Foundation design on problematic soils with high underground water level

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Abstract

In this study, the foundation systems of a structure on different soil profiles and different groundwater levels are modeled and analyzed. Several difficulties encounter during the basic design and application phases. In particular, the high groundwater level, the load on the soil under the load-bearing capacity, settlement, liquefaction causes many problems such as emergence. Within this study's scope, foundation systems based on six different soil profiles with a high groundwater level were modeled with the Plaxis 2D program for raft foundation and piled raft foundation. As a result of the analysis, it was seen that groundwater level, the soil characteristics, and the conditions are significant in the soil-foundation interaction in both static and earthquake situations.

Keywords: Foundations; Groundwater Level; Soil properties; Plaxis 2D.

Introduction

Geotechnical engineering studies start with determining the engineering properties of the soil layers on which a structure is constructed. Depending on these parameters, it is essential to choose the most appropriate and safest foundation for structural purposes. Additional load increases on the soil, stress due to these increases, deformation, and the structure's balanced states should be verified. Considering that soils are homogeneous and non-isotropic materials, the soil layers' characteristics, groundwater level, and depth will vary depending on the soil behavior. With the decrease of the areas with high strength with intensive construction, construction of engineering structures on problematic soils has become compulsory. Therefore, especially in the earthquake zone, the buildings' soil properties should be examined in detail, and appropriate foundation systems should be determined. Thus, depending on the parameters obtained from the studies, the design and application stages can be kept on the safe side. The high groundwater level raises many problems, such as loss of bearing capacity under loads from the structure, liquefaction, and settlement. Also, in areas with soft alluvial soils and loose soils, groundwater levels close to the surface cause earthquake waves to increase the earthquakes' amplitude in case of possible earthquakes. Damages such as tilting, sinking and bending of the buildings due to liquefaction observed on sand soils where the groundwater level was high on the 17 August 1999 Kocaeli earthquake. In the studies carried out in the foundation systems of buildings where there are damages, it was seen that the design was made independent of the soil feature. In general, when the settlement values on the shallow foundations exceed the limit values, a pile foundation or piled raft foundation design is made.

Randolph (1994) has explained the use of the design of piled foundations as settlement reducers. The use of piles reduces the settlements to an acceptable value, and the used pile leads to considerable economic savings and the safety and performance of the foundations (Burland, Broms, & De Mello, 1977; Poulos, 2001; Wulandari & Tjandra, 2015). The groundwater level hurts the soil parameters, the soil properties, and the carrying capacity are changed (Atkinson, 1993). As a result, the design should try to minimize groundwater damage on the foundation of the structure of problematic soils. In particular, with the advancement of computer technology, numerical solutions have become widespread in geotechnical engineering. Many researchers studied the shallow and pile foundation system on different soil profiles and conditions. Several studies have been modeled all kinds of problems of the foundation system by numerical solutions (Bartolomei, & Omel’chak, 2003; Bowles, 1996; Burd, & Frydman, 1997; Burland, 1995; Huang, Jiu, Jiang, &

Lie, 2017; Katzenbach, Arslan, & Moormann, 2000; Maharaj, & Gill, 2017; Mali, & Singh, 2018; Michalowski, & Shi, 1995; Oh, Hunag, Surarak, Adamec, & Balasurbamaniam, 2008; Oh, Lin, Bui, Huang, Surarak, & Balasurbamaniam, 2009; Potts, & Zdravkovic, 2001; Poulos, Small, & Chow, 2011; Prakoso, & Kulhawy, 2001; Roh, Kim, Kim, 2019; Shahriar, Sivakugan, & Das, 2012; Wulandari, 2013).

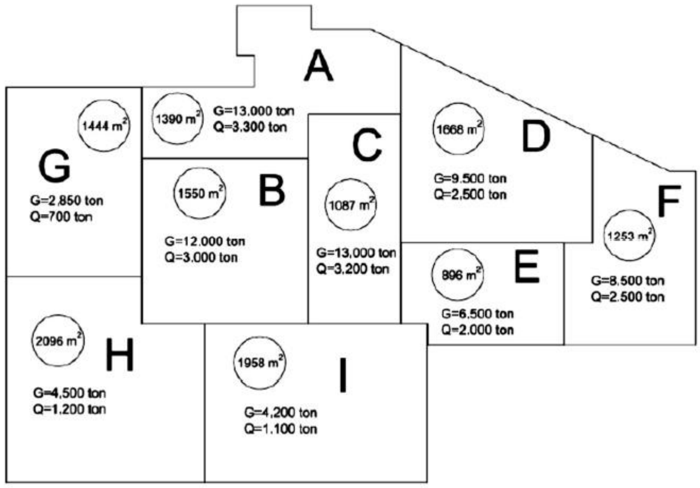
Prakoso, & Kulhawy (2001) studied the effects of raft width and pile depth on the raft piled foundation. The result indicated that the ratio of pile group to raft width and pile depth are the crucial elements. Bartolomei, & Omel'chak (2003) studied the effect of loading character on the analysis of pile settlements. They showed that if the soil where the piles locate is of high plasticity clay, the amount of settlement at the same load level will be higher than that of low plasticity medium-hard clay. Oh, Hunag, Surarak, Adamec, & Balasurbamaniam (2008) analyzed the piled raft foundation using finite element software on sandy soil. Pile spacing, number of piles, pile diameter, a ratio of raft dimensions, and raft thickness were changed, and modeling was made on the same soil. As a result, they observed that the piled raft's maximum seating rate depends on the pile spacing and the number of piles, independent of the raft thickness. Oh, Lin, Bui, Huang, Surarak & Balasurbamaniam (2009) investigated sandy soil and soft clay by numerical analysis. Results were shown maximum settlement depends on pile spacing and the number of piles for sandy soils, and raft thickness for clayey soils. Shahriar, Sivakugan, & Das (2012) investigated settlements of shallow foundations due to the water table's rise. They said an increase in settlement due to groundwater level is related to the applied load according to the finite difference analysis. Akl, Mansour, & Moustafa (2014) investigated load sharing characteristics of piled raft foundation in clay soil. For this purpose, researchers carried out models by the ANSYS program. At the end of the study, increasing the piles' length has a significant effect on the piled raft foundation average settlement and differential settlement between raft and piles. They also said that increasing the length of piles becomes more significant for softer soil profiles. Patowary, & Nath (2015) studied the effect of pile length, pile diameter, pile spacing, raft thickness, angle of internal friction of soil, and groundwater table using 3D analysis of piled raft using PLAXIS 3D. As a result, the settlement saw to decrease in the pile length increased in piled raft foundation, and the settlement of piled raft increased by groundwater table up. Maharaj, & Gill (2017) investigated load sharing in piled raft foundation on clay using the nonlinear finite element method. Consequently, researchers said that the load carried by pile decreases with at larger spacing, increased length of pile increases diameter ratio the load carried by pile and reduced the percentage load shared by raft, and increase in spacing to diameter ratio increases the percentage load shared by raft. Mali, & Singh (2018) investigated the behavior of long piled raft foundations on clay soil by Plaxis 3D software. Researchers used different pile spacing, length, diameter, and raft – soil stiffness ratio in analyses. Consequently, they said an increase in shear force causes an increase in the raft soil stiffness ratio. Roh, Kim, & Kim (2019) investigated axial load capacity for piled raft foundation by changes in groundwater level. Researchers said that the axial load capacity changed by groundwater level depths from 0 to 1.0 times the raft width, and raft size affected the groundwater level influence depth for piled rafts.

