raft ($B_r$), and the depth of soil is twice the pile length, as shown in Figure 1. The boundary conditions were presented as follows: the nodes at the edge of the vertical planes (except nodes along the plane of symmetry ($xz_{sym}$)) were allowed to move freely in the $z$ direction and were constrained from moving in the $x$ and $y$ directions. In the bottom plane, i.e. $z$ = 30 m, the movements of the nodes were restrained in each direction. For the plane of symmetry ($xz_{sym}$, or symmetry about plane $x$–$z$), the nodes were allowed to move freely in the z and x directions and prevented from moving in the $y$ direction. Rotation about $x$ and $z$ axes was restricted, where z is the gravitational axis.

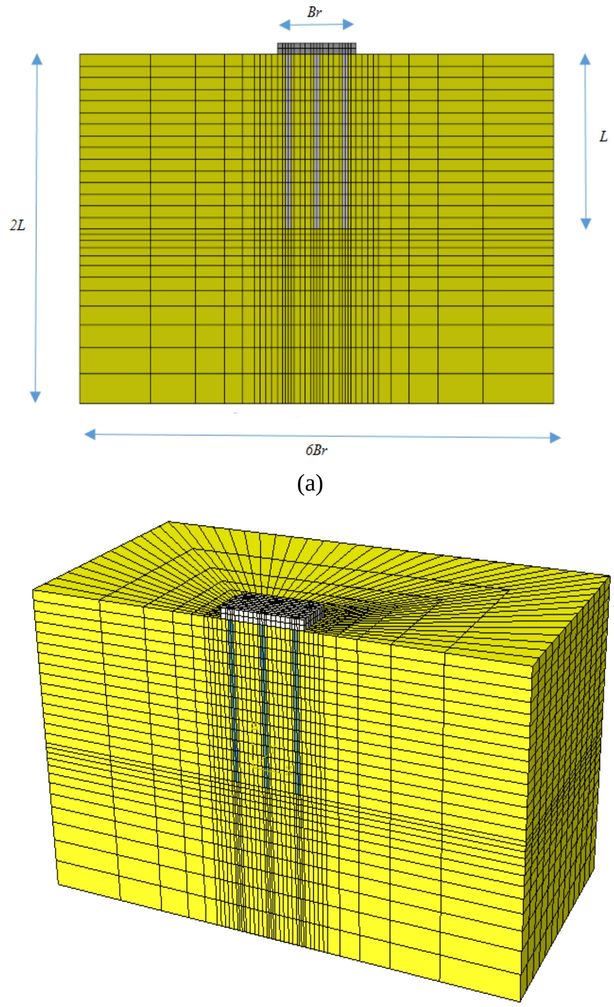


Figure 1 (a) Elevation view of finite element mesh, (b) one half symmetry view of pile raft models

### 4.1. Constitutive modelling

Sand was considered to behave as an elastoplastic material using the Mohr–Coulomb model. The values of cohesion for sandy conditions were set to zero (or 1 kPa in the Abaqus software). The dilation angle ($\psi$) is related to internal friction angle of soil ($\emptyset$) as $\psi = \emptyset - 30$. The lateral earth pressure coefficient ($K_0$) for different conditions of sand is related to the internal friction angle of the soil as $K_0 = 1 - \sin\emptyset$. Table 2 presents the characteristics of the three sand conditions. The raft and piles were considered as isotropic elastic material, $E$ is Young modulus, μ is Poisson ratio, γ is unit weight.

The pile head and raft for piled raft and pile group were rigidly connected. The pile–soil contact influenced the behavior of a vertically loaded piled raft. The modeling technique used for the pile–soil interface is a slip element (Sinha 2013), (Achmus et al. 2009). Interface elements of zero thickness can transfer shear stresses ($\tau$) across their surfaces when compressive normal stresses ($\sigma$) develop on these surfaces, the coefficient of friction at the interface ν is related to friction angle of the soil ∅ as $\nu = \tan(2/3\emptyset)$ (Das 2007).

