



Sensitivity Analysis of Factors Affecting Pile Bearing Capacity Based on Finite Element Simulation

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Abstract. With the continuous development of high-rise buildings, increasing use of pile foundations in actual projects. And the pile foundation is characterized by strong bearing capacity, high stability and good seismic performance. As pile foundations are often buried deep underground, the bearing capacity of pile foundations can be affected by various factors. Therefore, analyzing and studying the sensitivity of the peripile soil to the influence of pile bearing capacity is of great significance to the analytical study of pile bearing capacity. In this paper, combined with the actual project, using ABAQUS finite element analysis software for modeling, using the control variable method to change each parameter of the soil around the pile, to analyze the load-displacement and displacement changes of the top of the pile. Then the sensitivity formula is introduced to analyze and calculate the sensitivity of different parameters of peripile soil on the impact of pile bearing capacity for sensitivity analysis study. It was found that the changes in pile top displacement obtained by varying the density, modulus of elasticity, Poisson's ratio, cohesion, angle of internal friction and coefficient of friction of the soil around the pile were -2.41mm, 3.14mm, 5.03mm, -0.04mm, 0.26mm and 2.6mm respectively. The corresponding maximum sensitivities were 1.03, 0.87, 2.75, 0.014, 0.09, and 1.07, respectively. The study shows that the effect of Poisson's ratio of the soil around the pile is the most sensitive to the pile bearing capacity when it is changed, the effect of density, modulus of elasticity and coefficient of friction are more sensitive, and the effect of soil cohesion and angle of internal friction show insensitivity. This study provides reference value for subsequent studies related to pile bearing capacity.

Keywords: Pile bearing capacity; Finite element analysis; Computer modeling; Sensitivity analysis; Static load test

1 Introduction

With the continuous progress of the times, the scale and technology of engineering construction develops rapidly, no matter in the industrial and civil buildings or in some special buildings, piling is more and more widely used. Pile foundation has high

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strength and its own rigidity, which can effectively transfer the external loads borne into the hard rock. This avoids the destruction of buildings due to unstable settlement of foundations, so the study of the bearing capacity and stability of pile foundations is of great significance.

Pile bearing capacity can be divided into horizontal bearing capacity and vertical bearing capacity. For general industrial and civil buildings, the main consideration is the vertical bearing capacity of the foundation. There are many factors affecting the bearing capacity of pile foundations. The nature of the pile itself, the nature of the soil surrounding the pile, and the friction at the pile-soil interface all have an effect on the bearing capacity. Many scholars have studied the influence factors of pile bearing capacity. Bian Hanliang ^[1] and others used CPT and CPTU systems to analyze and study the vertical bearing capacity of pile foundations on the basis of engineering examples, and elaborated on the accuracy and reliability of CPTU system testing. Pells ^[2] and others established a physical modeling test on the basis of field tests, and took the roughness of the pile-rock contact surface as the main influencing factor of the Q-S curve at the top of the pile. Jin Shubin ^[3] and others applied analyzed the effect of rock and soil bodies at the pile end on the bearing capacity of pile foundation, and found that the deformation modulus of the pile end geotechnical body has a great influence on the bearing capacity. Jianlei Liu ^[4] et al. designed four model piles of the same size at the same test site. Four main parameters, namely, pile length, pile diameter, Young's modulus of soil and Young's modulus of pile, were considered, and a parametric sensitivity analysis was carried out for the complete piles under static loading. Finally, the relationship between the dynamic stiffness and bearing capacity of the pile foundation is illustrated. Xuefei Wang ^[5] et al. used numerical simulation to analyze the sensitivity of soil parameters and found that the angle of internal friction has a large influence. The effects of the number of piles, pile diameter, loading height and pile spacing on the bearing capacity were also investigated. The results showed that increasing the pile length and the number of piles can effectively improve the bearing capacity. Lin C ^[6] et al. investigated the effects of soil density, water content, and freezing and thawing on the shear behavior of the pile-soil interface. Ashish Mishra ^[7] et al. used numerical simulation for sensitivity analysis of different parameters affecting pile foundation under vertical load. The friction angle was found to have a significant effect on the settlement and bearing capacity of monopiles.