The Finite Element Method (FEM) has become the most widely used numerical analysis method in geotechnical problems because the soil is composed of layers and inadequate elastic methods. Flac, Plaxis, Midas GTS NX, Diana, Abaqus, Adonis, Crisp, Rocscience, Geoslope: Sigma/W, etc., numerical analysis software were developed. In this study, models were created Plaxis 2D and solved. The Plaxis 2D finite element program is a widely used program for designing and analyzing many problems related to geotechnical engineering. Stability, deformation, groundwater flow, and carrying power concepts are exam utilizing this program. This study investigated displacements that would occur on the soil according to different soil classes, groundwater, earthquake magnitude, and foundation system using Plaxis 2D for raft and piled raft foundation (Brinkgreve, & Waterman, 2002).

Materials and Methods

In geotechnical engineering applications, soil conditions should consider for the foundation design of a building. In addition to the loads coming from the superstructure in selecting the foundation design, another subject is the soil characteristics and the conditions. Especially groundwater level, it creates problems in foundation design depending on soil properties. In soil investigations, accurate determination of the groundwater level is essential. In this study, the effect of behavior related to the foundation design of soils with different groundwater levels, different characteristics, and conditions was investigated. For this purpose, To obtain the charge-displacement relationship was made, analyses performed on six soils with different parameters at two different groundwater levels as -2m and -5m. Also, the earthquake effect of the magnitude of 5.4 investigated soils.

Figure 1. Foundation area and building loads



Material

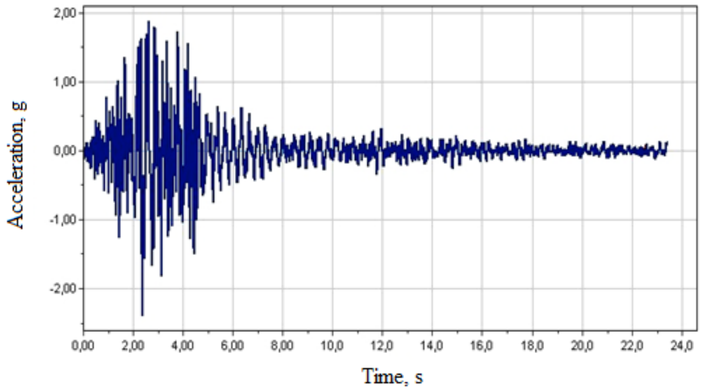
The models used in this study are given in Table 1. The soil parameters were chosen as typical soil friction angle values and cohesion by the soil class (Minnesota Department of Transportation, 2007). In this study, foundations were designed as the raft foundation and the piled raft foundation. Loads and structural features of a previously completed public service building were used in the models. The project consists of 9 blocks, and some of the blocks are a typical floor basement + ground floor + 4 floors, some of them are single layers. Approximate foundation areas for each block and building loads obtained due to static calculations showed in Figure 1. As a result of the static calculations made with the Sta4Cad program, the maximum load /m2 was found in the C block. Block C was obtained at approximately 16200 tons, and foundation analyzes of this block were performed. The raft foundation area is for block C is 1087m2; the average base pressure is 16200/1087≈15.00t/m2≈ 150 kN/m2. A foundation area of 22x50m was modeled for loads from the building. The soil profiles used in the models are problematic soil with many features. Two different groundwater levels were modeled in the analysis of soils, and six soil profiles were used in the study. In this study, the models created were made up of two horizontal layers, 10 m thick upper layer, and 56 m bottom layer.

Table 1. Soils parameters

Soil Model		Parameters								
		Soil Class (USGS)	Material Model	Material type	Unsaturated unit density (γ_{unsat}) kN/m³	Saturated unit density (γ_{sat}) kN/m³	Young Modulus (E) kN/m²	Poisson's ratio (μ)	Cohesion (c) kN/m²	Friction angle (ϕ) kN/m²
Model 1	Top Unit	SC	Mohr-Coulomb	Drained	18.0	19.0	20000	0.33	10	26
	Bottom Unit	GC	Mohr-Coulomb	Drained	19.0	20.0	60000	0.33	1	35
Model 2	Top Unit	SM	Mohr-Coulomb	Drained	19.8	20.8	15000	0.33	8	27
	Bottom Unit	GC	Mohr-Coulomb	Drained	19.0	20.0	60000	0.33	1	35
Model 3	Top Unit	ML	Mohr-Coulomb	Drained	17.7	18.7	18000	0.2	36	25
	Bottom Unit	SM	Mohr-Coulomb	Drained	18.5	19.5	15000	0.33	10	33
Model 4	Top Unit	MH	Mohr-Coulomb	Drained	18.0	19.0	16000	0.2	25	20
	Bottom Unit	SM	Mohr-Coulomb	Drained	18.5	19.5	15000	0.33	10	33
	Top Unit	CL	Mohr-Coulomb	Drained	18.8	20.8	21000	0.2	25	23

