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Evaluating the impacts of using piles and geosynthetics in reducing the settlement of fine-grained soils under static load

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Abstract. The construction of combined pile-raft foundations is considered as the main option in designing foundations in high-rise buildings, especially in soils close to the ground surface which do not have sufficient bearing capacity to withstand building loads. This paper deals with the geotechnical report of the Northern Fereshteh area of Tabriz, Iran, and compares the characteristics of the single pile foundation with the two foundations of pile group and geogrid. Besides, we investigate the effects of five principal parameters including pile diameter and length, the number of geogrid layers, the depth of groundwater level, and pore water pressure on vertical consolidation settlement and pore water pressure changes over a year. This study assessed the mechanism of the failure of the soil under the foundation using numerical analysis as well. Numerical analysis was performed using the two-dimensional finite element PLAXIS software. The results of fifty-four models indicate that the diameter of the pile tip, either as a pile group or as a single pile, did not have a significant effect on the reduction of the consolidation settlement in the soil in the Northern Fereshteh Street region. The optimum length for the pile in the Northern Fereshteh area is 12 meters, which is economically feasible. In addition, the construction of four-layered ten-meter-long geogrids at intervals of 1 meter beneath the deep foundation had a significant preventive impact on the consolidation settlement in clayey soils.

Keywords: consolidation settlement; deep foundation; geogrid; pile; pile group; PLAXIS

1. Introduction

It is practically impossible to prevent consolidation settlement in clayey fine-grained soil. Hence, soil settlement, as a function of time is due to the drainage of water from the soil voids, which is Landslides or slope failures, consolidation is a naturally occurring phenomenom known as geological erosion (Shariati *et al.* 2011a, Safa *et al.* 2019a, Shariat *et al.* 2019). However, artificially altered land by excavation, deforestation, and urbanization also contributed to these detrimental effects, followed by a change in the volume of fine-grained soil due to water removal from pore spaces and load transferal from excess pore water pressure (P_0) to primary consolidation soil particles. As Fig. 1 shows, the foundation settlement can be divided into three types: rigid block or uniform settlement (a), bending and tilting (b), and non-uniform settlement (c)

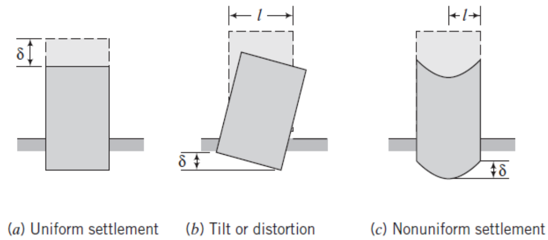

Fig. 1 Types of structural settlement

(Skempton *et al.* 1957, Budhu 2015, Shariati *et al.* 2019a, Shariati *et al.* 2019d, Trung *et al.* 2019a). The effect of the damage caused by uniform settlement is limited to surrounding drainage systems, adjacent buildings, and public utilities. Tilting and uniform settlement issue from uneven movement and may cause serious problems, especially in high-rise structures. Skempton and Bjerrum (1956) examined ninety-eight buildings, forty of which were damaged. The data from Skempton et al. (1956) cannot be used for buildings that have experienced settlement due to underlying thick sand deposit in clayey layers (Sinaei *et al.* 2012, Shao *et al.* 2015, Afrazi *et al.* 2018, Sari *et al.* 2018, Afrazi *et al.* 2019, Shariati *et al.*

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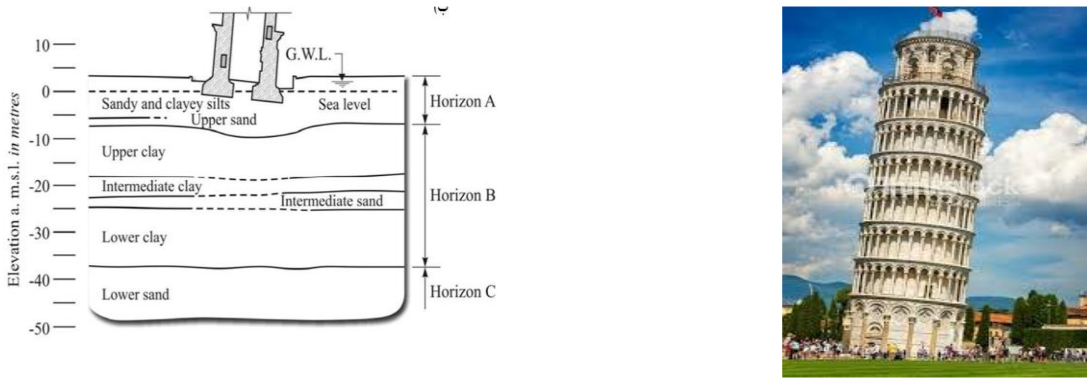


(a) Subsoils of Tower of Pizza (b) Tower of Pizza

Fig. 2 Geotechnical status of the layers under the foundation of the Pisa Tower

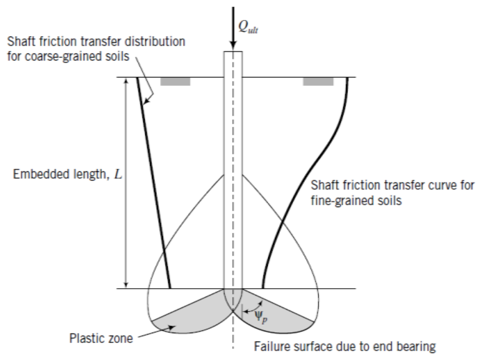


Fig. 3 Failure mechanism in single pile foundations

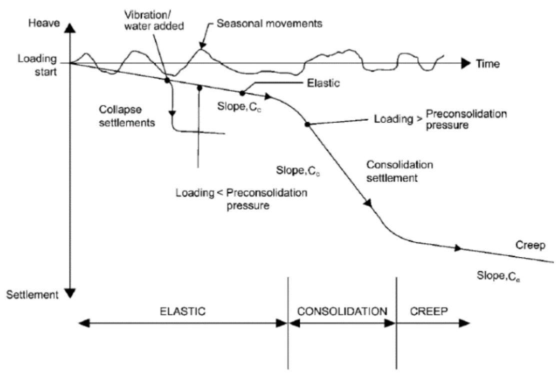


Fig. 4 Soil layer settlement in different conditions

Table 1 Settlement type of various layers

Principal Soil Type	Type of Movement			
	Immediate	Consolidation	Creep	Swell
Rock	Yes	No	No	some
Gravel	Yes	No	No	No
Sand	Yes	No	No	No
Silt	Yes	Minor	No	Yes
Clay	Yes	Yes	Yes	Yes
Organic	Yes	Minor	Yes	Yes

