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The Behavior of Axially Compression Loaded Barrette and Bored Piles with Model Tests

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ABSTRACT

Deep foundations could be preferred instead of shallow foundations in the event that the loads coming from the structure are excessive and the soil state is inconvenient. Rectangular shaped barrette piles are the one of them. In this study, firstly a series of laboratory tests have been conducted using three different sizes of barrette and bored piles placed in the sand soil. Then, finite element based three-dimensional back analyses have been performed using the data obtained from these tests. Afterwards; a series of parametric analyses were performed with different pile geometries, including real pile dimension used in current geotechnical applications. As seen that bored piles are exposed to displacement approximately 2 times more than barrette piles under the same force at all pile lengths. When the pile lengths used in real geotechnical applications are also investigated, it has been determined that bored piles have displacements between 1.5 and 2.3 times more than barrette piles. Numerical results with the piles of small cross-section area show that barrette piles have more bearing capacity compared with bored piles. As the pile length increases, barrette piles could be more loads from 2% up to 17%. When the piles in real geotechnical dimensions are examined, barrette piles have revealed more bearing capacity performance from 7% to 49% when compared to bored piles as the pile length increases. It also has been revealed that barrette piles show better performance than bored piles both in experimental and numerical analyses.

Keywords: Barrette pile, bored pile, sand, model test, numerical analysis

INTRODUCTION

Foundations are the construction elements ensuring the contact of the structure with the soil and transferring its own weight and superstructure loads to the soil with layout amounts without giving any damage to the structure. Deep foundations are constructed for transferring the superstructure loads to sound layers and keeping the layout amount at allowable levels when shallow foundations are insufficient. Though bored piles are generally used for this purpose, it is seen that the barrette pile applications have become widespread recently as an alternative to these piles. Having more friction surface when compared to the bored piles, providing more bearing capacity with the use of materials at the same amount and therefore, providing lower costs are the preference reasons of barrette piles (Yıldız, 2011, Okar, 2018). Barrette piles are reinforced concrete pile foundations, which are drilled with diaphragm wall equipment and obtained as a result of placing reinforcements of deep wells and concreting (Ramaswamy et al., 1986). Bored piles are cylindrical structures obtained by placing reinforcement in deep wells drilled with various methods and pouring concrete. The essential differences between barrette piles and bored piles are the equipment used and the pile geometry.

Barrette piles that could be manufactured in different cross-sections as +, T, H, Y and I are generally known as the rectangular piles. Regarding the dimensions of the barrette piles manufactured only as reinforced concrete, the long side changes between 2.20-3.0 m and the short side changes between 0.60-1.20 m (Yıldız, 2011).

Many advantages such as the applicability to all kinds of soils, having more bearing capacity than having at the same lateral friction area bored piles, being more economical and adjustability of the pile length according to the application conditions have caused the interest in the studies related to barrette foundations to increase. Some studies on barrette piles are given below.

Johnson et al. (2005) has been conducted a numerical study on sand soil using ABAQUS program. Axial, lateral and 45° curved loadings have been applied in this study by changing the sand properties, pile cross-section and pile length. It has been observed from the numerical analysis that i) the shape factor is dependent on the sand density, ii) square shaped piles have more shaft capacity than the circular shaped piles and iii) the tensile strength increases as the sand density increases. Besides; it has been understood that the lateral cross-section of the pile has a significant effect on the lateral bearing capacity.

In the study conducted by Basu et al. (2008), it has been observed the axial pile displacement depends on the pile installation depth. An analysis method has been developed for the barrette piles in different dimensions under axial load placed to three-dimensional multi-layered soil. These analytical results have been modeled and compared with finite element-based program 3D ABAQUS. As seen analytic approach results match with the results of the finite elements very closely, pile shape effects the pile capacity and the total displacement in the circular piles having the same cross-section area with barrette piles is more than the displacement in barrette pile.

Seo et al. (2009) presents a settlement analysis for the barrette and circular piles placed in multi-layered soils. Axial loading has been conducted on the rectangular and circular piles with the same cross-section area and same length. Then analytical numerical results obtained from finite element-based were compared. An acceptable consistency was observed from this comparison. And also, it was concluded that the displacements of barrette pile are less than the displacements of circular piles. Bored piles placed on different soil environments were investigated theoretical, empirical and semi-empirical analyses (Salihi et al., 2015).

It has been examined whether the pile surroundings and pile cap have cohesion or not in the analyses conducted by using various approach methods and the results of the analyses have been compared by taking the results of the field loading tests as reference. As concluded from this comparison that the attained results give the closest values to the result of pile loading in the field.

Chung and Yang (2016) conducted a laboratory test on 1.6 cm diameter, 40 cm long steel pile at different clay soil environment with different degrees of saturation. The test results were compared with the analysis results obtained from the Plaxis 2D finite element program. And similar trend was observed. It was determined that the ultimate load bearing capacity of the pile decreased by 56.6% when the water content of the soil was increased from 15% to 21%.