Model 5	Bottom Unit	SC	Mohr-Coulomb	Drained	18.0	19.0	40000	0.33	15	32
Model 6	Top Unit	CH	Mohr-Coulomb	Drained	16.0	18.0	42000	0.3	65	18
	Bottom Unit	SC	Mohr-Coulomb	Drained	18.0	19.0	40000	0.33	15	32

Figure 2.The 5.4 magnitude of earthquake acceleration record



Method

In this study, the foundation design modeled with the Plaxis 2D program (Plaxis, 2018), which is a finite element analysis program widely used by geotechnical engineers in the world. In Table 1, model 1, model 2, model 3, model 4, model 5, and model 6 were modeled as separate. The water level was defined at -2.0 m and -5.0 m depth, respectively. First of all, the raft foundation applied to the characteristics specified in Table 2. A total of 12 different combinations were designed for the raft foundation. It is common practice in Foundation Engineering design to limit permissible settlement footing 40-65 mm on sandy soil and 65-100 mm on cohesive soils for raft foundation (Skempton, & McDonald, 1956). Models were analyzed for all soil for earthquake loads of magnitude 5.4 on raft foundation and L=10m piled raft foundation, and earthquake effect on all soil models was investigated. The properties used in a piled raft foundation modeling shown in Table 3. The acceleration record of the earthquake of magnitude 5.4 was given in Figure 2.

Table 2. Properties of raft foundation.

Thickness (d) (m)	0.5
Material Model	Elastic
EA (kN/m)	$6.0*10^6$
EI ($kN/m^2/m$)	$333.3*10^3$
Weight (w) (kN/m/m)	6
Poisson Ratio	0.2

Table 3. Properties used for piled raft foundation.

Design Element	Embedded Beam Row
Material Model	Elastic
E (kN/m^2)	$30.0*10^6$
γ (kN/m^3)	0.150
D (d) (m)	0.8
A (m^2)	0.5027
I (m^4)	0.02011
$L_{spacing}$ (m)	2.0
$T_{skin, start, max}$ (kN/m)	100
$T_{skin, end, max}$ (kN/m)	200
F_{max} (kN)	500

After 12 different combinations of analysis, the displacement values of the designed foundations were obtained. The soil's displacement gave high values due to the soil's properties on which the raft foundations were located. It was decided that the superstructure's load can not be carried by soil safely with a raft foundation. Therefore, the foundation design method was remodeled with a pile application. Generally, the piled raft system used a high amount of permissible settlement, and the pile foundation system reduces the settlement as close to the allowable value (Cooke, 1986; Poulos, 2001). Piled raft foundation systems are used as a foundation to support wide or high structures. Notably, the piled raft foundation is preferred for reducing settlement and increasing the bearing capacity. Also, piled raft foundations are more economical than other alternatives (Omeman, 2012). In this study, pile lengths are modeled as 10 m, 15 m, 20 m, and 25 m, respectively. Thus, it has been observed that the pile length is essential. Within this study's scope, the soil models were established using the PLAXIS 2D program based on the finite element method (Figures 3 and 4).

Figure 3. Geometry of the model (Raft foundation and Piled raft foundation)

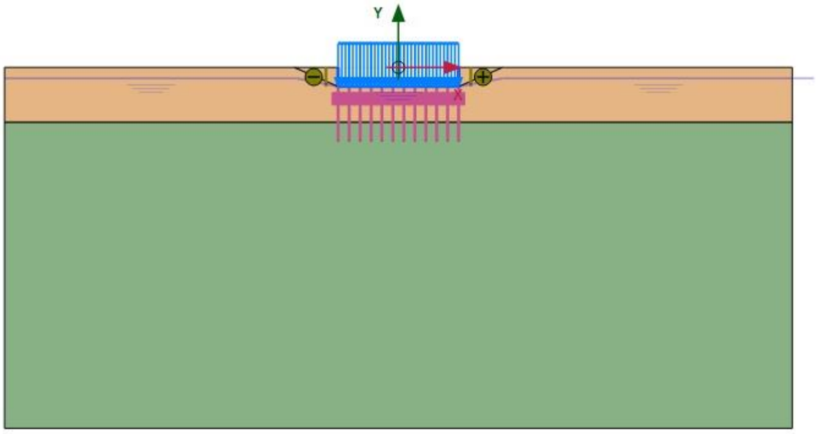
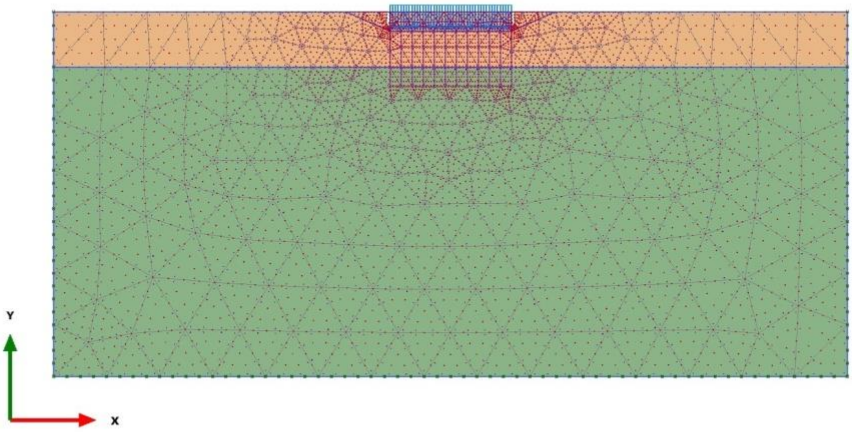


Figure 4. PLAXIS 2D Finite element mesh (Raft foundation and Piled raft foundation)



Displacements of Raft Foundation Under Static Load

Analysis for raft foundation application carried out at the groundwater level of -2.0 m and -5.0 m using Model 1. The vertical displacements obtained as a result of the analysis are shown in Figure 5. It saw from the figures that the deformation decreases with the lowering of the groundwater level. To the raft foundation was made analyzes at the groundwater level of -2.0 m and -5.0 m for each of Model 1 through 6. In the soil profiles with the bottom layer GC, the vertical deformation values of the upper soil SM are higher than the upper layer SC. In soil profiles with the bottom layer SM, the vertical deformation values of the upper layer MH are higher than the upper layer ML. In the soil profiles with the bottom layer SC, the vertical deformation values of the upper layer CH are smaller when the upper layer was CL. As a result, the models' vertical deformation values made as raft foundation design gave the largest is the bottom layer SM, the upper layer MH (Model 4), and the smallest is the bottom layer GC, the upper layer CH (Model 2). Accordingly, parameters such as modulus of elasticity (E), Poisson ratio (μ), cohesion (c), and internal friction angle (φ) have essential effects on the load on the soil. In the the raft foundation analyses created for all soil models were seen that more vertical displacement occured at the groundwater level close to the surface than the deeper groundwater level. More than the allowable amount of deformation was observed in this study with the raft foundation application on the modeled soils. It was decided that the applied load could not carry safely. These results in the literature are compatible with water that affects clay soil behavior (Holtz, Kovacs, & Sheahan, 2011). As a result, in the raft foundation design, the vertical displacement values obtained by changing the soil properties and location and the under groundwater level at the same load have changed. These findings is also consistent with those of Shahriar, Sivakugan, & Das (2012).