Table 2 Material Parameters Used in Finite Element Analyses for Parametric Study

| Para-meter | unit | Loose Sand | Medium Sand | Dense Sand | Raft | Piles |
|---|---|---|---|---|---|---|
| ***E*** | MPa | 20 | 40 | 80 | 30000 | 30000 |
| ***μ*** | ----- | 0.3 | 0.3 | 0.3 | 0.2 | 0.2 |
| ***γ*** | kN/m$^3$ | 15 | 17 | 20 | 25 | 25 |
| ***$K_0$*** | ----- | 0.5 | 0.426 | 0.357 | ----- | ----- |
| ∅ | Deg. | 30 | 35 | 40 | ----- | ----- |
| ***c*** | kN/m$^2$ | 1 | 1 | 1 | ----- | ----- |
| ***ψ*** | Deg. | 0 | 5 | 10 | ----- | ----- |

## 5. VALIDATION OF NUMERICAL MODEL

The main aim of this procedure is to obtain reliable results from a numerical model. It is necessary to begin with the verification process (back analysis) of the model. Therefore, the verification is a process of comparison between situ measurements, or prescribed data with the computed results of the developed model. In this research, the data used for this process was the pile load test of the first tall building in Brooklyn (Khoury et al. 2011). The characteristics of the test were as follows: a pile, with a 0.35 m diameter and 12 m length, was constructed in a glacial sand and analyzed using an elastoplastic Mohr–Coulomb model using the parameters of the subsoil given in Table 3. The pile was loaded to 2.85 MN, which was incrementally increased in steps of 0.5 MN. The pile concrete was a linear elastic material. Young's modulus, Poisson's ratio, and a unit weight of concrete are $2\times10^7$ kPa, 0.15, and 25 kN/m$^3$, respectively. Figure 2 shows load-settlement of in situ measurement of pile load test and the developed model, the settlement computed for with developed model is larger than the in-situ measurement of settlement.

Table 3 Summary of Geotechnical Profile and Parameters (Koury et al. 2011)

| Soil | *γ* | *E* | *c* | ∅ | *μ* | *ψ* | z |
|---|---|---|---|---|---|---|---|
| **Unit** | kN/m$^3$ | kN/m$^2$ | kPa | Deg. | | Deg. | m |
| **Fill** | 17.5 | 24,000 | 1 | 30 | 0.33 | 0 | 3 |
| **Glacial Sand** | 19.5 | 275,000 – 375,000 | 1 | 40 | 0.26 | 10 | 22 |

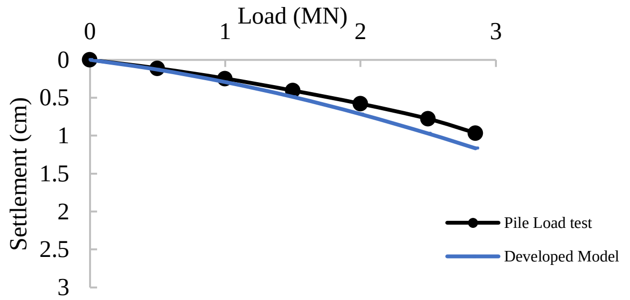


Figure 2 Load–Settlement Curves for pile load test and developed model

Additional validation was conducted by using PDR model (piled raft model of Poulos Davis Randolph) (Poulos 2002). The PDR model consists of nine piles that connected to a raft. The surrounding soil is considered as a homogenous and an elastic material. The geometries and material properties of the model are illustrated in Table 4. The value of the vertical concentrated load $P_1$ at the edge row of the pile is half that of the vertical concentrated load at the center row of pile $P_2$. In literature, this model was simulated using several programs such as FLAC 3D, FLAC 2D, GARP5, and GASP. The fundamental mechanism of GARP, GASP, PDR, FLAC 2D, FLAC 3D are as follow: GARP (Geotechnical Analysis of Raft with Pile), the raft is represented by an elastic plate, the soil is represented by an elastic continuum and the piles are modelled as interacting springs. GASP (Geotechnical Analysis of Raft with Pile), the raft is represented by a strip, and the supporting piles by springs. The interaction (raft-raft elements, pile-pile, raft-pile, pile-raft, and the effects of the parts of the raft outside the strip section being analyzed are taken into account. These settlements are then incorporated into the analysis, and the strip section is analyzed to obtain the settlements and moments due to the applied loading on that strip section and the soil settlements due to the sections outside the raft. FLAC has been employed to model the piled raft, assuming the foundation to be a two-dimensional (plane strain) problem FLAC 2D, or an axially symmetric three-dimensional problem FLAC 3D.