Jitesh et al. (2017) performed finite elements (FE) analysis to be able to determine ultimate capacity of a single barrette pile. In the analyses; the effect of strength parameters, unit volume weight of the soil, surcharge load, the interface strength value between the barrette and soil and the barrette geometry have been examined on the ultimate bearing capacity. Mohr-Coulomb (MC) model, Hardening Soil (HS) model, Hardening Soil model (HSsmall) and Soft Soil (SS) model have been used for the purpose of evaluating the bearing capacity. As seen the ultimate load increases together with the increase in the strength parameters of the soil, unit weight of the soil and the magnitude in the surcharge load. It has also been revealed that the ultimate load is dependent on the barrette geometry and interface strength value.

Numerical analyses have been conducted for the purpose of examining the behaviors of circular piles and barrettes under compression using Plaxis 3D (Rafa and Moussai, 2018). Besides; the interaction between the test pile and reaction pile and the interactions between test barrette and reaction barrette have also been examined. It has been examined that this interaction is dependent on the shape of the pile and the distance between the reaction piles and test piles. Huang et al. (2020) have been conducted to pile foundation post-grouting and static load test, in which the tested value is used to compare with the different standard with China, America and Europe. Bauer et al. (2018) investigated a method of analyzing head displacements of piles subjected to lateral load test that is acceptable for reliability calculation.

In the study by Tolun et al. (2020), two-dimensional analyzes have been conducted using the finite element method to investigate the behavior of a single pile embedded in loose and dense sand soil under dynamic loads. It has been observed that the results obtained in the study are presenting good insights specifically for the design issues of pile settlements. However, the displacements reveal that high vibrations (> 0.1 g for loose sand, > 0.2 g for dense sand) influencing the pile deformations are critical for the issues of settlements. Consequently, the findings from the study are promising good contributions for pile design under the dynamic effect

The pile load test data of the barrette piles applied in the field and the 3D finite element analysis results, the 2D finite difference analysis results and the results calculated by the analytical methods were compared by Chang et al. (2019). Analyzes have been conducted for layered soil layers, both clayey and sandy, under compressive and tensile forces. Mohr-Coulomb (MC) was chosen as the Soil Model. As seen the finite element analysis results are better than the finite difference analysis result when compared with pile load test results. It has been determined that the results of analytical methods in clay soil environment are consistent with field tests, but the results are inconsistent under tensile force in sand soil environment.

Poulos et al. (2019) modeled bored piles with equivalent dimensions to represent barrette piles using finite element program under vertical and horizontal loadings. Although equivalent sized bored piles give similar results to barrette piles in single piles, less satisfactory results were obtained in group piles.

Znamenskii et al. (2019) analyzed full-scale barrette foundation loading test of a 56-storey building constructed in Moscow (Russia). As seen the displacement in the numerical analysis is approximately 26% higher than the displacement in the full-scale loading test. However; it has been observed that the load-settlement curves for full-scale tests and numerical models are generally similar and linear.

Laboratory tests have been conducted on six model piles made of steel with a diameter of 4.2 cm and a length of 1 m placed in a sand soil (Baca et al., 2020). In the study, a new method is presented for bi-directional static load tests used in piles. The results were compared with the results of traditional loading tests performed in the laboratory. It has been suggested that the bearing capacity of the proposed method are 20% lower than the traditional loading test results.

A series of laboratory tests have been conducted on sand soil to determine the load-displacement relations of vertically loaded barrette piles (Erginer, 2021). Model piles have been constructed for the purpose of comparing the circular piles and rectangular barrette piles. Rectangular barrette piles being from the model piles have been manufactured in a way that they will be equal to 1/10, 1/20, 1/30 and 1/40 of the real pile scales. Circular model piles have been manufactured in a way that they will have approximately the same cross-section area with the barrette piles. Compression tests have been conducted on the model piles buried in loose sand and the ultimate bearing capacities of the piles have been examined. Then the test results have been compared with the analytical methods. The effects of pile geometry, pile cross-section area and pile length on bearing capacity have been including the scale effect. As seen barrette pile bearing capacity is 1.22-1.42 times more than the circular pile bearing capacity when the pile lengths are kept equal in the circular and barrette piles with the same cross-section area.

Xu et al. (2021) proposed a new load transfer model in which the softening and strengthening of super-long pile skin friction was considered. Moreover, the influence of parameters variation on the softening load transfer model was discussed in detail.

As understood the literature review above, many studies have been generally conducted by being case studies, laboratory tests and numerical analyses related with the barrette piles. No studies have been seen in the literature in which both laboratory model tests and three-dimensional numerical analyses have been conducted together for the purpose of comparing the barrette pile and bored pile behavior to each other.