Displacements of Piled Raft Foundation Under Static Load

Analysis for 10 m piled raft foundation application was carried out at the groundwater level of -2.0 m and -5.0 m using Model 1. The vertical displacements obtained as a result of the analysis were shown in Figure 6. It was seen from the figures that the deformation decreases with the lowering of the groundwater level. Analyzes were made for 10 m piled raft foundation at groundwater level of -2.0 m and -5.0 m for each of Model 1 through 6. Vertical displacements at the groundwater level of -2.0 were determined between 36 mm and 131 mm. Vertical displacements at the groundwater level of -5.0 were determined between 32 mm and 116 mm. At both the groundwater level, the lowest displacement value was observed in Model 1, and the highest displacement value found in Model 3 and Model 4.

Analysis for 15 m piled raft foundation application was carried out at the groundwater level of -2.0 m and -5.0 m using Model 1. The vertical displacements obtained as a result of the analysis were shown in Figure 7. It was seen from the figures that the deformation decreases with the lowering of the groundwater level. Analyzes were made for 15 m piled raft foundation at groundwater level of -2.0 m and -5.0 m for each of Model 1 through 6. Vertical displacements at the groundwater level of -2.0 were determined between 32 mm and 119 mm. Vertical displacements at the groundwater level of -5.0 were determined between 29 mm and 105 mm. At both the groundwater level, the lowest displacement value was obtained in Model 2, and the highest displacement value was observed in Model 3 and 4.

Figure 5. Model 1 vertical displacement on the soil with raft foundation applied.

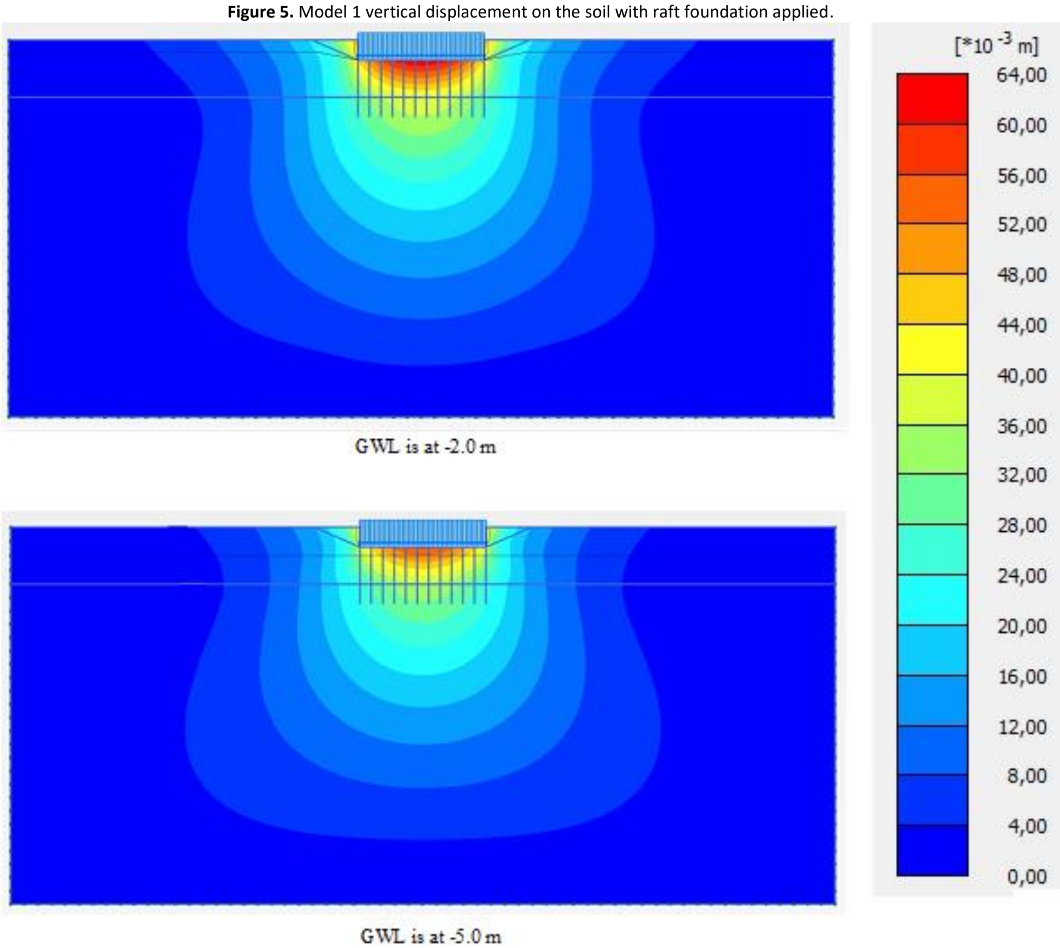


Figure 6. Model 1 vertical displacement on the soil with 10 m piled raft foundation applied.