2019e, Shi *et al.* 2019b, Suhatril *et al.* 2019, Xie *et al.* 2019, Safa *et al.* 2019).One of the most interesting examples of structural damage caused by the settlement of saturated fine-grained layers is the tilting of the Pisa tower in Italy, as shown in Fig. 2(b). Extensive studies have been conducted on the geotechnical status below the foundation of this structure. For example, several studies have been carried out by Burland *et al.* (2009) on the status of this tower after stabilization operations (Shao and Vesel 2015, Heydari *et al.* 2018). The layers under the foundation of this structure consist of three types of layers, as can be seen in Fig. 2(a). There is a layer of delta sediments with a thickness of about 13 m including clayey sandy silt under tidal conditions and the foundation (layer A). Beneath this layer, there is a normal consolidated soft clay layer up to a depth of 43 m (layer B), and under this layer, there is a dense sea sand layer up to a depth of 63 m (layer C). Groundwater level is in the range of 1-2 m under the foundation, which means 3 m above sea level (Meyerhof *et al.* 1978, Ovando-Shelley *et al.* 2007, Burland *et al.* 2009, Mahmoudi Azar *et al.* 2017, Ziaei-Nia *et al.* 2018).

According to Fig. 2(a), at the boundary between layers A and B, the presence of a concave surface at a depth of 3 to 3.5 m indicates the occurrence of consolidation settlement in layer B due to the inflicted loading on the foundation of the tower (Sharma *et al.* 2009, Khorramian *et al.* 2015, Khorramian *et al.* 2017). In 1990, the Italy government ordered the formation of a technical committee and implementation of strengthening measures due to the incremental rate of tilting and the possibility of the structural collapse of the tower (Sadrekarimi *et al.* 2007, Alizadeh *et al.* 2018, Hosseinpour *et al.* 2018, Armaghani *et al.* 2019, Jahandari *et al.* 2019). Another famous city which deals with the issues of fine-grained soils is Mexico City, the capital of Mexico. Large city structures like most historical structures, such as those in Fig. 3, have settled into the clay layer, where settlement rates are within the range of 5 to 40 cm per year for different areas based on satellite measurements (Meyerhof and Hanna 1978, Ovando-Shelley *et al.* 2007, Shao *et al.* 2018, Shi *et al.* 2019a). Sometimes, a pile group may sink down on a layer of soft clay, apply enough load on it (soft clay) and results in a consolidation settlement. To estimate the consolidation settlement as a function of time, it is assumed that the whole design load has been inserted at 2/3L depth and then distributed with the ratio of 1:2. In order to mobilize skin friction and resistance of the pile tip, some degree of movement is necessary for the pile (Sharma *et al.* 2009, Arabnejad Khanouki *et al.* 2010). Field tests have shown that vertical displacement of about 5 to 10 mm is required to fully employ skin friction. Vertical and horizontal displacements depend on soil strength as well as pile length and diameter. In driven concrete piles, full resistance of the end of the pile will be employed when the vertical displacement is about 10% of the total diameter of pile tip, and slip and failure areas are formed similar to shallow foundation, as shown in Fig. 3.

Occasionally, the deep layers are stiffer than the top layers, and in this case, the pile function is to transfer the load to the deep layers. Load transfer to deeper layers reduces settlement. The initial effective stress is higher in deep layers; thus, the ratio of increment in overburden to the initial stress in the deep layers is less than this ratio in top layers, so the settlement decreases. In fact, the reduction of this ratio is the main reason of the decrement in settlement in foundations with the piles in comparison to shallow foundations. In other words, the piles transfer the load to the layers where the initial effective stress is large, and as a result, the ratio of increase in the initial stress decreases and the settlement diminishes (Budhu 2015). Single piles are rarely used, so it is necessary to study the group behavior of piles in engineering. The arrangement of the piles in a group, meaning their number and their distances from each other as well as their vertical orientation is momentous. It is also essential to optimize the length of the single pile or the diameter of the pile tip and the number of pile groups used. A stronger pile is needed as the the distance of piles increases from one another (Sadrekarimi and Zekri 2007). The next issue is the consolidation settlement discussed in this project. Fig. 4 presents the soil layer settlement under various conditions such as swelling and shrinkage due to seasonal changes in the moisture, elastic settlement, consolidation of pre-consolidated state for lower stresses, and normal consolidation for larger stresses, creep, collapse owing to vibration or increased moisture in the layer. The type of the settlement varies for different types of layers. The consolidation settlement and creep occur in the clayey and silty layers and the immediate or elastic settlement appears in all the layers. This is presented in Table 1 (Prasad 2018).

2. Geotechnical characteristics of the under-study area

Tabriz, as one of the major metropolises of the country, has special geotechnical conditions. In some areas of this city, some structures have been damaged due to the presence of fine-grained layers and high groundwater level. The Northern Fereshteh in Baghmisheh suburb is one of those areas. The location of the boreholes has been selected within rather intact and natural land of that region. According to Fig. 5, borehole is considered in the Northern Fereshteh area and within silty clayey soils, which is shown with red color. The location of the boreholes was selected within rather intact and natural land of that region. The borehole location on the geological reference map is presented in Fig. 6. In this area, layers have been formed

Fig. 5 The location of Fereshteh Street on the Google Earth map in Tabriz city

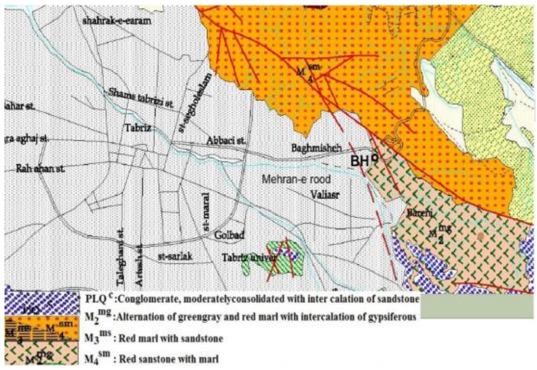


Fig. 6 Borehole location on the Geological Reference Map of the region (Based on map 1:100000 Mapping Organization of the Country)