In order to examine the behavior of barrettes and bored piles under load and to compare them with each other, in this study, barrette and bored piles with small scale and with the equal cross-section area have been firstly subjected to compressive loadings in the laboratory in the sand soil environment. After that; the test results have been three dimensionally simulated to be able to estimate the elasticity module of the soil. Conformity has been observed between the back-analyses and model tests. After these studies, 3D numerical analyses have been conducted for the purpose of i) examining the scale effect on the bearing capacity of the piles and ii) comparing the load-displacement behavior of the barrette and bored piles. In this part of the numerical study, the cross-section areas of the piles manufactured for the model tests were kept constant and the pile lengths were increased at certain ratios. After these analyses; barrette and bored piles dimensions frequently used in real geotechnical applications have been three dimensionally modeled under the same soil conditions and in the same cross-section area to investigate the scale effects and the load-displacement behavior. The new contribution of this study to the literature could be shown as i) the examination and comparison of the load-displacement behavior of the axial loaded barrette and bored piles with the same cross-section area and ii) the investigation of scale effect on the ultimate load of the barrette and bored piles.

In this study, the advantages of barrette piles over bored piles were investigated. Theoretically, it is known that the barrette pile has more surface friction capacity than the bored pile with the same cross-sectional area. This means that barrette piles can be more economical. From this point of view, it is aimed to demonstrate this superiority both experimentally and numerically in this study. In addition to these, parametric studies have been conducted to examine the effect of scale effect on pile bearing capacity.

MATERIAL AND METHOD

Experimental study

The soil used in the experimental studies has been supplied from a local quarry for the easiness of transportation. This sandy soil has been laid for 28 days and left for drying at room temperature. A series of tests have been conducted to determine the properties of the soil. The index and strength properties of the soil have been determined with the sieve analysis, pycnometer test, shear box test and natural unit volume weight test performed according to (Baca et al., 2020). The sand soil used in the test has been placed in the test box, to create a soil with low bearing capacity in a loose sand condition (Dr=30%). In order to do this, the dry sand floor was placed in the required number of layers according to the previously determined 5 cm horizontal lines in the test case.

Model tests have been conducted in a rectangular box with 1500 mm in length, 1200 mm in width and 950 mm in height. The frame of the test box consists of steel profile with a thickness of 8 mm. The front and left side surface of the test case consists of glass panel with a thickness of 5 mm. The rear surface and right-side surface are made of metal sheet material with a thickness of 3 mm.

There is the loading engine in the upper part of the test case. Loading engine is embedded in a rail system and loading could be performed at any desired point of the test case. Loading engine could conduct loading at the speeds between 10 rpm - 300 rpm and to represent a slowly loading, the loading speed has been kept stable as 50 rpm in all the tests conducted within the scope of this study. Electrical load cells with a capacity of 2 and 5 thousand kg placed in the piston have been used for the purpose of reading the load values coming on the piles in the conducted test studies. The load values attained as a result of the conducted loadings have been collected in the collector unit. Moreover; displacement gauges have been placed at equal distance to both sides of the axis on which load is applied and load-displacement relations have been examined.

For experimental purposes, three concrete barrette piles whose short side is 80 mm, long side is 280 mm and lengths are 240, 320 and 400 mm and concrete circular piles with the same cross-section area, a diameter of 169 mm and lengths of 240,320 and 400 mm have been manufactured. The barrette piles with 800 mm x 2800 mm (width x length) cross-section area as the real pile dimension have been taken as reference while manufacturing the model barrette piles. Table 1 and Table 2 give data of piles of different lengths in test pile cross-sections and large pile cross-sections, respectively.

Table 1. Data of piles of different lengths in test pile cross-sections

Barrette Pile			**Bored Pile**		**Dimensions of the soil environment**		
B mm	H mm	L mm	D mm	L mm	B mm	H mm	L mm
80	280	240	169	240	2000	2000	3000
80	280	320	169	320	2000	2000	4000
80	280	400	169	400	2000	2000	5000

Table 2. Data of piles of different lengths in large pile cross-sections

Barrette Pile				**Bored Pile**		**Dimensions of the soil environment**	
B mm	H mm	L mm	D mm	L mm	B mm	H mm	L mm
800	2800	8000	1690	8000	15000	15000	20000
800	2800	12000	1690	12000	15000	15000	20000
800	2800	16000	1690	16000	15000	15000	20000
800	2800	20000	1690	20000	15000	15000	30000
800	2800	24000	1690	24000	15000	15000	30000
800	2800	28000	1690	28000	15000	15000	40000
800	2800	32000	1690	32000	15000	15000	40000

Piles have been placed in the test box and their surroundings have been filled with sand. Metal sheets have been adhered to the middle parts of the upper surfaces of the piles to be able to make axial loading. The images of the manufactured piles are given in Figure 1.

Figure 1. Barrette and bored piles made of concrate

Numerical Study

Many mathematical solution methods such as finite elements method, finite difference method or boundary elements method are frequently used nowadays. When numerical methods are used to solve the faced problems, it is necessary to make some assumptions in the solution of the problems. It should not be forgotten that direct acceptance of the results attained with numerical methods may bring together serious errors. Therefore; it is very important to verify the numerical solutions with experimental methods. On the other hand; many engineering problems could be solved in a much faster way when compared to experimental methods with numerical methods and in this way, significant labor force and cost efficiency could be provided.