The research on the influencing factors of pile foundation bearing capacity has been relatively perfect and comprehensive. Different scholars analyze the influence of different influencing factors on pile foundation bearing performance from his own point of view. And they give optimization scheme or provide basis for subsequent engineering design. However, as a whole, the current research lacks a discussion of the sensitivity of the factors affecting pile bearing capacity. This paper uses ABAQUS finite element analysis software, combined with the actual project from the nature of the peripile soil, using the quantitative change of each parameter, to determine the degree of sensitivity of each parameter to the bearing capacity of the pile foundation.

2 Engineering Background and Modeling

2.1 Engineering Background

The project is located on the east side of Binhai Avenue, Jimo District, Qingdao City, adjacent to the Yellow Sea, in a superior location with convenient transportation conditions. The foundation type of the project is precast square pile foundation with 450mm side length and C60 concrete strength class. In this paper, 63# piles of Building 48#-2 are selected for testing. The pile length is 12.33m, the designed vertical compressive bearing capacity of single pile is 2300kN, and the holding layer at the pile end is strongly weathered granite.

The on-site pile foundation static load test experiment is carried out according to the Technical Specification for the Detection of Foundation Piles for Construction (JGJ106-2014) [8]. The test site was loaded by the slow sustaining load method, with a maximum loading of 4600kN and 9 levels of loading, respectively 920kN, 1380kN, 1840kN, 2300kN, 2760kN, 3220kN, 3680kN, 4140kN and 4600kN. The first stage is loaded with 1/5 of the maximum loading capacity, and the remaining stages are loaded with 1/10 of the maximum. And each level of loading reaches the corresponding stability standard before adding the next level of loading. The test was conducted using a ballast platform counterforce device (shown in Figure 1). Figure 2 shows the field load experiment. The figure 3 shows the Q-S curve derived from the field test.

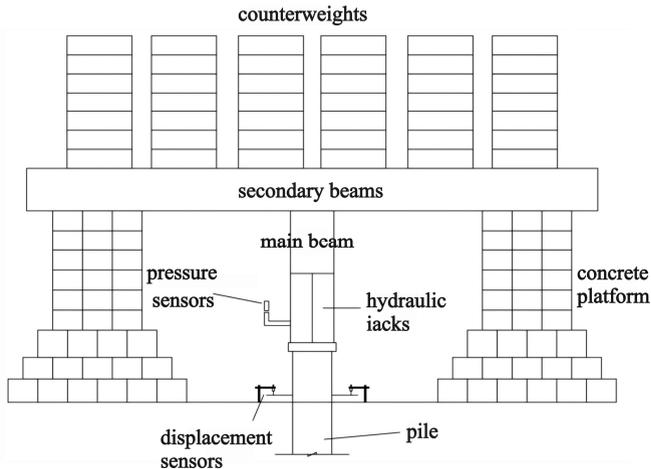


Fig. 1. Counterforce device of the pressurized weight platform.



Fig. 2. Pile foundation field experiment.

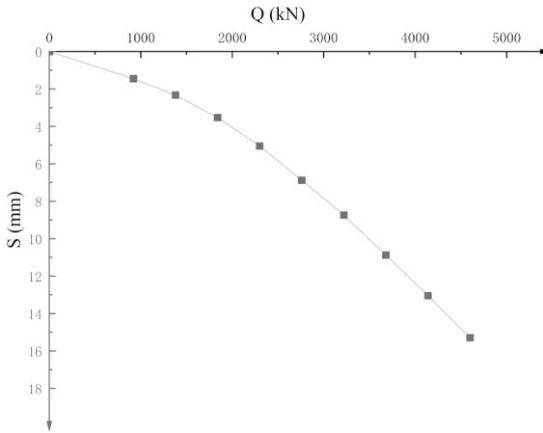


Fig. 3. Q-S curve for single pile field load test.