(a) A cracked structure (b) A tilted structure

Fig. 7 An example of structure in Northern Fereshteh area

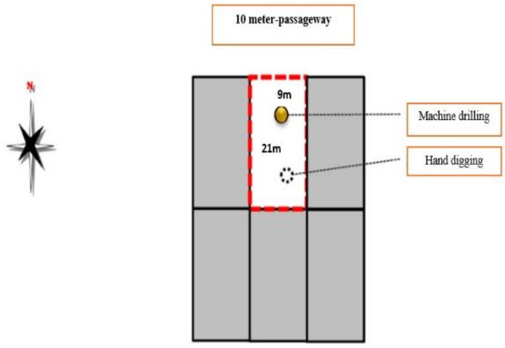


Fig. 8 Location of the property under study and drilled borehole

from fine-grained sandy silty clayey soils due to the topography of the area and without any significant

(a) 2 m (b) 4 m (c) 6 m (d) 8 m

Fig. 9 Samples taken from boreholes of study at depths of (a)-(d)

Table 2 Characteristics of the under-study structure

Depth of drilling	Embedment depth	Number of floors	Area of the land
-1.2 m	-1.2 m	6	189 m^2

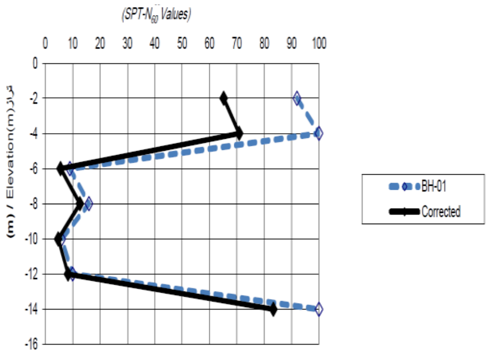


Fig. 10 SPT value changes with depth

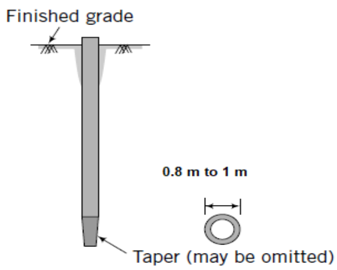


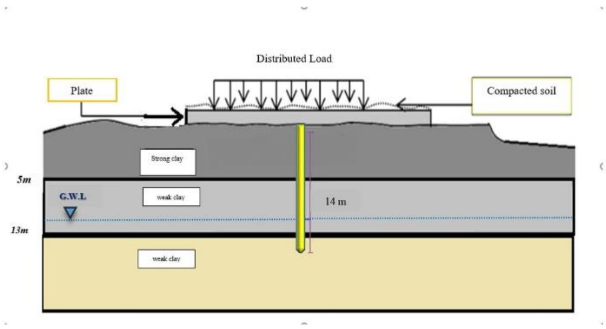
Fig. 11 Precast and pre-stressed single concrete pile with a circular cross section of different diameters

compression and consolidation. Unwillingness of some owners and employers to construct deep foundations due to economic issues in a number of projects implemented in Fereshteh area of Tabriz, and the manipulation of legal stipulations as a result of disobeying the opinions of design engineers, supervisors, and executors in another side led to unallowable settlements. On the other hand, infiltration of surface waters and precipitation in the area has resulted in water accumulation under the foundations and the saturation of the mentioned layers (The water level is less than 2 meters deep). Thus, as a result of indiscriminate construction of foundations and ignorance of the geotechnical status of these layers in the foundation design, some of these structures have titled. An example of these structures with a relative settlement of around 33 cm is shown in Fig. 7.

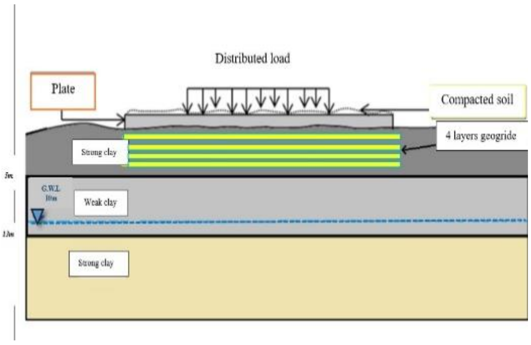
In this project, the locations of the boreholes in the land under study are shown in Fig. 8. During drilling, samples were taken for examination and laboratory tests. After analyzing the obtained data, we determined the bearing capacity of the soil presented in this report.

A borehole with a depth of 15 m and another one with the depth of 1 meter were drilled using machine drilling and hand digging in the studied land. During drilling and along with in-situ tests, the samples were taken from different depths, packed appropriately, and transferred to the lab for various physical and mechanical tests. In Fig. 9, sample images are shown.

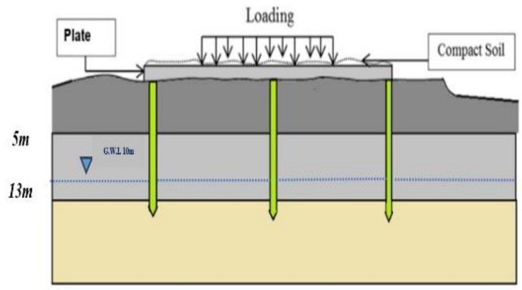
According to the drilled borehole log and the state of the layers, it should be mentioned that in the soil of the under-study region, the top soil with a thickness of about 0.5 m was observed. Under the disturbed soil up to a depth of 5



(a) Single pile



(b) Geogrid



(c) Pile group

Fig. 12 Geotechnical models of the soil profile of the studied area in the presence of (a)-(c)

Fig. 13 Uniaxial geogrid

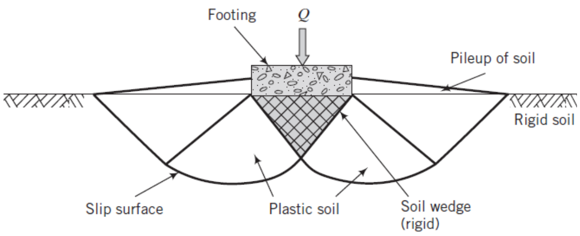


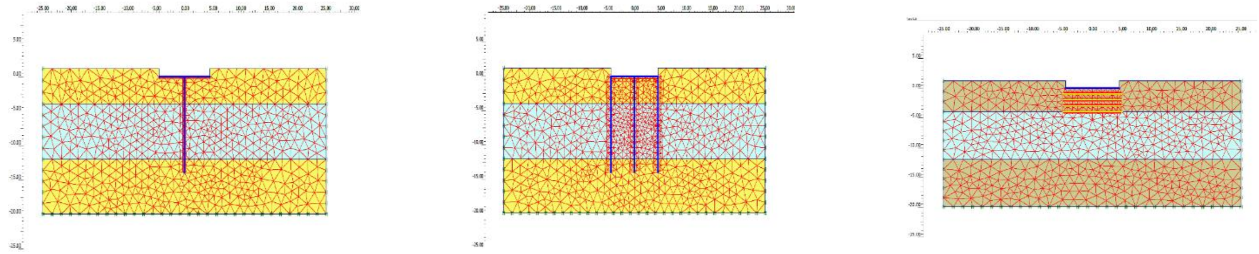
Fig. 14 Failure mechanisms

meters, a fine-grained layer with sand grains and a relatively suitable compaction can be observed. From the depth of 5 meters to the depth of 13 meters, brown-red sandy fine-grained soil, which is very loose, is seen as the dominant soil layer. From the level of 13 meters to the end of the borehole (depth of 15 meters), silty clayey soil is seen with a relatively high compaction, and water level was observed at a depth of 10 meters with respect to previous drilling experiments.