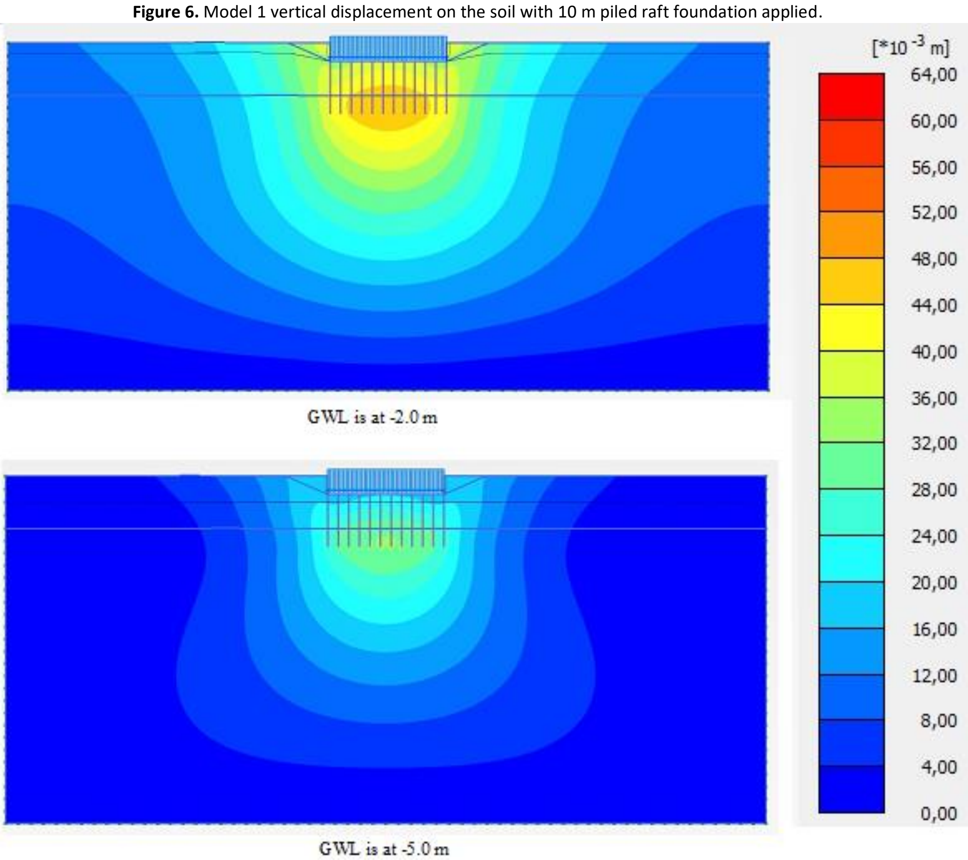
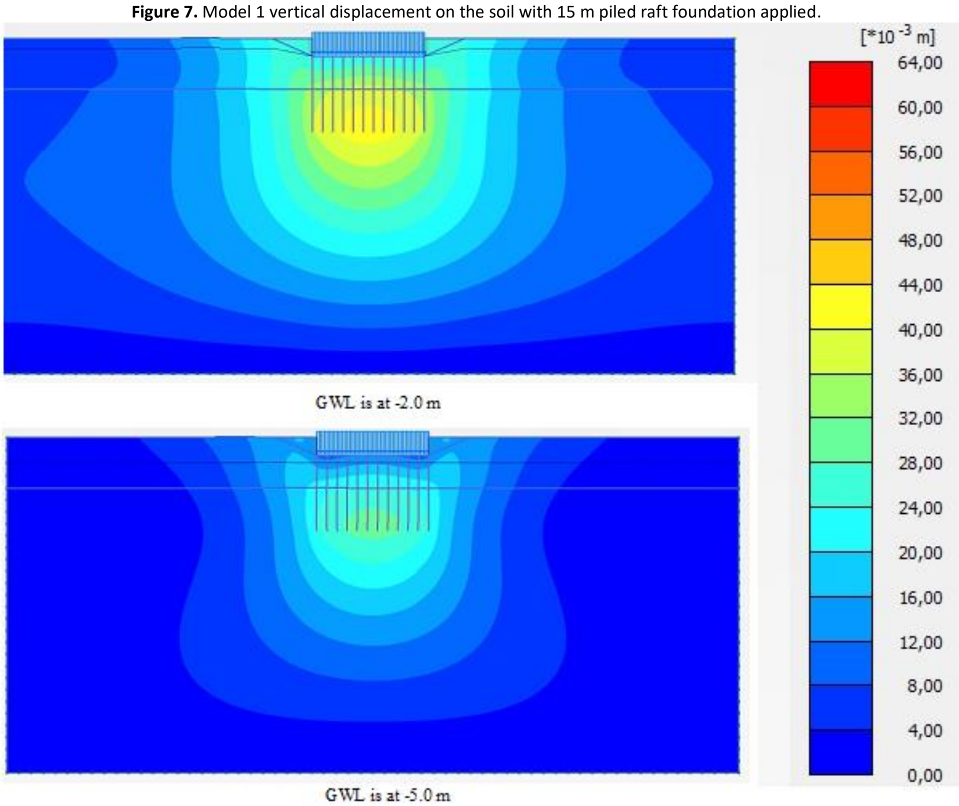


Figure 7. Model 1 vertical displacement on the soil with 15 m piled raft foundation applied.



Analysis for 20 m piled raft foundation application was carried out at the groundwater level of -2.0 m and -5.0 m using Model 1. Analyzes were made for 20 m piled raft foundation at groundwater level of -2.0 m and -5.0 m for each of Model 1 through 6. From the figures were observed the deformation decreases with the lowering of the groundwater level. The vertical displacements were obtained as a result of the analysis was shown in Figure 8. Vertical displacements at the groundwater level of -2.0 were determined between 30 mm and 109 mm. Vertical displacements at the groundwater level of -5.0 were determined between 26 mm and 97 mm. At both the groundwater level, the lowest displacement value was obtained in Model 2, and the highest displacement value was observed in Model 3 and 4.

Analysis for 25 m piled raft foundation application was carried out at the groundwater level of -2.0 m and -5.0 m using Model 1. The vertical displacements obtained as a result of the analysis- showed in Figure 9. Analyzes were made for 25 m piled raft foundation at groundwater level of -2.0 m and -5.0 m for each of Model 1 through 6. From the figures were observed the deformation decreases with the lowering of the groundwater level. Vertical displacements at the groundwater level of -2.0 were determined between 27 mm and 101 mm. Vertical displacements at the groundwater level of -5.0 were determined between 24 mm and 90 mm. At both the groundwater level, the lowest displacement value was obtained in Model 2, and the highest displacement value was observed in Model 3 and 4.

Figure 8. Model 1 vertical displacement on the soil with 20 m piled raft foundation applied.