2.2 ABAQUS Finite Element Modeling

This paper takes 63# piles in the actual project as the research object, the ABAQUS software is used for finite element modeling and analysis. The material parameters of piles and peripile geotechnical bodies are determined based on field measurement data and relevant experience [9-11]. The parameters of the specific materials are listed in Table 1. The soil around the pile was modeled using the Mohr-Coulomb principal model [12]. Since the pile body is made of C60 high-strength concrete, the stiffness is much higher than other geotechnical bodies, and can be considered to be in an elastic state during the application of loads. Therefore, an isotropic linear elastic principal model is adopted for the pile body. Pile-soil contact surfaces are set in surface-to-surface contact where the pile sides are in contact with the bottom surface and the geotechnical body. The face on the pile is set as the main surface at the location where the pile and the peripile geotechnical body are in contact with each other, and the face on the peripile geotechnical body is set as the slave surface. The slip formulation uses finite slip, which allows for relative sliding or rotation between contact surfaces. The contact properties are chosen as tangential and normal. The friction equation in the

tangential direction uses a penalty function with the friction coefficient taken as $\mu = \tan(0.67\phi)^{[13]}$, and hard contact is used in the normal direction. Initial geostress balancing is done using the automatic balancing method by creating a Geostatic analysis step and setting the gravity loads in that step. The equilibrium of the ground stress is carried out in two steps using the birth-death cell method. The first step simulates the initial ground stress state of the soil under gravity loading, and the second step simulates the initial stress state of the pile foundation under gravity loading after it is driven into the soil layer.

Table 1. Table of material parameters.

Material Parameters	$H(m)$	$\rho(kg/m^3)$	ν	$E(MPa)$	$c(kPa)$	$\phi(^{\circ})$	μ
Fine sand or silty fine sand	2.65	1850	0.3	8	3	22	0.263
Silty clay-1	2.19	1920	0.4	14	17.5	16	0.189
Silty clay-2	0.95	1950	0.4	15	35	18	0.214
Coarse sand	3.46	1950	0.35	20	0	32	0.393
Coarse gravel sand	0.76	2050	0.34	25	0	36	0.448
Fully weathered granite	1.04	2100	0.27	30	60	38	0.476
Strongly weathered granite	1.6	2270	0.26	35	70	40	0.505
Moderately weathered granite	—	2650	0.22	6000	300	50	—
Pile	12.33	2400	0.2	36000	—	—	—

The reasonableness and feasibility of the model need to be verified, when we apply ABAQUS finite element software to analyze the bearing characteristics of pile foundation. Ensure that the error between the simulated and actual results is within acceptable limits. Thus, the simulation results can reliably represent the actual results and truly reflect the actual engineering situation. The 63# pile in the project was selected as a typical working condition for finite element modeling the established model is shown in Fig 4. Comparison of field static load test results with simulation results. The comparison of Q-S curves is shown in Fig 5.

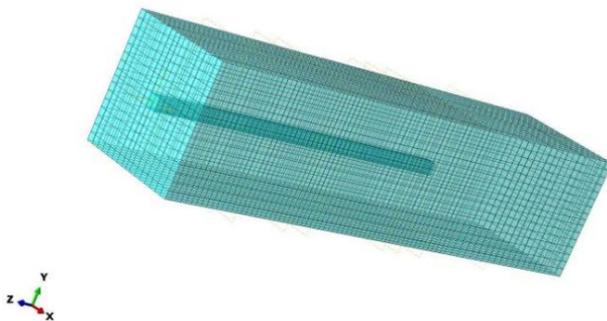


Fig. 4. Pile-soil finite element modeling.

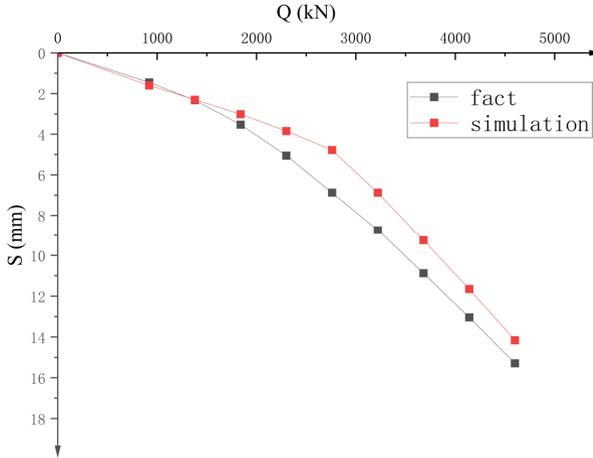


Fig. 5. Comparison of measured and calculated Q-S curves in the field.