Table 4 Characteristics of Piles, Raft, and Soil in PDR Model

| | Size | *γ* | E | *μ* |
|---|---|---|---|---|
| Unit | m | kN/m$^3$ | kN/m$^2$ | ------ |
| Pile | D=0.5, L=10 | 25 | $2\times10^7$ | 0.2 |
| Raft | 6x10x0.5 | 25 | $2\times10^7$ | 0.2 |
| Soil | 60x60x20 | 20 | 20000 | 0.3 |

Then, the load-settlement curve of the developed model was compared with the load-settlement of the previous models as shown in Figure 3. The results indicate a reasonably good agreement.

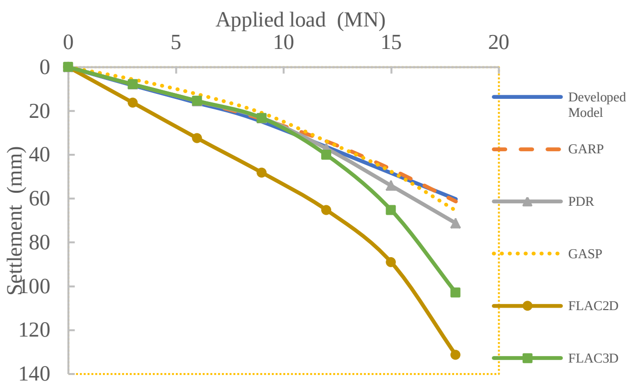


Figure 3 Load-settlement curves of piled raft model

## 6. COMPUTATION AFTER ANALYSIS

After conducting the validation and analysis of the models using the Abaqus software, some values obtained by 3D FE analysis, such as average settlement and axial pile load, were required for treatment. The vertical settlements can be directly obtained from the 3D FE analyses, and the average settlement $\delta_{avg}$ was determined by Eq. (6) (Lee et al. 2010), (Reul, and Randolph 2004).

$$\delta_{avg} = (2\delta_{center} + \delta_{corner})/3 \tag{6}$$

where $\delta_{center}$ is a settlement of the top raft center, and $\delta_{corner}$ is a settlement of the top raft corner. The stresses obtained from the integration points of the pile elements were used to determine the axial pile load. The axial pile load ($R_{pile}$) was therefore calculated from the vertical stress in the pile element by using Eq. (7) (Lee et al. 2010).

$$R_{pile} = (\pi D^2/4)\ \sigma_v, \tag{7}$$

where $D$ is the pile diameter, and $\sigma_v$ is the vertical stress in the pile element. In the case of the piles in a 3D analysis, the vertical stress was averaged at the pile head. The percentage of load that is carried by piles (*Pile*%) is the ratio of the sum of all pile loads ($\sum R_{pile}$) to the total vertical load of the foundation $R_{total}$ as obtained from Eq. (8) (Reul, and Randolph 2004), (Mandolini et al. 2013).

$$Pile\% = \frac{\sum R_{pile}}{R_{total}} \tag{8}$$

If the total applied load is carried by the piles, *Pile*% is one hundred (100%), it represents a freestanding pile group, whereas a *Pile*% of zero (0%) describes an unpiled raft. *Pile*% ranges from 0% to 100% for a piled raft.