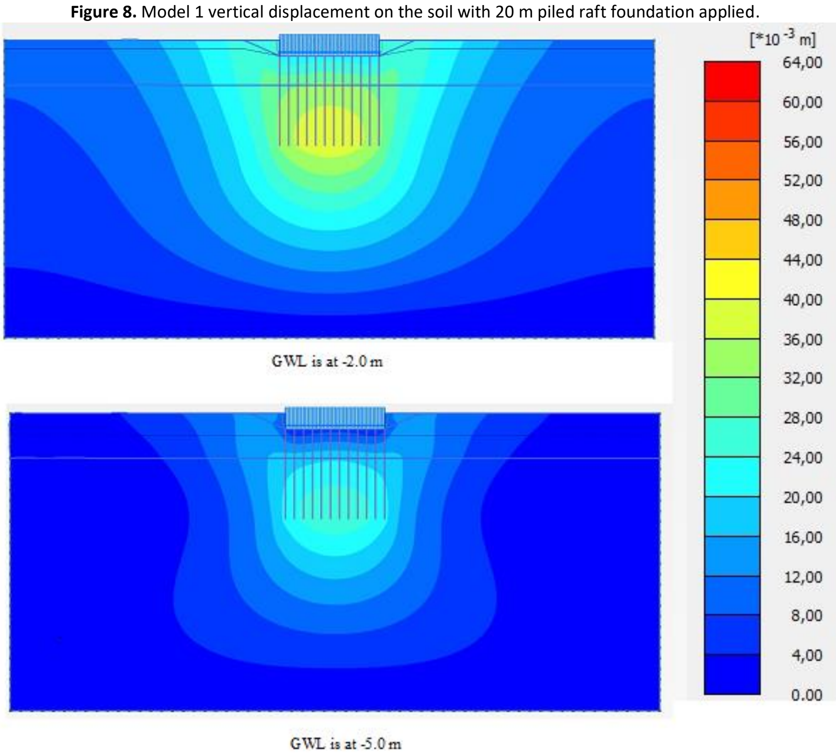
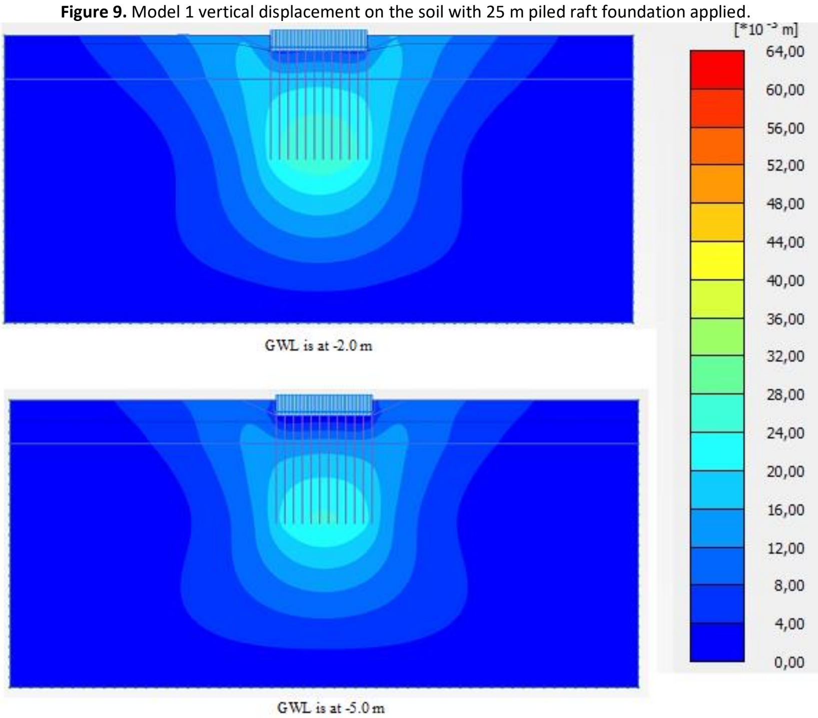


Figure 9. Model 1 vertical displacement on the soil with 25 m piled raft foundation applied.



As a result, the models' vertical deformation values made as piled raft foundation design gave the largest in the bottom layer SM (Model 3 and 4). The smallest is the bottom layer GC and the upper SM (Model 2). Generally, in soil profile with the bottom layer GC, the vertical deformation value of the upper layer SC is higher than the upper layer SM. In soil profiles with bottom layer SM, the upper layer MH and ML's vertical deformation values were equaled. In soil profiles with bottom layer SC, the vertical deformation values of the upper CH were higher than the upper CL. From all analyses, it has been observed that vertical displacement decreases in all models by designing the piled raft foundation instead of the raft foundation. Similar findings were observed by Shukla, Desai, & Solanki, 2011, and Wulandari, & Tjandra 2015. In the piled raft foundation analyses created for all soil, models were seen that more vertical displacement occurred at the groundwater level close to the surface than the deeper groundwater level.

Results and Discussion

Plaxis 2D analyses of basic designs were made based on the structural load on two different groundwater levels. The changes in the total values resulting from the analyzes were given in Figure 10. In the soil designs at the vertical displacement groundwater level close to the surface, the deformation values were higher than the groundwater level at a more profound level. A decrease in groundwater level provides a reduction in deformation values, and permanent drainage systems can be applied to the soil with a high groundwater level to eliminate this adverse situation. It was observed that the vertical displacement values decrease as the pile length increases. These findings are also consistent with those of Patowary, & Nath (2015), Sinha, & Hanna (2017) and Khanvilkar (2018). Also, if we compare the deformation according to the L/D ratio, deformation increases with the decrease of the L/D ratio (Figure 11). Similar findings were observed by Neto, Cunha, Santos, Albuquerque & Garcia (2014) and Elwakil, & Azzam (2016).