Due to the significant reasons aforementioned, experimental studies have been modeled in Plaxis 3D computer software based on finite elements method. Load-displacement relations of barrette and bored piles have been examined. After observation of the conformity between experimental and numerical results, barrette and bored piles in various lengths and cross-sections have been modeled and the bearing capacities of the piles have been determined. Afterwards; the load-displacement results of the barrette and bored piles have been compared.

Mohr-Coulomb (MC) model is frequently used in the analysis of basic engineering problems. The reason for this is that the collapse mechanism of the soil could be modeled with the parameters such as cohesion and internal friction angle that could be attained with the experiments of main soil mechanics. There are many studies in the literature using the Mohr-Coulomb (MC) model (Jitesh and Dodagoudar, 2017, Chang et al., 2019, Znamenskii et al., 2019, Shechuan et al., 2022, Abou-Samra et al., 2021, Gatto and Montrasio, 2021, Madkour, 2012, Zhiyuan et al., 2016). For this reason; Mohr-Coulomb (MC) model has been used in numerical analyses.

The dimensions of the numerical model formed to be able to model the experimental study have been selected in a way that they will be the same as the dimensions of the test box (1000 mm width, 1200 mm length and 950 mm height). After that; while forming the same models with the cross-section dimensions of the piles used in the experiments, models in the cross- sections used in real life have been formed at the next stage. The data of the formed models are given in Table 1 and 2. Then; the properties of the sand soil and piles have been assigned to the respectively defined volume and the zone where piles are in. Same soil parameters have been used in all numerical studies. The parameters belonging to both soil and concrete piles are given in Tables 3 and 4.

Table 3. Geotechnical properties of sandy soil

Parameter		Value
γ_{unsat}	(N/mm^3)	17.9
γ_n	(N/mm^3)	27.28
E	(N/mm^2)	30
v	-	0.3
c	(N/mm^2)	1×10^{-3}
ϕ	(°)	33
Ψ	(°)	0
R_{inter}	-	0,7
Dr	%	30
Soil class according to USCS		SW

Table 4. Material properties of the piles

Parameter	Value
Material type	Elastic
E (N/mm^3)	27×10^3
γ (N/mm^3)	24
v	0.2

Elasticity module value has been estimated via the back-analyses conducted by modeling the load-displacement results of the piles. There are many studies in the literature in which the properties of soils are determined with the help of these types of back-analyses (Emilios et al., 2009, Staubach et al., 2021, Un and Yıldız 2021). An average value has used for Poisson ratio Plaxis 3D Material Models Manual (Plaxis 3D Manual, 2020).

One of the most important factors of finite elements method is the small pieces called as mesh and forming the whole. Mesh density is an important parameter affecting the result in the solution of a problem. The more we divide the problem into pieces, the better we will be able to approach the result; but, the excessiveness of the number of elements will increase the complexity of the finite elements problem and therefore, the solution period. Therefore, optimum element dimensions that will ensure us to save time and that will give the correct result should be selected. Some analyses have been conducted to be able to determine the optimum mesh density due to the aforementioned reasons. Firstly; one of the barrette piles (barrette pile with 80 mm width, 280 mm length and 400 mm height) used in the experimental studies has been modeled (Figure 2). Five different mesh densities (very coarse, coarse, medium, fine, very fine) existent in Plaxis program as default have been applied for the mesh analyses. When the results are examined; while the element number increases 44 times more at the transition from very coarse mesh density to very fine mesh density, the change in the pile bearing capacity has been seen to be approximately 21%. As a result of the mesh analysis, it is seen that the mesh density directly affects the results of the problems. For this reason, optimum mesh density selection is important. Medium mesh density has been selected due to the fact that excessive analysis periods occur at very fine mesh density and the problem to be solved is not very complex. Additionally, mesh intensification has been conducted in the pile surroundings. Consequently, it has been seen that the experimental results and numerical results are in conformity with this approach.

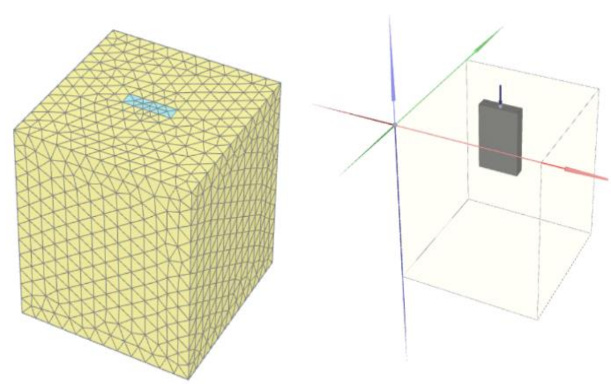
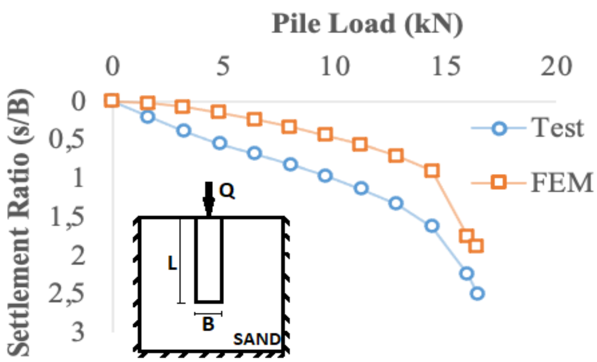