As can be seen by the picture: under the first three levels of loading, the difference between the simulated vertical displacements of the pile tops and the actual values measured in the field is very small. However, the error between the simulated and measured values gradually becomes larger under the fourth to sixth level loads. When the seventh to ninth level loads are applied, the error gradually decreases again. Eventually it converges to the measured displacement. The measured curves from the field tests are in general agreement with the trends of the curves obtained from the numerical simulations. The error between the simulated and measured values of the final settlement of the pile tops is 6.74%, which is within the allowable error. Therefore, it shows that the established finite element model has a certain degree of reliability and can reflect the engineering reality to a certain extent.

3 Sensitivity Analysis

Single pile vertical compressive static load test is the most used and reliable way to reflect the bearing capacity of pile foundation. The single-pile finite element calculation model established by relying on the actual pile foundation project can reflect the bearing capacity of pile foundation more realistically.

3.1 Sensitivity Analysis Steps

First delineate the range of variation of the parameter. Take the approach of controlling a single variable and substituting changes in a single parameter into the model for calculation. Record load-displacement data from its analog outputs. Changes in the output load-displacement data are used as an indication of the changes in bearing capacity affecting the pile foundation.

Then the pile top displacement under the same load is chosen and the sensitivity equation is introduced. Calculation and analysis of the effect of different parameter variations on the bearing capacity of pile foundation. The sensitivity equations^[14-16] are:

$$K = \frac{|\Delta S|/S}{|\Delta i|/i} = \frac{\Delta S}{\Delta i} \cdot \frac{i}{S}$$

Where *K* is a dimensionless non-negative real number, the magnitude of *K* represents the sensitivity of the change in soil properties around the pile to the displacement of the pile top. *S* and *i* are the values of pile top settlement and parameters when the parameters are not changed, and ΔS and Δi are the amount of change in pile top displacement with respect to the parameters.

Finally, based on the formula, the sensitivity of each parameter is calculated, and the influence degree of each parameter is comprehensively judged.

3.2 Sensitivity Analysis of the Influence of Peripile Soil Properties on Pile Bearing Capacity

The density, modulus of elasticity, Poisson's ratio, coefficient of friction, and cohesion and angle of internal friction of the rock and soil bodies on the side of the pile were varied, respectively, while other parameters remained unchanged. Changes are all 20% increase, 10% increase, 10% decrease, 20% decrease. Then using ABAQUS to build a finite element model, the load-displacement relationship at the top of the pile is analyzed and studied.

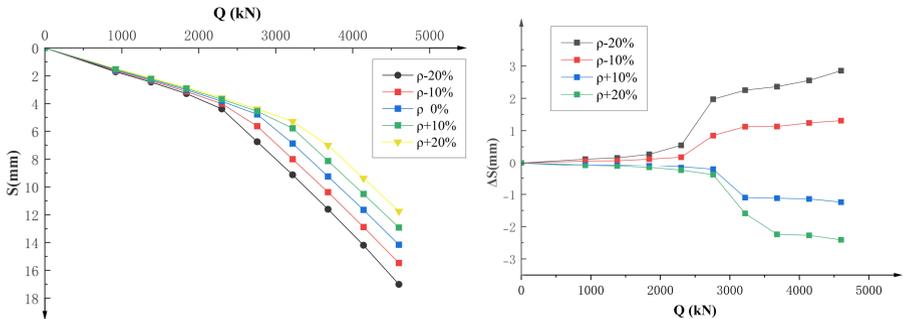


Fig. 6. Q-S curve and displacement change curve obtained by changing the density of the soil.

Figure 6 shows the pile top displacements and the change in displacements by varying the soil density around the pile. The maximum displacement changes corresponding to 20% increase, 10% increase, 10% decrease, and 20% decrease in density are 2.85, 1.31, -1.24, -2.41, respectively. The change in density makes the displacement of the pile top more variable, which has a greater impact on the pile bearing capacity.

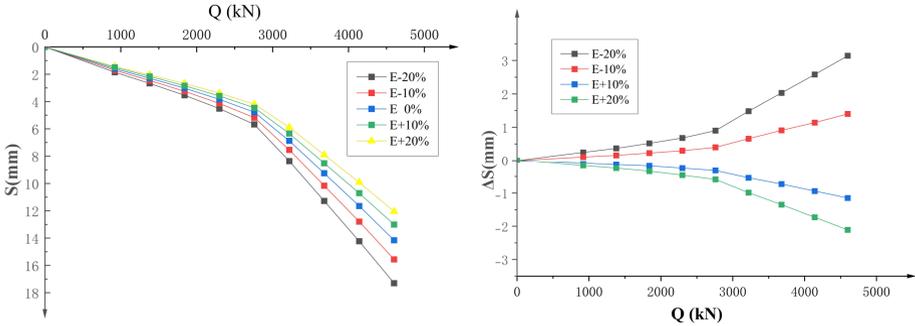


Fig. 7. Q-S curves and displacement change curves corresponding to changes in soil elastic modulus.