Displacement of Foundations Exposed to Earthquake Impact

Raft foundation and L=10 m piled raft foundation were modeled with a 5.4 magnitude earthquake load at -2.0 m under groundwater level on all models. The models were exposed to earthquake load after static loading with drainage. Figure 12 was given relation to given time-displacement during an earthquake. Time-displacement graphs were shown on selected three Models and was taken from the midpoint of the foundation area for Ux and Uy. Ux values are very close for raft and pile raft foundation for all models. Uy values are different for raft and pile raft foundation for all models. Model 4 showed the largest displacement when the raft foundation and piled raft foundation were designed during an earthquake. In the soil profiles with bottom layer GC, the vertical deformation values of the upper layer SM (Model 2) were higher than the upper layer SC (Model 1) during the earthquake for both foundation design. In the soil profiles with bottom layer SM, the vertical deformation values of the upper soil MH (Model 4) were higher than the upper ML (Model 3) during the earthquake for both foundation design. In the soil profiles with bottom layer SC, the vertical deformation values of the upper layer CL (Model 5) were higher than the upper layer CH (Model 6) during the earthquake for raft foundation design, but the vertical displacement values are the same in these soil profiles for piled raft foundation. As a result, the largest vertical displacement in earthquake load was also seen in models with the bottom layer SM and the upper layer ML and MH. This situation can be explained as the excessive deformations of sandy and silty soils under earthquake loads (Erken, Özay, Kaya, Ülker, & Elibol, 2004).

Figure 10. Total displacement according to different fundation types applied on the soil.

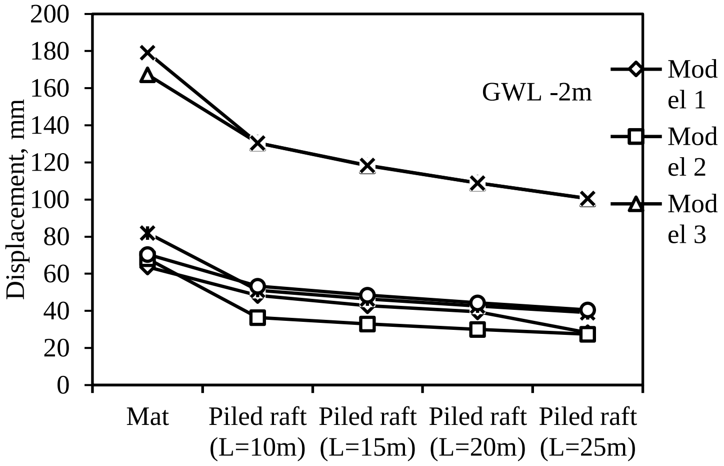


Figure 11. Comparing deformation and pile length/pile diameter.

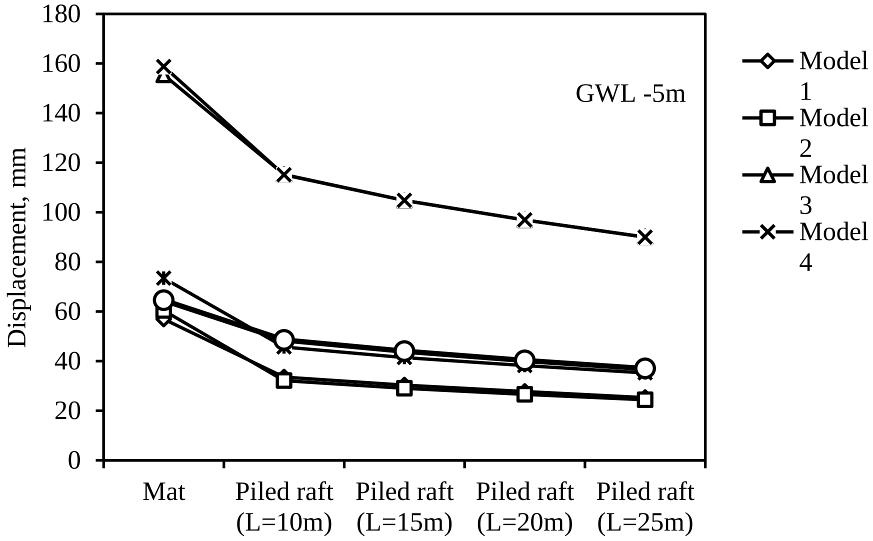
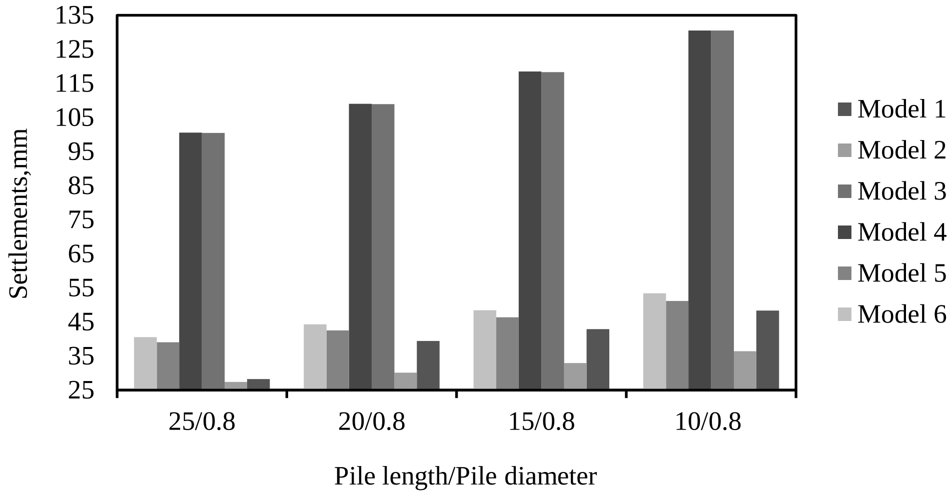
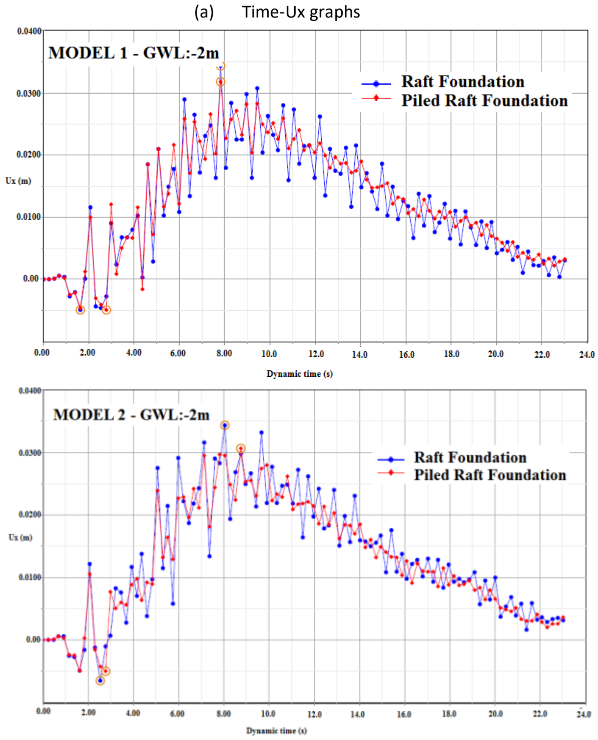
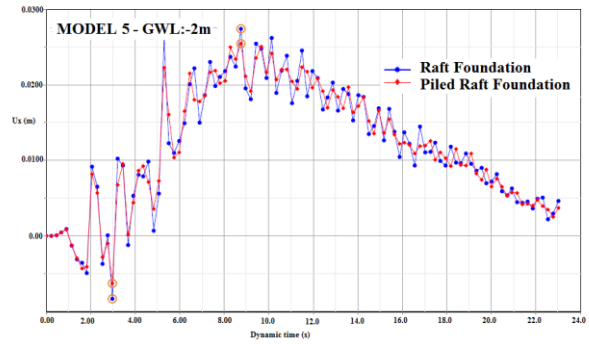