Figure 2. Finite element mesh structure and numerical model

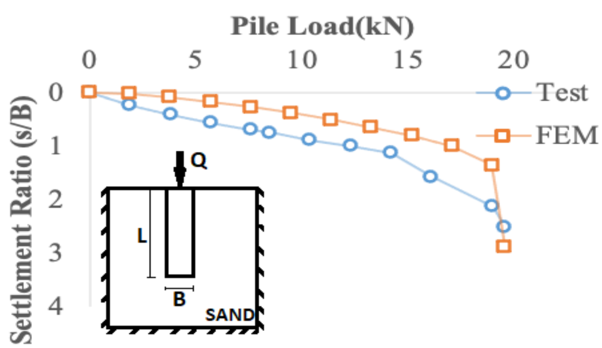
RESULTS

Verification of the numerical model

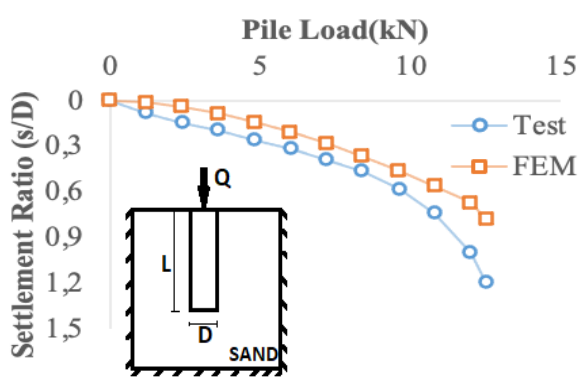
The experimental verification of a numerical analysis is very important in terms of being able to use the numerical analysis results. In this study, axial loadings have been conducted on three different barrette piles, and three different bored piles and load-displacement curves have been drawn. Displacement controlled laboratory tests have been conducted up to 20 mm settlement for both pile types. The reason for choosing 20 mm is that it corresponds to approximately 10% of the bored pile diameter. Afterwards; test apparatus has been simulated in Plaxis 3D program in the same dimensions. As seen the test and numerical analysis results are in conformity in both barrette piles and bored piles. The results regarding the conducted analyses are given in Figure 3.



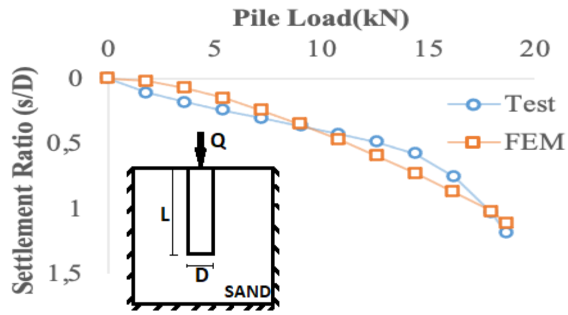
(a) Barrette pile 80/280/240 (B/H/L)



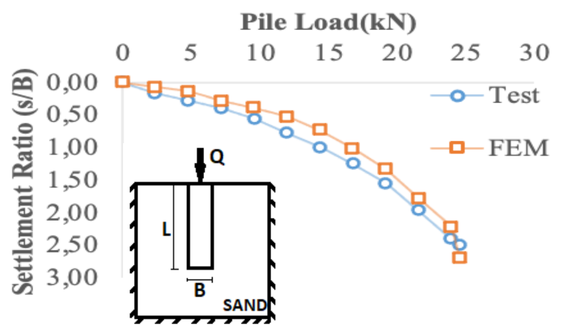
(b) Bored pile 169/240 (D/L)



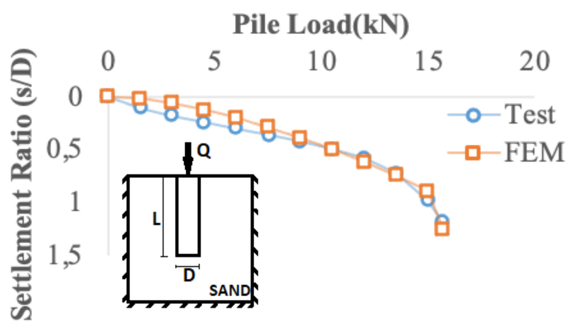
(c) Barrette pile 80/280/320 (B/H/L)