## 7. SIMPLIFIED METHOD

The assumptions made in the developed simplified method are as follows: the soil is sandy, the loading condition is a uniform vertical loading, the configuration of the piles is a regular distribution, and there is a differential settlement on the raft. Loadings of the piled raft ($Q_{pr}$), pile group ($Q_{pg}$), and unpiled raft ($Q_{ur}$) were determined from load–settlement curves, as shown in Figure 4. The average settlements ($\delta_{ave}$) that were generated by the loads were 25 mm. From piled raft models, the load share of the raft "*Raft* %", load share of the pile "*Pile* %", and stiffness of the piled raft ($K_{pr}$) were computed, where $K_{pr}$ is the ratio of the load to the average settlement of the piled raft ($K_{pr} = \frac{Q_{pr}}{\delta_{ave}}$). The stiffness values of the unpiled raft ($K_{ur}$) and pile group ($K_{pg}$) were determined from the models of the unpiled raft and pile group; here, the stiffness values of the unpiled raft ($K_{ur}$) and pile group ($K_{pg}$) are the ratios of the load to the average settlement of the unpiled raft and pile group, respectively. Figure 5 show the relation between the ratio of the pile group coefficient and unpiled raft coefficient ($\alpha_{pg}/\ \alpha_{ur}$) and the ratio of the stiffness of the unpiled raft to the stiffness of the pile group ($K_{ur}/K_{pg}$) for different conditions of sand. The correlations of these data ranged from 0.97 to 98, which can be considered excellent. Based the Figure 5, it is worth noting that when the ratio stiffness $K_{ur}/K_{pg}$ increases, the ratio of efficiencies load factors $\alpha_{pg}/\ \alpha_{ur}$ will decrease. On other mean, when the raft stiffness increases or the pile group stiffness decreases, the load carried by piles will decrease. To find "*Raft*%" and "*Pile*%", equations (4) and (5) were first considered. According to Figure 5 and the condition of sand, the value of ($\alpha_{pg}/\ \alpha_{ur}$) can be calculated from the given value of ($K_{ur}/K_{pg}$). The value of $T$ is determined as $T = \frac{\alpha_{pg}/\alpha_{ur}}{K_{ur}/K_{pg}}$. Finally, *Raft*% and *Pile*% can be computed by using equations (9) and (10) respectively.

$$Raft\% = \frac{1}{1+T} \tag{9}$$

$$Pile\% = \frac{T}{1+T} \tag{10}$$

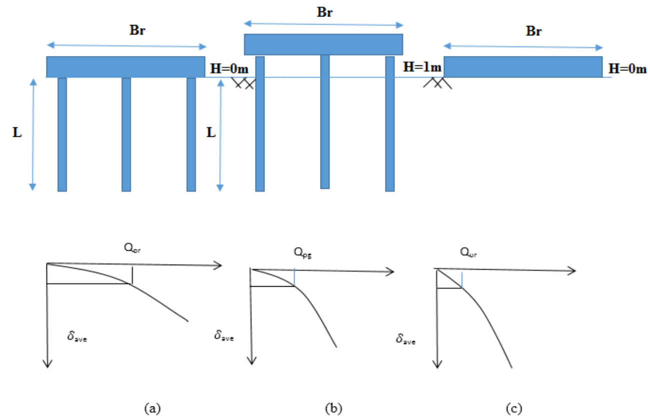


Figure 4 Typical configuration and load–settlement curves of (a) piled raft (b) pile group (c) unpiled raft

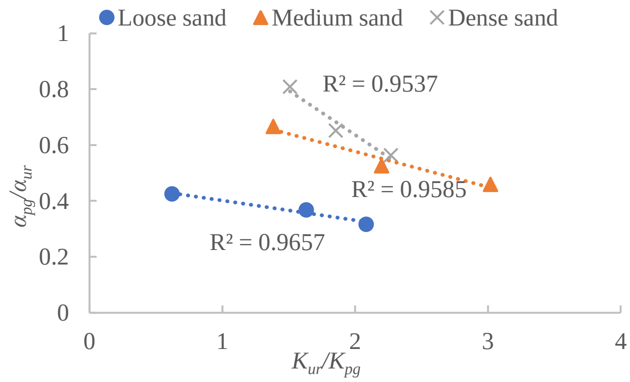


Figure 5 ($\alpha_{pg}/\ \alpha_{ur}$) versus ($K_{ur}/K_{pg}$) for loose, medium, and dense sand