Figure 12. Time-displacement graphs during an earthquake of models.

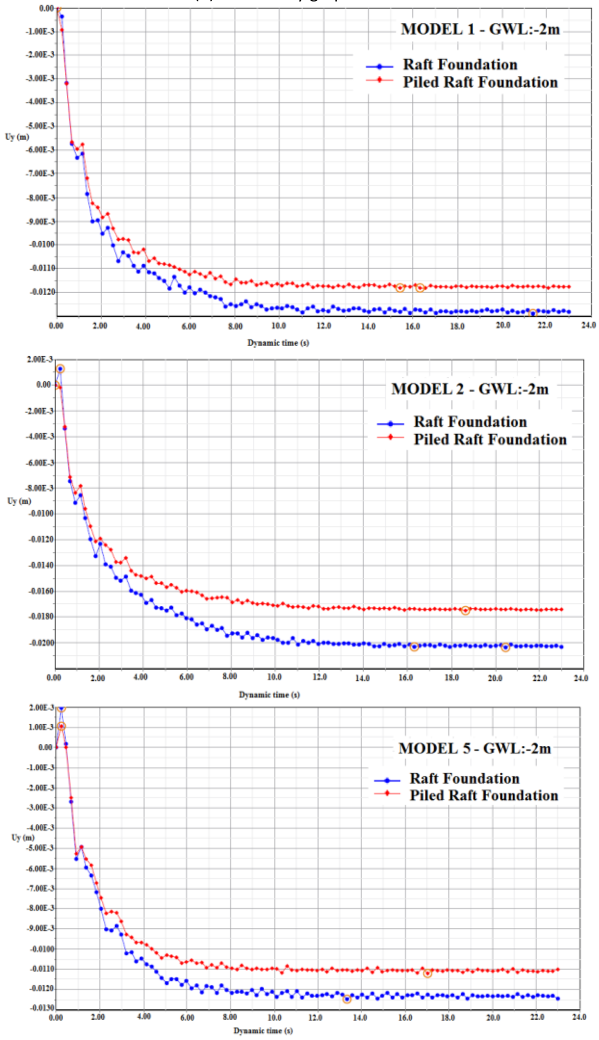


(a) Time-Ux graphs





(b) Time-Uy graphs



Conclusions

In this study, displacements were examined on the soil according to different soil classes, groundwater, earthquake magnitude, and foundation system using Plaxis 2D for raft and piled raft foundation. The models were created on a two-layer ground 66m thick at the groundwater level of -2.0m and -5.0m. In models, upper layer soil classes are clayey sand, silty sand, low plasticity silt, high plasticity silt, low plasticity clay, high plasticity clay, and bottom layer soil classes, silty sand, and clayey sand. In the six different problematic grounds, raft and piled raft foundations formed, respectively, and deformations under static load calculated. The raft foundation and L=10 m piled raft foundation were modeled with a 5.4 magnitude earthquake load at -2.0 m under groundwater level on all models. The following conclusions can be drawn from this study:

- Vertical displacements obtained fom in raft foundation anayses were seen be different depending on soil profiles and groundwater level. Vertical deformation values at -5m under groundwater level decreased by 7-11%. Among the soil models, the piled raft foundation's largest vertical displacement value was in the bottom layer SM and upper layer MH soil profile, and the smallest vertical displacement value of piled raft foundation was in the bottom layer GC and upper layer SC soil profile for both groundwater level.

- Vertical deformation values for D = 0.80m were decreased by 22-47% for L = 10m, 29-52% for L = 15m, 35-56% for L = 20m, and 40-60% for L = 25m at -2.0 m under groundwater level. Vertical deformation values for D = 0.80m were decreased by 25-46% for L = 10m, 32-52% for L = 15m, 38-56% for L = 20m and 42-60% for L = 25m at -5.0 m under groundwater level. It observed that the deformation values that occur as the pile length, which settles on the soil layer in the piled raft foundation system decreases. The piled raft foundation system was seen that provided a great advantage compared to the raft foundation system in keeping the deformations under control.

- All models were analyzed by exposure to the earthquake. Ux values are very close for raft and pile raft foundation for all models. Uy values are different for raft and L=10m pile raft foundation for all models. In Model 1, the raft foundation has made about 8% more displacement than the pile raft foundation, and in Model 2, this value increased to about 13%. In Model 3, the raft foundation has made about 6% more displacement than the pile raft foundation, and in Model 4, these values decreased to 4%. In Model 5, the raft foundation has made 28% more displacement than the pile raft foundation, and in Model 6, these values were very close. As a result, the largest vertical displacement in earthquake load was also seen in models with the bottom layer SM.

In the foundation designs created in all soil models, in the analyses carried out at the groundwater level close to the surface, higher deformation values were obtained than the deeper groundwater level. It recommended applying permanent drainage systems on the soils with a high groundwater level to eliminate this adverse situation. This study has again demonstrated the necessity to make a complete foundation system designed under existing loads. However, it can be choose correct the foundation system by staying on the safe and economic side.

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