(d) Bored pile 169/320 (D/L)



(e) Barrette pile 80/280/400 (B/H/L)

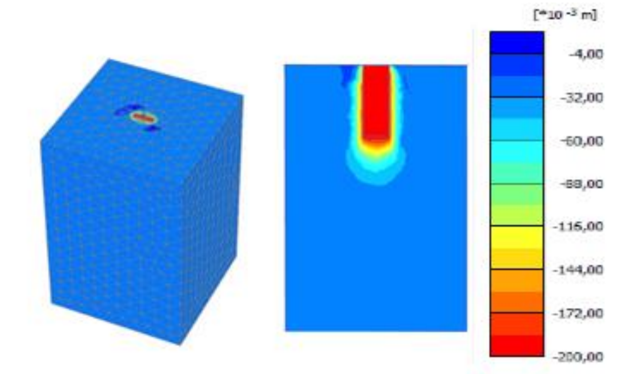


(f) Bored pile 169/400 (D/L)

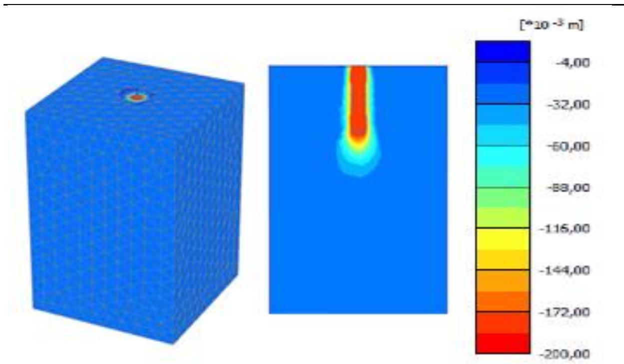
Figure 3. Test and numerical results

Parametric study

Numerical parametric studies have been conducted in this stage after verification of numerical analyses with experimental data. A series of numerical analyses have been performed to examine the superiorities of barrette piles over bored piles both in terms of bearing capacity and load-displacement performance. Firstly; numerical analyses have been conducted for the piles with the lengths of respectively 800, 1600, 2400 and 3200 mm and with the same cross-section area (80 mm width, 280 mm length and 169 mm diameter) with the barrette piles and bored piles used in the experimental study for the purpose of examining the length effect on the piles. Then, the pile lengths of 800, 1200, 1600, 2000, 2400, 2800, 3200 mm have been selected for the barrette and bored piles with the dimensions (800 mm width, 2800 mm length and 1690 mm diameter) used in real geotechnical applications for numerical analyses (Figure 4).

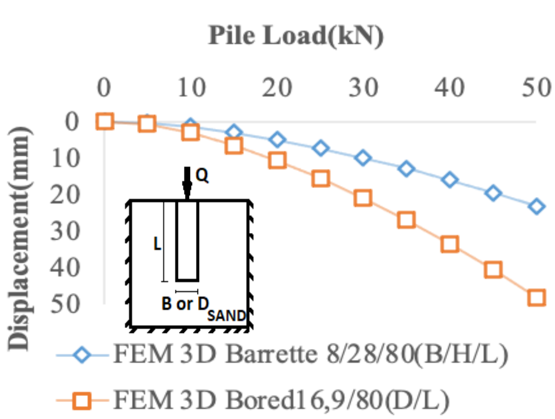


(a) Barrette pile 80/280/800 (B/H/L)

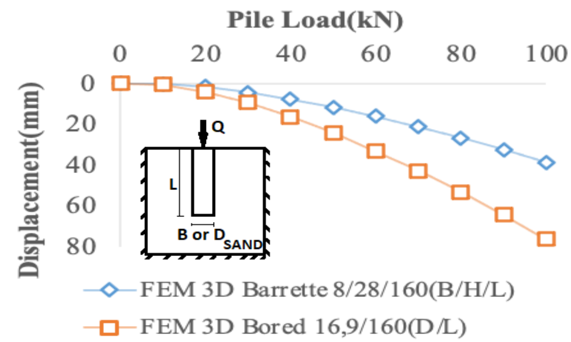


(b) Bored pile 169/800 (D/L)

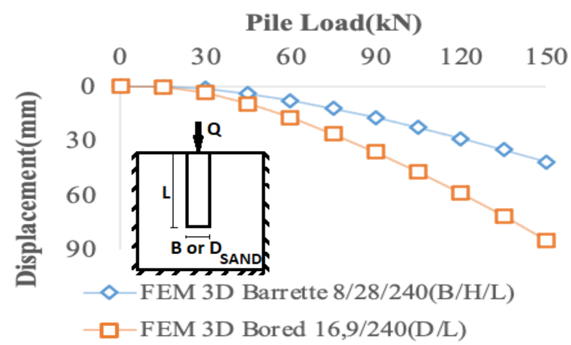
Figure 4. Pile views from parametric study