Figure 7 shows the pile top displacements derived from changing the modulus of elasticity of the soil around the pile and the change in displacements. The maximum displacement changes corresponding to a 20% increase, 10% increase, 10% decrease, and 20% decrease in the modulus of elasticity are 3.14, 1.4, -1.15, -2.11, respectively. The amount of change in pile top displacement when the modulus of elasticity is changed is similar to that when the density is changed, and it can be known that the modulus of elasticity has a large effect.

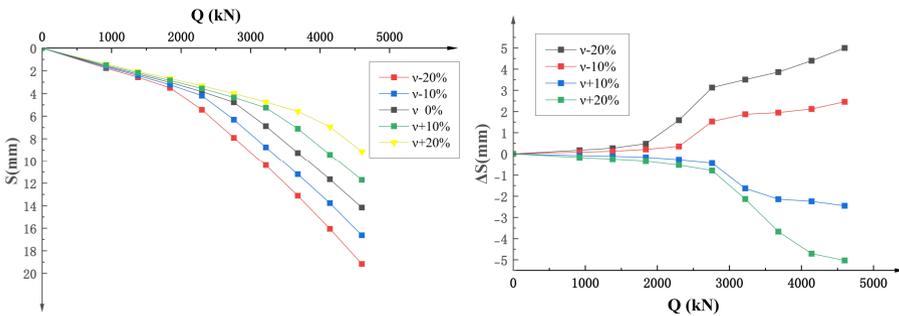


Fig. 8. Q-S curve corresponding to Poisson's ratio of the soil change and the amount of change in pile top displacement.

Figure 8 shows the Q-S curves at the top of the pile and the curves of the displacement changes obtained by varying the Poisson's ratio of the soil around the pile. The maximum displacement changes corresponding to 20% increase, 10% increase, 10% decrease, and 20% decrease in soil Poisson's ratio are 5.00, 2.46, -2.45, and -5.03, respectively. Large change in pile top displacement when Poisson's ratio is changed, it can be seen that the change of Poisson's ratio of the soil is very sensitive to the degree of influence on the bearing capacity of the pile foundation.

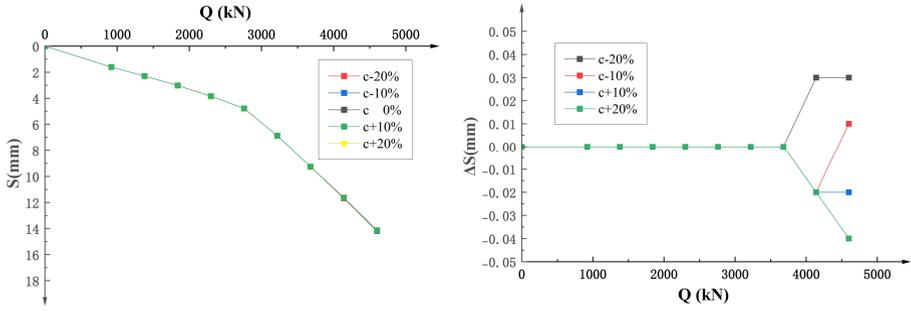


Fig. 9. Q-S curve and displacement change curve corresponding to soil cohesion change.

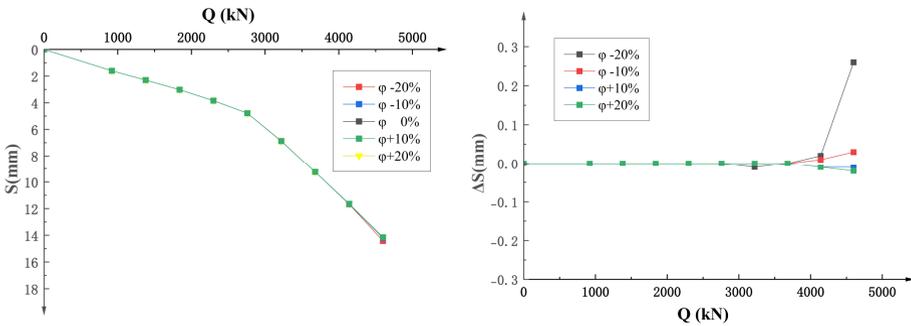


Fig. 10. Q-S curves and displacement changes corresponding to changing the friction angle within the soil body.