The characteristics of the studied property are summarized in Table 2. Fig. 10 illustrates the graph of SPT (Standard Penetration Test) value variations based on borehole information. As can be seen, despite SPT value increased up to the depth of 2 m, this value has plummeted at depths of 2 to 26 m. Hence, by referring to these data, numbers of $N_1 = 8$ for the loose soil layer (for depths between 5 to 13 m) and $N_1 = 35$ for the underlying layer (at the depth of 26 m) can be cautiously considered as average SPT value. Atterberg test was performed on disturbed soil samples according to ASTM-D4318. The average Liquid limit (LL) was almost in the range between 16 and 27, and the plastic limit (PL) was ranged from 8 to 14. Therefore, the plasticity index was equal to PI = 12.

Considering the fact that in recent years the structures of the Northern Fereshteh area have been susceptible to consolidation settlement, we used a 14-meter-long precast concrete pile with a circular cross-section, a capacity of 39 tons, and a diameter of 0.8 meters for the stability of the structure, as shown in Fig. 11. This type of pile was selected according to the dead and live loads of the structure. Fig. 12 presents a comparison of the studied geotechnical models for the examination of what matters in this project which is the impact of all three conditions on soil consolidation settlement results over the period of a year, so that a comparison could be made for the consolidation settlement level in the single pile foundation (Fig. 12(a)). In the presence of geogrid (Fig. 12(b)), the pile group foundation (Fig. 12(c)) was drawn, and the geogrid layering was finalized through changing the groundwater level and the length and diameter of the piles.

Based on the results of field and laboratory tests and engineering judgment, the geotechnical parameters were estimated as follows and are used in the following calculations. It is noteworthy that the mechanisms of clay soil failure under a deep foundation (single pile, pile group) and in the presence of reinforcing material like geogrid, which is a type of geotextile, are compared in this study. In the following sections, a terse description of the utilized



(a) Single concrete piles (b) Pile group (c) Geogrid

Fig.15 Modeling for six-floor structure with (a)-(c) in different layers and lengths

Table 3 Properties of soil layers

Type of soil layer	Soil sampling	Depth of layer (m)	Es (kN/m^2)	Constitutive model	γ_s (kN/m^2)	PI (%)	C (kN/m^2)	C_u (kN/m^2)	ϕ(°)	Mv (kN/m^2)	v
CL	undisturbed	4.5	20000	Mohr-coulomb	18.1	12	7	30	24	1.25	0.30
CL	undisturbed	8	10000	Mohr-coulomb	16.6	8	10	30	18	0.9	0.35
CL	undisturbed	2	10000	Mohr-coulomb	18	14	7	10	24	1.25	0.30

Table 4 Concrete wall properties

EA (kN/m^2)	EI (kN/m^2/m)	L (m)	B (m)	d (m)	W (kN/m^2)
18×108	107×15	9	1	1	7

Table 5 Geogrid properties

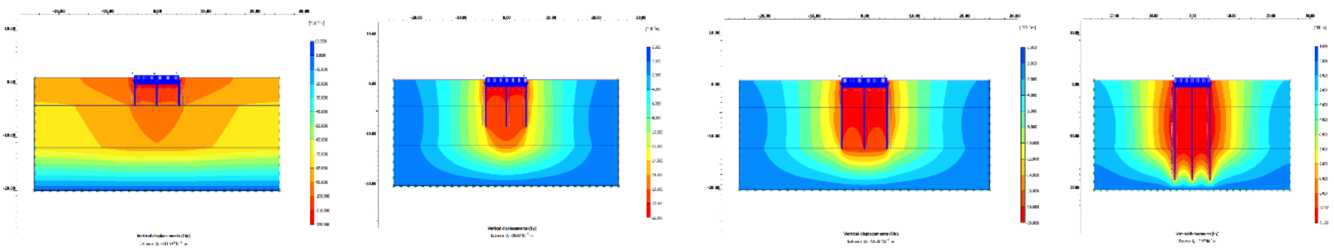
Normal stiffness EA (kn/m^2)	Material Type	L (m)
104	Linear Elastic	10

geogrid in modeling and numerical analysis is provided. Owing to the fact that geogrid is widely used for reinforcing the soil, its properties such apertures with suitable dimensions for fixing and fastening to the surrounding soil can play a reinforcing role in settleable soils. The geogrid used to examine its effect on increasing or decreasing soil consolidation settlement in Northern Fereshteh, which was modeled as a uniaxial type in PLAXIS software (Fig. 13). In order to improve the foundation, we use geogrid in the distance range of 0.33 to approximately 0.7 times width under the foundation to achieve better results. In other words, considering distance of geogrid from the bottom of the foundation with D and the width of the foundation with W, the best performance for the geogrid when the D/W ratio between 0.33 and 0.4 is observed.

Prandtl (1920) theoretically showed that when a rigid body is exposed to centric loads, a stiff wedge of material is trapped under that body, as shown in Fig. 14. Tarzaghi applied Prandtl's theory in the case of a strip footing, assuming that soil is a rigid, weightless, isotropic, semi-infinite, and homogeneous plastic material. According to Prandtl's theory, a foundation failure occurs due to a stiff wedge of the soil under the foundation, which continues its way into the soil downwards (Daie *et al.* 2011).