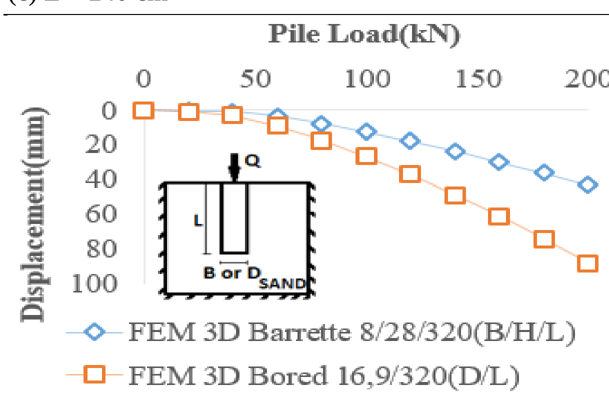
(a) L = 80 cm



(b) L = 160 cm

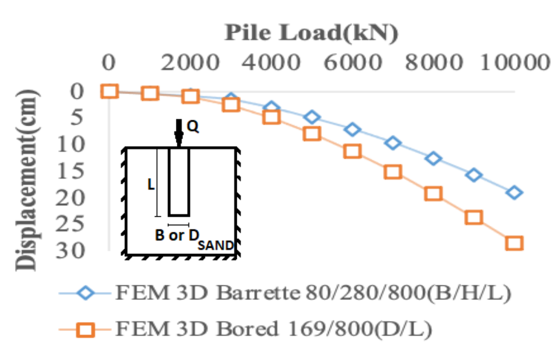


(c) L = 240 cm

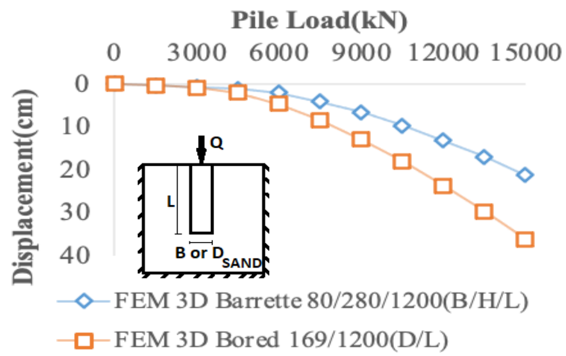


(d) L = 320 cm

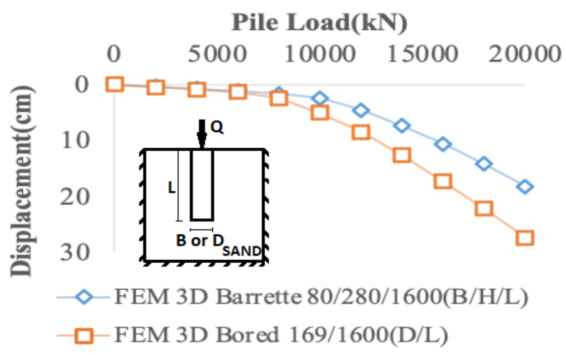
Figure 5. Load - settlement curves of parametric studies