### 7.1. Validation

To verify the method, its predictions of a percentage of a load carried by the piles "*Pile%*" for many models of the piled rafts were compared to predictions made by the PDR method. Mandolini et al. (2013) stated that the PDR method is based on the following assumptions: the piles and raft behave in a linearly elastic stage until failure, the raft is very stiff, the raft subjects to vertical concentrated load. Hence only a uniform vertical displacement can occur. Based on the assumption about raft stiffness, in principle, the method is applicable only to small-piled rafts ($B_r/L$ < 1), where $B_r$ is the raft width, and $L$ is the pile length. Differential settlements would not represent a major problem. From Tables 5–7, the relative difference in the values of the load percentage carried by the pile between the PDR method and the simplified method increases with increasing pile spacing in different sand conditions.

Table 5 Comparison of *Pile%* between PDR Method and Simplified Method for Loose Sand

| Pile spacing | PDR (Pile%) | Simplified Method (Pile%) | Relative difference% |
|---|---|---|---|
| 3D | 91.72 | 87.27 | 5.09 |
| 5D | 88.38 | 80 | 10.45 |
| 7D | 85.12 | 62.8 | 29.76 |
| 9D | 81.36 | 48.23 | 68.6 |

Table 6 Comparison of *Pile%* between PDR Method and Simplified Method for Medium Sand

| Pile spacing | PDR (Pile%) | Simplified Method (Pile%) | Relative difference % |
|---|---|---|---|
| 3D | 88.41 | 86.27 | 2.48 |
| 5D | 84.13 | 81.83 | 2.81 |
| 7D | 78.45 | 66.65 | 17.7 |
| 9D | 74.91 | 51.8 | 44.6 |

Table 7 Comparison of *Pile%* between PDR Method and Simplified Method for Dense Sand

| Pile spacing | PDR (Pile%) | Simplified Method (Pile%) | Relative Difference % |
|---|---|---|---|
| 3D | 86.13 | 79.75 | 8 |
| 5D | 81.08 | 74.88 | 8.26 |
| 7D | 75.03 | 49.7 | 15.5 |
| 9D | 69.4 | 51.9 | 33.72 |

This is because the simplified method assumes that there are differential settlements on a piled raft foundation, and differential settlement increases with an increase in pile spacing. The piled raft stiffness in the PDR method depends on the stiffness of the raft and pile group, it is applicable until the pile capacity is fully mobilized. The pile capacity of the piled raft was fully mobilized at the pile spacing of *7D* (load–settlement is nonlinear) as shown in Figure 6. Therefore, there is a high relative difference between the PDR method and simplified method with regard to load share of the pile.

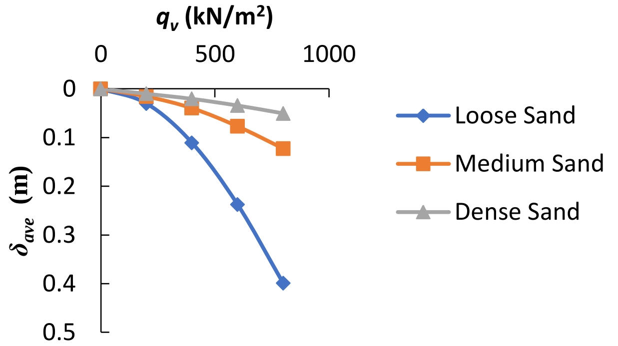


Figure 6 $q_v$–$\delta_{ave}$ of piled raft of $S$ = *7D* for different sand conditions