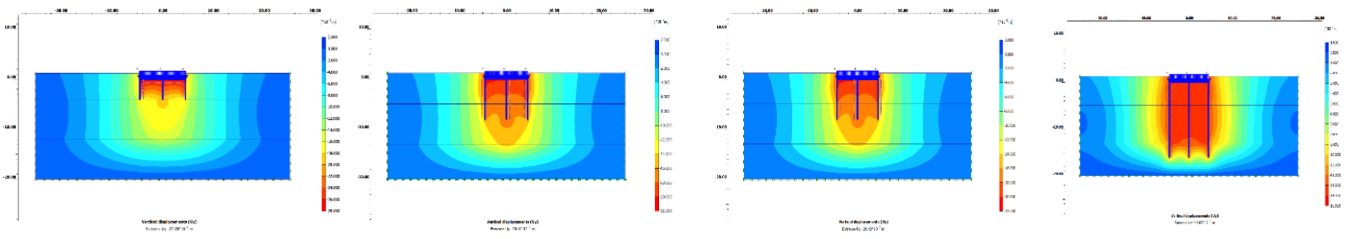
3. Numerical modelling

There are different available techniques for data validations and predictions such as employing artificial neural networks. varoius techniaues have been employed for data validatinon where the best methods has been reported as extreme learning machine (Hamidian *et al.* 2012, Shariati *et al.* 2019c, Shariati *et al.* 2019e, Trung *et al.* 2019b), genetic programming , neural network and other natural basis functional networks (Shariati *et al.* 2011a, b, Sinaei *et al.* 2011, Schumacher *et al.* 2013, Mohammadhassani *et al.* 2014b, c, Shariati 2014, Toghroli *et al.* 2014, Shah *et al.* 2015, Shariati *et al.* 2015a, b, Shah *et al.* 2016, Shahabi *et al.* 2016, Shariati *et al.* 2016, Khorami *et al.* 2017, Khorramian *et al.* 2017, Shariati *et al.* 2017, Heydari and Shariati 2018, Hosseinpour *et al.* 2018, Ismail *et al.* 2018, Nasrollahi *et al.* 2018, Nosrati *et al.* 2018, Paknahad *et al.* 2018, Sadeghipour Chahnasir *et al.* 2018, Sedghi *et al.* 2018, Shariat *et al.* 2018, Wei *et al.* 2018, Zandi *et al.* 2018, Katebi *et al.* 2019, Li *et al.* 2019, Luo *et al.* 2019, Sajedi *et al.* 2019, Xie *et al.* 2019), also finite element and finit strip method have been proved to be as a reliable data authenfication and prediction (Sinaei *et al.* 2012, Shah *et al.* 2015, Shariati and Schumacher 2015a, Shariati *et al.* 2015b, Safa *et al.* 2016, Sadeghipour Chahnasir *et al.* 2018, Sedghi *et al.* 2018, Sharafi *et al.* 2018a, Sharafi *et al.* 2018b, Toghroli *et al.* 2018, Chuanhua Xu 2019, Kildashti *et al.* 2019, Mahdi Shariati 2019, Milovancevic *et al.* 2019, Shariati *et al.* 2019b, Shariati *et al.* 2019c, Shariati *et al.* 2019e, Taheri *et al.* 2019, Trung *et al.* 2019b, Mortazavi *et al.* 2020), Finite element method (Mahdi Shariati 2019, Taheri *et al.* 2019, Usefi *et al.* 2019), Finite strip method (Sharafi *et al.* 2018b, Sharafi *et al.* 2018c, Mansouri *et al.* 2019). Finite element method which is generally carried out by FE programs as ABAQUS and



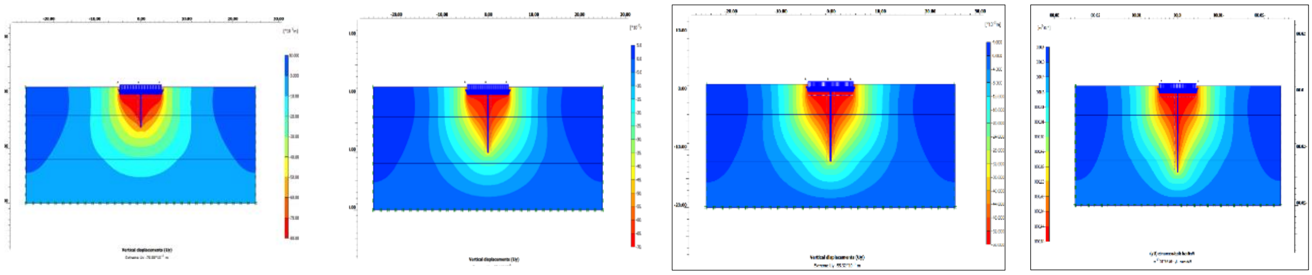
(a) 4 m (b) 8 m (c) 12 m (d) 18 m

Fig. 16 The settlement of the six-floor structure in the presence of a raft foundation based on a pile group with the diameter of 0.8 meter in cm



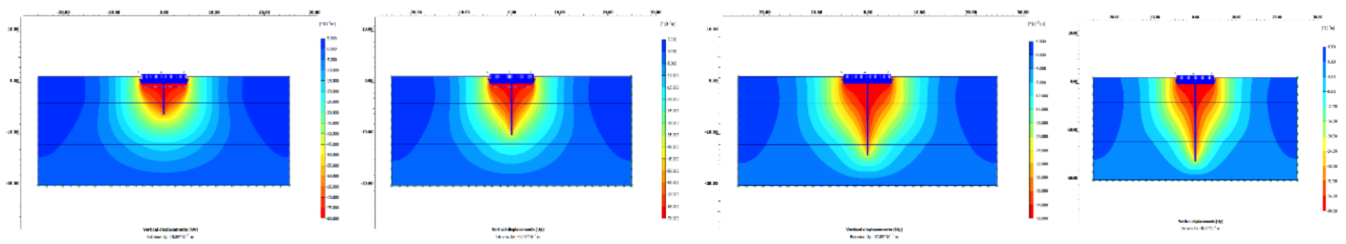
(a) 4 m (b) 8 m (c) 12 m (d) 18 m

Fig. 17 The settlement of the six-floor structure in the presence of a raft foundation based on a pile group with the diameter of 1 meter in cm



(a) 4 m (b) 8 m (c) 12 m (d) 18 m

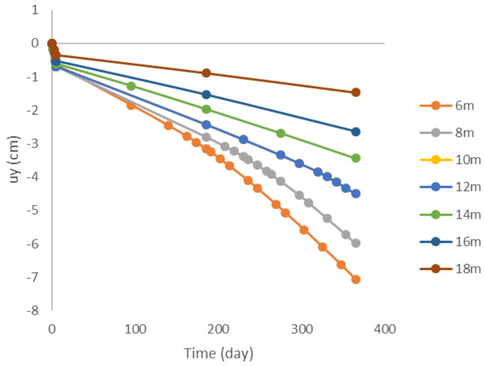
Fig. 18 The settlement of six- floor structure in the presence of raft foundation based on a single pile with a diameter of 0.8 in cm