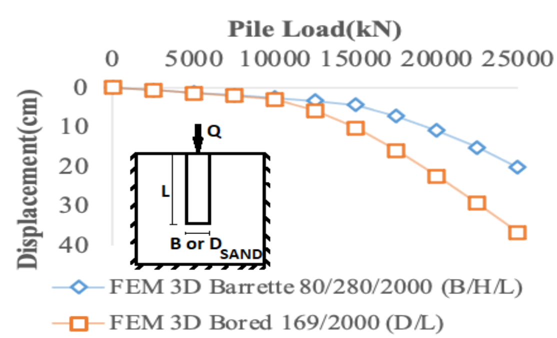
a) L = 800 cm



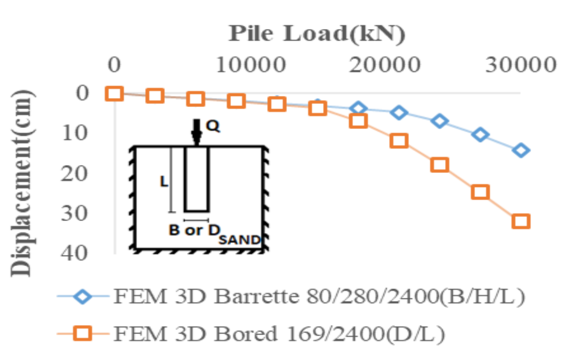
b) L = 1200 cm



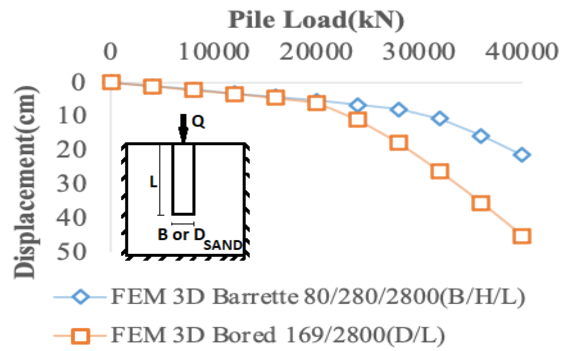
c) L = 1600 cm



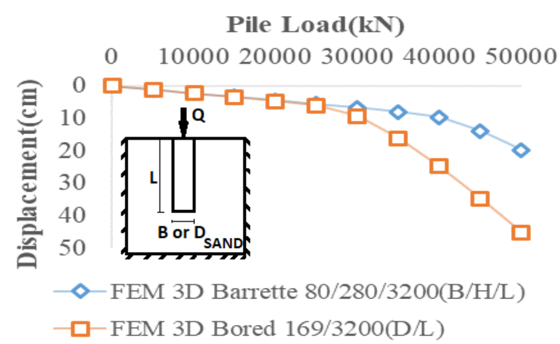
d) L = 2000 cm



e) L = 2400 cm



f) L = 2800 cm



g) L = 3200 cm

Figure 6. Load-displacement results for real dimensions

When considered in terms of bearing capacity, it is observed that the ultimate loads of the barrette piles have increased from 6,5% to 49% when compared to bored piles together with the increase in pile lengths (Figure 7).

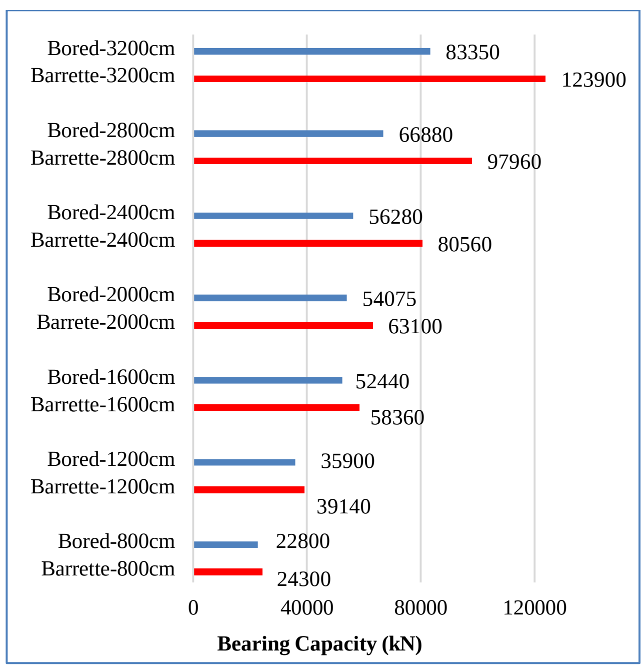


Figure 7. Bearing capacities of real dimensions

CONCLUSIONS

In this study, laboratory model tests have been firstly conducted on loose sand soil and modeled in finite element-based program. Then the elasticity module of the used soil has been estimated with back-analysis procedure. At the next stage, numerical analyses have been conducted to examine the effects of pile length change on the bearing capacity of the piles. The displacements of barrette and bored piles under the equal axial forces have been determined and compared to each other. Finally; a series of numerical analyses have been conducted in the pile cross-sectional area same with real geotechnical applications and also in various pile lengths. The results of this analysis have been compared to each other in terms of bearing capacity and load-displacement relations. The beneficial findings of this study are given below:

(1) Finite element method is successful in determination of load bearing capacities and load-displacement relations of barrette and bored piles.

(2) Bored piles with small cross-sections have had displacement approximately two times more than the barrette piles in all pile lengths when exposed to the same load under loose sand soil conditions. The reason for this is that the friction surface of barrette piles is more than that of the bored piles with the same cross-section area.

(3) When the pile lengths used in real geotechnical applications are also investigated under the same soil conditions, it has been determined that bored piles have displacements between 1.5 and 2.3 times more than barrette piles. Barrette piles provide less displacement than bored piles at every pile cross-section area and every pile length. From this point of view, it will be more beneficial to prefer barrette piles for the problems in which structure settlement has more importance.

(4) Numerical results with the piles of small cross-section area show that barrette piles have more bearing capacity compared with bored piles. As the pile length increases, barrette piles could be more loads from 2% up to 17%. When the piles in real geotechnical dimensions are examined, barrette piles have revealed more bearing capacity performance from 7% to 49% when compared to bored piles as the pile length increases. Barrette piles show better performance than bored piles in terms of bearing force capacity. In this situation, it is very clear that the bearing capacity problems of the structure could be solved with fewer costs when compared to bored piles.

DECLARATIONS

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Data availability

The datasets used and/or analysed during the current study available from the corresponding author on reasonable request.

Author’s contribution

Ömer Yeşiltepe: Conceptualization, methodology, laboratory tests, writing original, review and editing;

Merve Erginer: Laboratory tests, validation;

Murat Örnek: Review, editing, and validation.

Competing interests

The authors declare no competing interests in this research and publication.

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