Horikoshi and Randolph (1997) conducted a simple test to check a rigidity of a raft. The test may be performed by calculating the raft–soil stiffness ratio ($K_{rs}$) defined as follows:

$$K_{rs} = 5.57 \frac{E_r}{E_s} \frac{(1-\mu_s)}{(1-\mu_r)} \left(\frac{B_r}{Lr}\right)^{0.5} \left(\frac{t_r}{Lr}\right)^3 \quad (11)$$

where $E_r$ , and $E_s$ are Young's modulus values of the raft and the soil respectively, $\mu_s$, and $\mu_r$ are Poisson ratios of the raft and soil respectively; $L_r$ and $B_r$ are a length and width of the raft, espectively, and $t_r$ is a thickness of the raft. For a raft–soil stiffness ($K_{rs}$) value greater than five, the raft can be considered as rigid. For the piled raft model, the raft–soil stiffness ($K_{rs}$) for the pile spacing values of *3D* and *5D* were greater than ten (i.e., in the rigid range); for a pile spacing of *7D,* and *9D,* the values were less than five (i.e., a flexible raft) for different conditions of sand. For obtain clear picture, Figure 7 shows the profile of the settlement along the top of raft, the profile is taken at mid-distance between the two rows of the piles. The type of sand is dense, the pressure subjected on the piled raft is 600 kN/m$^2$. Based on the Figure, the differential settlement disappears in piled raft at pile spacing *3D*, and *5D*, and it pronounces at pile spacing *7D*, *9D*.

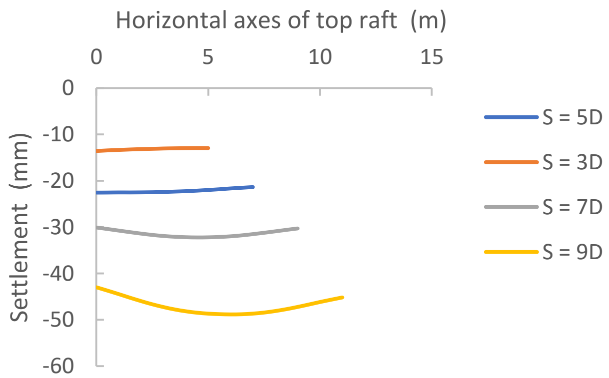


Figure 7 Profile settlement of top raft of piled raft mid-distance between the two rows of the piles in dense sand for different pile spacing ($q_v$ = 600kN/m2)

To compute the stiffness of the piled raft, the two relations $\alpha$ r–(Kur/Kpg) and $\alpha$ $_p$–($K_{ur}/K_{pg}$) were studied for different conditions of sand as shown in Figures 7 & 8. The relation ($\alpha_{ur}$–($K_{ur}/K_{pg}$)) is direct, while the relation ($\alpha_{pg}$–($K_{ur}/K_{pg}$)) is an inverse relationship. The correlation value of that data ranges from 0.77 to 0.99 (i.e., good to excellent correlation). Based on this correlation, the stiffness of the unpiled raft and pile group, efficiency factors for the raft and pile, and equation (8), the stiffness of the piled raft could be determined. According to Figures 8, and 9, it is worth to noting that when stiffness of pile group increases, the ration stiffness $K_{ur}/K_{pg}$ decreases, and $\alpha_{ur}$ decreases and $\alpha_{pg}$ increases. On other mean, the load carried by raft decreases and the load carried by pile increases. Therefore, the pile capacity will be increased in piled raft foundation. The stiffness values of the piled raft computed by FE analysis were compared to those computed by the simplified method. Tables 8, 9, and 10 present the stiffness of the piled raft computed by the two methods and their relative difference. The results indicate that the stiffness determined by the simplified method is in good agreement with that obtained from FE analysis, as indicated by the obtained relative difference.

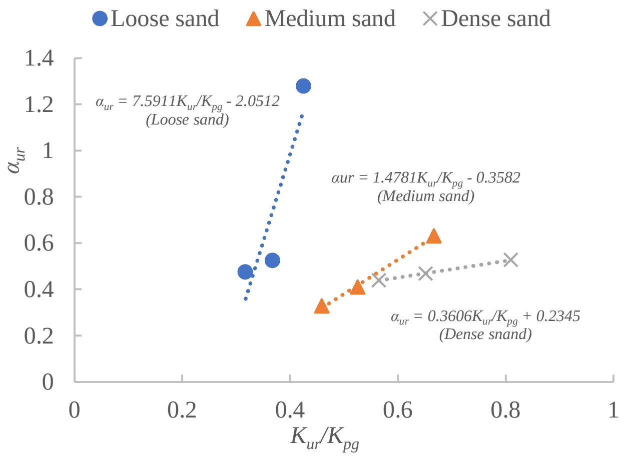


Figure 8 $\alpha_{ur}$ versus ($K_{ur}/K_{pg}$) for loose, medium, and dense sand