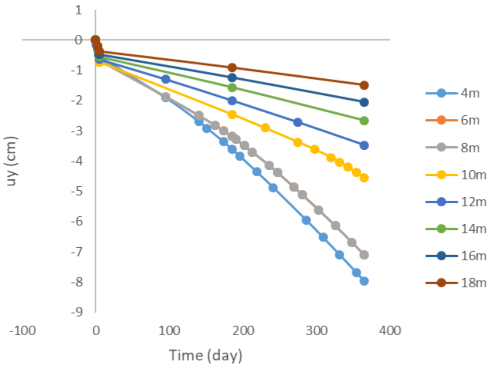
(a) 4 m (b) 8 m (c) 12 m (d) 18 m

Fig. 19 The settlement of six- floor structure in the presence of raft foundation based on a single pile with a diameter of 1 in cm

ANSYS performed as a reliable technique for empirical data validation and response prediction. Different kind of algorithms has introduced which have their traits and advantages (Shariati *et al.* 2014b, Shariati *et al.* 2018, Milovancevic *et al.* 2019). Using the relevant algorithms in order to analytical assessment has been carried out on different types of studies (Shariati *et al.* 2012, Mohammadhassani *et al.* 2013, Schumacher and Shariati 2013, Shariati *et al.* 2013, Mohammadhassani *et al.* 2014a, 2Shariati *et al.* 2014a, Shahabi *et al.* 2016, Sedghi *et al.* 2018, Davoodnabi *et al.* 2019, Katebi *et al.* 2019, Luo *et al.* 2019). That being the case, performing the artificial intelligence algorithms is a potential method to avoid non-linearity and sophisticated analysis of the nanoscale problems. In a geotechnical analysis, because of the existence of elasto-plastic behavior, it is necessary to calculate the increase in plastic and elastic strains and stress, which can be done using constitutional models.

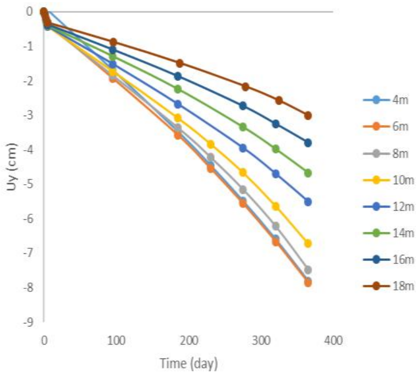


(a) 0.8 m

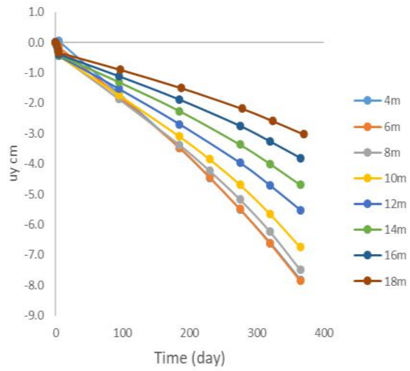


(b) 1 m

Fig. 20 The Settlement-Time graph for pile group length with diameters of (a)-(b) for 365 days



(a) 0.8 m



(b) 1 m

Fig. 21 The Settlement-Time graph for single pile length with diameters of (a)-(b) for 365 days

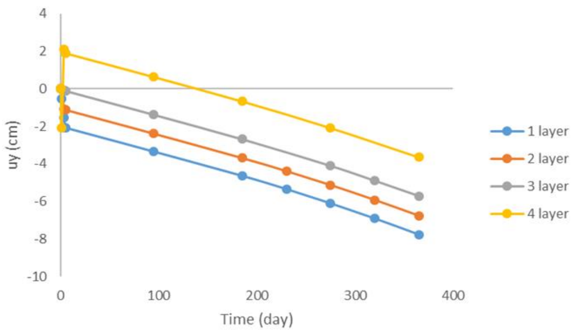
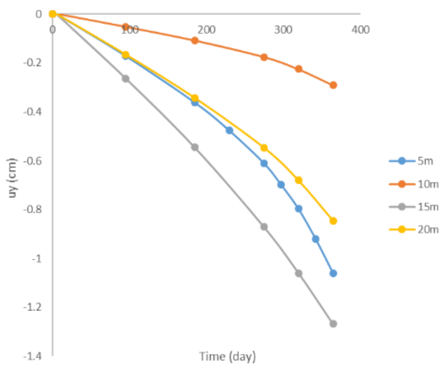
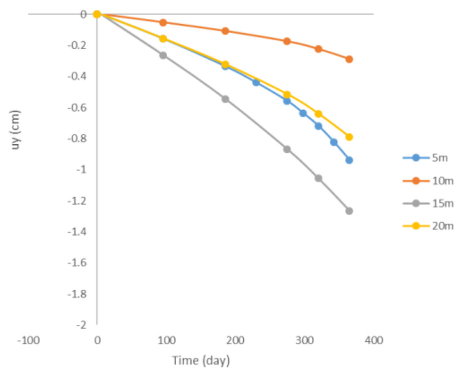