Figures 9 and 10 show the Q-S curves at the top of the pile and the displacement change curves corresponding to changing the soil cohesion and internal friction angle around the pile, respectively. The displacement change of the pile top is negligible when the cohesion and internal friction angle are changed. It can be seen that the influence of cohesion and internal friction angle is very small.

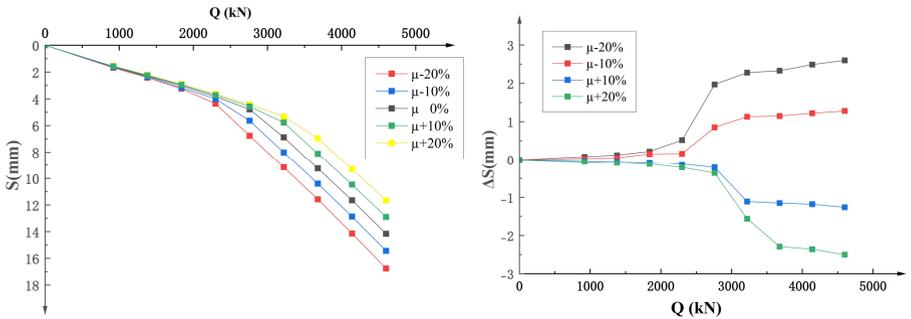


Fig. 11. Q-S curve and displacement change corresponding to changing the friction coefficient of pile-soil contact surface.

Figure 11 shows the Q-S curves at the top of the pile and the displacement change curves obtained by changing the friction coefficient of the pile-soil contact surface. The maximum displacement changes are 2.60, 1.28, -1.26, and 2.50 for 20% increase, 10% increase, 10% decrease, and 20% decrease in friction coefficient, respectively. the change in friction coefficient causes a large change in the displacement of the pile top, which has a large effect on the bearing capacity of the pile foundation.

4 Results

Analyze and study the pile top displacement curve and the amount of change of pile top displacement according to the ABAQUS software simulation. Then bring in the sensitivity formula for a computational study. Therefore, this leads to the conclusion that changes in peripile soil properties are sensitive to the effects of pile bearing capacity. The sensitivities corresponding to the change of each parameter are shown in Table 2. From the maximum sensitivity, it can be seen that the Poisson's ratio of the soil around the pile is the most sensitive to the bearing capacity of the pile foundation. The density, elastic modulus and pile-soil friction coefficient are more sensitive. The cohesion and internal friction angle of the soil are not sensitive to the bearing capacity of the pile foundation.

Table 2. Summary of sensitivities for each parameter.

Parameters	Sensitivity				
	-20%	-10%	10%	20%	Max
ρ	0.84	0.85	0.96	1.03	1.03
E	0.87	0.85	0.84	0.86	0.87
ν	1.31	1.48	2.01	2.75	2.75
c	0.09	0.02	0.007	0.007	0.09
φ	0.011	0.007	0.014	0.014	0.014
μ	0.78	0.83	0.98	1.07	1.07

5 Conclusion

(1) From the analysis of the maximum sensitivity results of each parameter, it is concluded that the sensitivity of the peripile soil properties to the effect of pile bearing capacity is most sensitive to the effect of Poisson's ratio, second most sensitive to the effect of density, modulus of elasticity, and the coefficient of pile-soil friction, and least sensitive to the effect of cohesion and angle of internal friction.

(2) By comparing actual engineering with finite element numerical simulation data, fully validated reliability of finite element simulations. The reasonable establishment and use of finite element model provides important support and help for the design and decision-making of the actual project.

(3) An analytical study of the sensitivity of the peripile soil properties affecting the pile bearing capacity using ABAQUS simulation has resulted in the more sensitive

factors affecting the pile bearing capacity. It can help to improve the pile foundation bearing capacity in practical engineering, and Provide a basis for subsequent pile foundation studies and the research of pile foundation using machine learning.

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