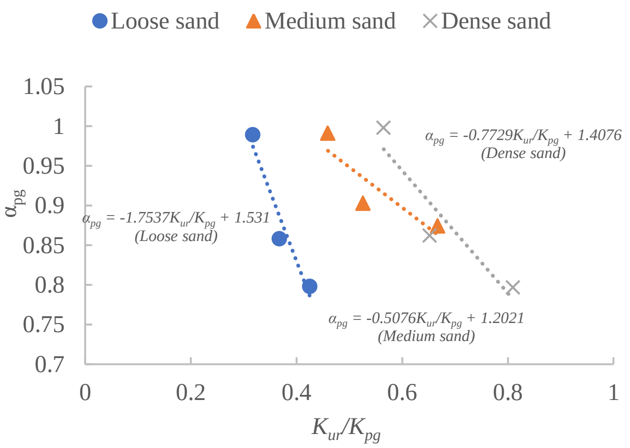


Figure 9 *αpg* versus ($K_{ur}/K_{pg}$) for loose, medium, and dense sand

## 8. APPLYING THE SIMPLIFIED METHOD

To determine the stiffness of the unpiled raft, the following equation is adopted as;

$$\delta = \frac{Q_{ur} B_r (1-\mu_s{}^2)}{E_s} I_s \tag{12}$$

where $\delta$ is a settlement, $Q_{ur}$ is the vertical uniform load, $\mu_s$ is Poisson ratio of the sand, $E_s$ is young modulus of sand, Br is breadth of the unpiled raft, and $I_s$ is a settlement influence factor, which is a ratio of length to breadth of the unpiled raft, $I_s$ equal to 1.12, and 0.56 at center and corner of the unpiled raft respectively. The above equation depends on the elasticity theory. To consider the plasticity in Eq (12), the center and corner settlements for several size of the unpiled raft and different type sand conditions were computed depending on Eq. (12). Then, the average settlement are computed by using Eq. (6). After that, the average settlement that calculated by elasticity theory (by using Eq. 12) were compared with the average settlement of the unpiled rafts that modelled by FEA. The difference between these settlement represent by plasticity factor $\beta$

$$\delta_{ave(FEA)} = \beta\, \delta_{ave(elasticity)} \tag{13}$$

$\beta$ depends on size of the unpiled raft and type of sand (loose, medium, or dense), where $\beta$ is 1.01 for medium and dense sand, and β is 1.22 for loose sand.

Table 8 Stiffness of piled raft $K_{pr}$ for FE model and simplified method for loose sand

| **Pile spacing** | **$K_{pr}$ of FE Model of piled raft ($kN/m^3$)** | **$K_{pr}$ of the simplified method of piled raft ($kN/m^3$)** | **Relative difference (%)** |
|---|---|---|---|
| *3D* | 14,619.43 | 13,962.88 | 4.7 |
| *5D* | 9,159.943 | 10,090.91 | 10.1 |
| *7D* | 8,169.79 | 8,218.87 | 6.01 |
| *9D* | 4,800 | 4,910.45 | 2.31 |

Table 9 Stiffness of Piled Raft $K_{pr}$ for FE Model and Simplified Method for Medium Sand

| **Pile spacing** | **$K_{pr}$ of FE Model of piled raft ($kN/m^3$)** | **$K_{pr}$ of the simplified method of piled raft ($kN/m^3$)** | **Relative difference (%)** |
|---|---|---|---|
| *3D* | 23,397.783 | 22,875.94 | 2.28 |
| *5D* | 16,026.419 | 16,559.062 | 3.32 |
| *7D* | 12,582.809 | 12,457.094 | 1.01 |
| *9D* | 8,000 | 7,937.08 | 0.79 |