Fig. 22 The Settlement-Time graph based on geogrid layout for 365 days

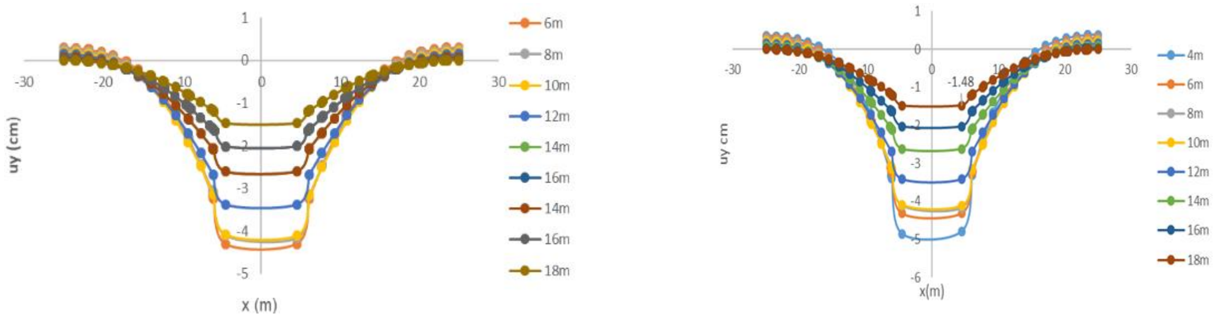


(a) 0.8 m



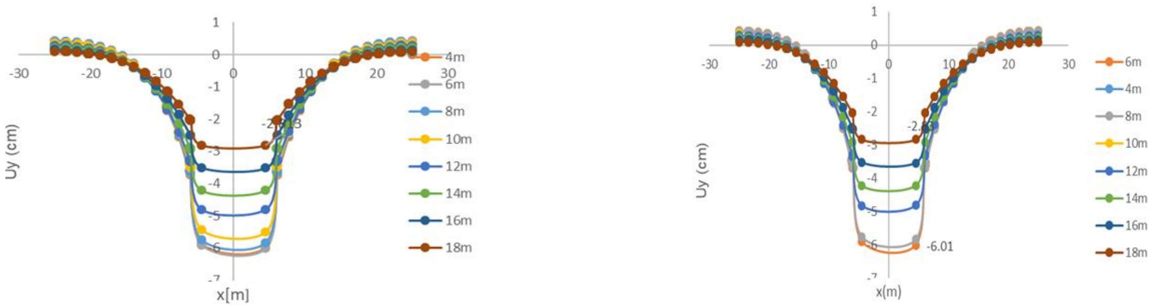
(b) 1m

Fig. 23 The Settlement-Time graph based on groundwater level in single pile with a length of 14 m and diameters of (a)-(b) for 365 days



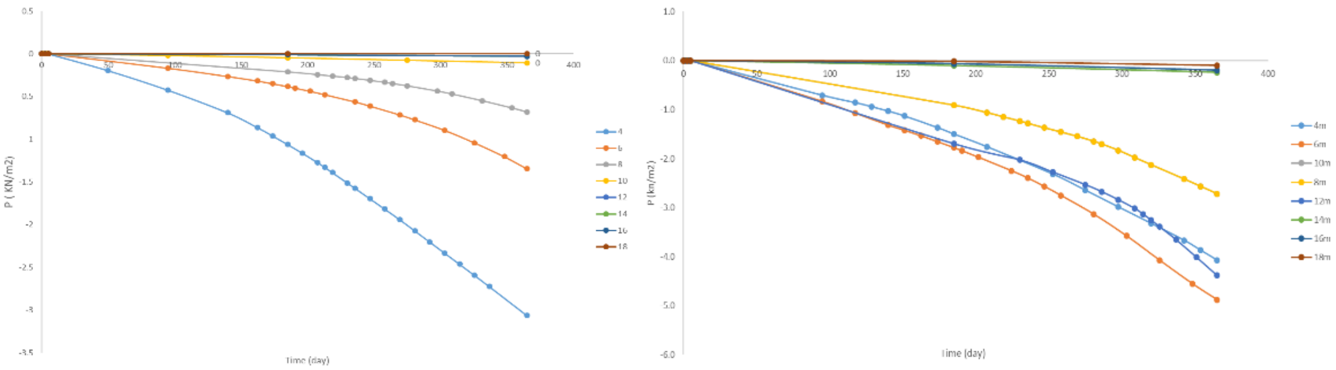
(a) 0.8 m (b) 1m

Fig. 24 The effect vertical settlement changes on failure mechanism: length of the pile group with a diameter of (a)-(b)



(a) 0.8 m (b) 1 m

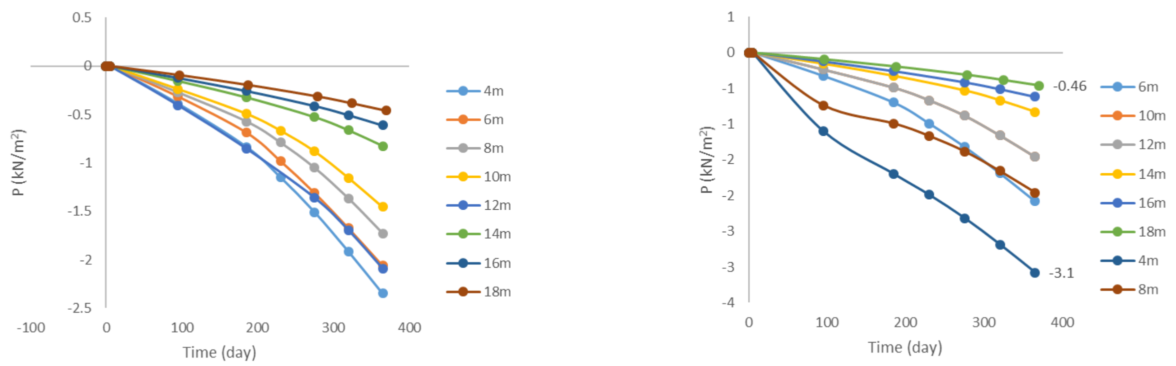
Fig. 25 The effect vertical settlement changes on failure mechanism: length of the single pile with a diameter of (a)-(b)



(a) 0.8 m (b) 1 m

Fig. 26 Pore water pressure - Time graph: Length of pile group with the diameter of (a)-(b) for 365 days

In constitutional mdeling, the relationships between force and stress (ΣF=ma), displacement and strain, and stress and strain are settled. One of the methods of numerical analysis in the case of continuous environments such as soil is the finite element method, which is also the basis of the PLAXIS program (Lozovyi *et al.* 2014, Safa *et al.* 2016, Chen *et al.* 2019). The finite element method is one of the most widely used numerical methods in engineering and was first proposed by Trener *et al.* (1956) to be used in building analysis. In this paper, as illustrated in the Fig. 14, the purpose is to compare the basis of single pile foundation with the two other conditions including pile group and geogrid in terms of geotechnical characteristics. The position of the lateral boundaries has been selected, and therefore, the presence of artificial boundaries does not have a significant effect on the stress-strain field. In other words, the dimensions of the model have been selected so that if the dimensions exceed the selected values, there will be no significant effect on the amount of stresses and strains created in the soil mass around the drilling area and surface structures. Boundary conditions and type and density of element were also selected based on sensitivity analysis, and the results were not affected. For the sake of the accuracy of the meshing calculations, the model has been selected to be minuscule in all areas. The meshing of the model was done within the area four times of the width of the foundation along the vertical axis and nine times of the width laterally, which is in accordance with the recommendations of previous researchers. Ultimately, the model was 25 meters deep and 25 meters wide. Moreover, regarding to groundwater depth, 10m, soil behavior was in a drained condition. Since homogeneous clayey soils are practically impermeable, the coefficient of permeability kz for the selected area was considered to be <10-7 m/day