Table 10 Stiffness of Piled Raft $K_{pr}$ for FE Model and Simplified Method for Dense Sand

| **Pile spacing** | **$K_{pr}$ of FE Model of piled raft ($kN/m^3$)** | **$K_{pr}$ of the simplified method of piled raft ($kN/m^3$)** | **Relative difference (%)** |
|---|---|---|---|
| *3D* | 41,029.781 | 40,113.76 | 2.28 |
| *5D* | 27,208.815 | 28,023.726 | 3 |
| *7D* | 19,753.086 | 19,506.726 | 1.26 |
| *9D* | 14,875 | 12,541.7 | 18.604 |

Based Eqs. (12), and (13), the unpiled raft stiffness $K_{ur}$ is calculated.
where the average settlement of the unpiled raft is a function of applied load $Q_{ur}$, this function must be equal to 25 mm (i.e., the maximum allowable settlement) to find $Q_{ur}$. Therefore, the unpiled raft stiffness can be defined as; $K_{ur} = Q_{ur}/\delta_{ave}$. To determine a stiffness of a pile group, the load–settlement curve of the pile load test is available. Davisson's method is used to determine the load that resulted in a settlement of 25 mm. Davisson's method uses the following equation:

$$s = 0.012D_r + 0.1\left(\frac{D}{D_r}\right) + \frac{QL}{A_p E_p} \tag{14}$$

where $L$ and $D$ are a length and diameter of pile, respectively, $D_r$ is the reference pile diameter, which is equal to 300 mm, $A_p$ and $E_p$ are an area of cross-section and Young's modulus of the pile, respectively; $Q$ is the applied load, and $s$ is settlement of a single pile. The load on the pile group is computed based on the load of a single pile ($Q$) and the pile group efficiency (η) as

$$Q_{pg} = \eta \sum Q. \tag{15}$$

A pile group efficiency depends on a type of soil, installation of a pile, a pile length and a pile spacing, a pile diameter, and a number of piles. There are several equations such as Converse–Labarre equation, and Los Angeles Group Action equation. However, the equations are empirical. The stiffness of the pile group can be defined as $K_{pg} = Q_{pg}/(s_{pg} = 25\text{ mm})$. Based on $K_{ur}$ and $K_{pg}$, Figures 5–7, and Equations (9), and (10), the carried loads of the pile and raft are calculated. To determine the average settlement of the piled raft, the stiffness of the piled raft is computed based on Figures 9–11 and Eq. (3). Therefore, the average settlement of the piled raft can be determined as;

$$\delta_{ave} = (K_{pr})(Q_{applied}) \tag{16}$$

where $Q_{applied}$ represents the load applied on the piled raft.

## 9. CONCLUSION

A simplified method for computing the carried load of the pile, and stiffness of the piled raft is developed based on the stiffness ratio of the un-piled raft ($K_{ur}$) to the pile group ($K_{pg}$) and the interactions between them (them being components of the piled raft), by accounting for the efficiency factors of the raft and pile ($\alpha_r$, $\alpha_p$). In addition, the stiffness can be defined as the ratio of the load that caused a settlement of 25 mm (i.e., the maximum allowable settlement) to the settlement (25 mm). The assumptions of the simplified method are as follows: 1) The soil is the sand, 2) The load is a uniform vertical load, 3) The configuration of piles follows a regular distribution, and 4) There is a differential settlement on the foundation. The validation results indicate that the load share of the pile determined by the simplified method is in good agreement with the PDR method for pile spacing values of *3D* and *5D*. However, there are significant differences for pile spacing value of *7D*. This is due to the differential settlement in piled raft models in which the differential settlement increases with increasing pile spacing. The raft–soil stiffness ($K_{rs}$) for pile spacing values *3D* and *5D* was higher than that for a pile spacing of *7D*.

## 10. ACKNOWLEDGMENT

The authors would like to acknowledge the support provided by the Research Centre (RC) of College of Engineering and the Deanship of Scientific Research (DSR) at King Saud University.
The authors thank the staff of the Mechanical Engineering department of King Saud University for their help and support.

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