(a) 0.8 m (b) 1 m

Fig. 27 Pore water pressure - Time graph: Length of single pile with the diameter of (a)-(b) for 365 days

Table 6 Settlement of the six-floor structure foundation based on the variables of length and diameter of the pile group

	Diameter (m)	Length (m)	Settlement (cm)	Shear force (kN/m^2)	Status of the settlement regulations
Pile groups	0.8	4	7.8	40	Unallowable
		6	7.5	159	
		8	6	210	
		10	6	262	
		12	4.5	294	Allowable
		14	3.4	318	
		16	2.6	292	
		18	1.4	258	
	1	4	7	54.3	Unallowable
		6	7	43.4	
		8	5.9	181	
		10	4.5	88	
		12	3.4	256	
		14	3.1	195	
		16	2.6	176	
		18	1.4	185	

Table 7 Settlement of the six-floor structure foundation based on the variables of length and diameter of the single pile

	Diameter (m)	Length (m)	Settlement (cm)	Shear force (kN/m^2)	Status of the settlement regulations
Single pile	0.8	4	8.1	1.3	Unallowable
		6	7.9	1.53	
		8	7.5	17.7	
		10	6.7	15.7	
		12	5.5	16	Allowable
		14	4.7	18.3	
		16	3.8	9.3	
		18	3	22.7	
	1	4	8	107	Unallowable
		6	7	1.4	
		8	6.5	22.8	
		10	6	32	
		12	5.1	42	Allowable
		14	4.7	59	
		16	3.8	79	
		18	3	81	

(Mahdi Shariati 2019). Besides, the properties of the soil layers, concrete wall and geogrid used in the software, are specified in Tables 3-5. In this numerical study, a total of 52 two-dimensional numerical models were formulated for a static analysis based on the Mohr-Coulomb constitutional model. Settlement values of the soil in the study area were compared in 3 conditions: 1- Considering the length of a single concrete pile with a circular cross-section with a diameter of 0.8 m, as shown in Fig. 15(a), and height parameter and diameter of 1m, 2- Using the concrete pile group considering the length and diameter of the pile group (see Fig. 15(b)), and 3- Considering the presence of only one to four layers of geogrids (Fig. 15(c)). The distributed load of 120 kN/m2 six-floor structure was applied to the deep foundation. Fig. 15 illustrates an example of meshed models in a single concrete pile with a diameter of 0.8, in which the boundary conditions of the model are assumed to be similar to those of ground conditions having fixed supports at the bottom of the pile, the roller supports on the sides, and the freedom on the upper surface which is shown in Tables 3-5.

In the presented article, since the construction of the foundation and the structure is sequential, stress analysis was used for sequential construction, and the stages of model analysis are as follows:

1) Activation of soil layers and specification of groundwater level. In these stages, the displacement due to soil weight is considered to be zero.

2) Activation of the single pile foundation, pile group, and geogrids as well as the interaction between soil and foundation system.

3) Construction of the building floors and loading in separate phases.

Figs. 16, 17, 18, and 19 show the effect of the length of the pile group with diameters of 0.8 and 1 m and different lengths of 4, 8, 12, and 18m on the vertical settlement level over a year codes (see Figs. 22- 27).

Table 6 presents the maximum settlement level of the structure during a 365-day period, in which the settlement occurs, as well as the diameter and length of the pile group. Table 7 shows the maximum settlement of the structure during a 365-day period, in which settlement happens in the center, based on the variables of the diameter and length of the single pile. According to Table 6 and Fig. 20, the maximum soil settlement below the center of the foundation is 1.4 cm on the 365th day of the year if the six-floor structure is constructed only on a raft foundation based on the pile group with the diameter of 1m and length of 18m. According to Tables 2, 4, and 7 of the seventh part of National Building Code of Iran (2013), which specifies the allowable range of uniform and non-uniform settlements of deep and shallow foundations, the maximum allowable uniform settlement for the strip footing and raft foundations constructed on clayey soil is 5 cm. Tables 6 and 7 point out the compliance of foundation settlement in different modeling states with the building codes. According to it, using the pile group changes the status of unallowable structure settlements to an allowable state in all models. Given Table 7 and Fig. 21, in case of single concrete piles of 12 to 18 meters long with a diameter of one meter, the foundation settlement level decreases from 8 cm to 1.4 cm on the 365th day of the year. Based on the overall results, increasing the length of the pile, either individually or in groups, had a significant decreasing effect on soil consolidation settlement in the Northern Fereshteh area. Increasing the length of the piles at lower depths had less significant decreasing effects on the consolidation settlement.

4. Conclusions

In the current study, after examining 54 models and the effects of four parameters including length, diameter, depth of groundwater, and number of geogrid layers under the foundation, the increasing or decreasing trend of consolidation settlement perpendicular to the foundation. The performances of pile-raft foundation with reinforced soils and geogrid under the same geotechnical conditions as well as the effects of piles with different lengths and diameters on the pile foundation system (to achieve an optimal design) are the main issue to be addressed in this chapter.

• If pile group and single pile with a length between 12 to 18 m are not used, the structure settlement will reach 6 cm in order to reduce the effect of under-foundation settlement, which is unallowable according to the seventh part of National Building Code (2013).

• The minimum required length for piles in a pile raft foundation system to change the status of the settlements from unallowable to allowable is specified according to six to eight floor structures.

• Groundwater level had the lowest settlement level in the foundation based on the single pile with a length of 14 meters and a depth of 10 meters. In general, the proximity of the groundwater level to the ground surface, especially in settleable areas, indicates a high level of consolidation settlement. The optimum depth to have the maximum settlement of 0.2 cm is 10 meters from the ground.

• Numerical analysis showed that constructing four layers of geogrid and placing them at intervals of one meter beneath the foundation to reinforce the soil under the foundation of the Northern Fereshteh area can decrease the level of consolidation settlement by 3.1 cm.

• The results of numerical modeling indicate that changing the diameter of the piles does not have a significant effect on diminishing the settlement of the structure. In other words, the stiffness provided by one-meter-diameter piles is appropriate for stabilizing and reducing the settlement, and increasing the diameter of the piles is not an optimal choice.

• In order to prevent possible future damages and based on the results of the present study, due to the weakness of the soil in Northern Fereshteh area of Tabriz city and its high settleability, avoiding shallow foundations in all structures of this area is highly recommended.

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