Study on the uplift bearing capacity of belled piles

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Abstract: In this study, a three-dimensional finite element analysis of the uplift bearing capacity (R) of belled piles is performed using ABAQUS finite element software. The reliability of the numerical calculation is validated. On this basis, the uplift load (P)–displacement (δ) distribution characteristics of the pile shaft under vertical and oblique loadings are analyzed. Additionally, the effects of the elastic modulus (E), cohesion (c) and angle of internal friction (φ) of the soil on the R of the pile shaft are also analyzed. The results show that a vertical P is gradually transferred from the top of a belled pile to its tip. Under a vertical P, the R of a belled pile increases as the E and coefficient of c uniformity (k) of the soil increase and is relatively insignificantly affected by the φ of the soil. Under an oblique P, the R of a belled pile decreases as the inclination (θ) of P increases and increases as the E and φ of the soil increase. As θ increases, the effect of k on the R of a belled pile gradually weakens.

1. Introduction

Pile foundations have always been used to address various foundation problems. As a special type of foundation form, belled piles are characterized by high vertical bearing capacity, high shaft stiffness, high seismic capacity, ease of quality control, and small settlement and are thus widely used in the highway engineering, bridge construction and industrial and civil building fields [1]. Many researchers have studied the bearing capacity of belled piles and have mostly focused on single piles under vertical and transverse loads. Zhang et al. [2] conducted a model test on a belled pile under a transverse load and found that under a transverse load, the pile was under tension on the loading side and under compression on the other side, and the maximum tensile stress appeared in the middle-upper portion of the pile shaft. Kong et al. [3] conducted a model test to examine the vertical compression bearing capacity of belled wedge piles in two types of soil typically surrounding piles (sandy and clayey soils). They measured pile-top load–settlement curves and determined the distribution patterns of pile-side frictional resistance and pile-tip resistance and load share ratios under various levels of loading. Zhang et al. [4] conducted a field static load test on manually bored equal-diameter cast-in-place piles, manually bored belled cast-in-place piles and manually bored branch cast-in-place piles at the same site. Based on the test results, they comparatively analyzed the distribution characteristics of several parameters (including the axial force on the pile shaft, pile-side frictional resistance, pile-tip resistance, ultimate bearing capacity and pile shaft settlement) of the three types of piles under upper loading.
Based on a composite slip surface assumption, Zhao et al. [5] derived equations for calculating the ultimate uplift bearing capacity \( R \) of belled piles in homogeneous and stratified foundations using a limit equilibrium method that overcomes soil gravity and failure surface frictional resistance. Gao et al. [6] constructed finite element (FE) models for a belled pile and an equal-diameter pile using ABAQUS FE software and focused on analyzing the stress behavior of the soil surrounding the belled pile under wind and wave loads. Additionally, they also comparatively analyzed the rotation angle of the principal axis of the stress of the soil surrounding the belled and equal-diameter piles. Based on a field test on a belled uplift pile, Wang et al. [7] examined the effects of enlarged base size, pile diameter, rock-socketed depth, cover layer thickness and gradient on the ultimate \( R \) of the rock-socketed belled pile using PLAXIS\(^3\D) FE software. Based on a field immersion loading test on large-diameter belled piles in a collapsible loess area, Li et al. [8] numerically simulated and quantified the effects of the thickness and deformation modulus of the pile-tip supporting layer on the vertical bearing capacity of a single pile using PLAXIS FE software while considering the collapsible deformation of collapsible loess. Gong et al. [9] constructed a three-dimensional (3D) solid pile–soil system model using ABAQUS software while considering the pile–soil contact conditions and used the model to numerically analyze the stability of belled piles for transmission towers under oblique loading. They found that as the load inclination \( (\theta) \) increased, the pile foundation gradually capsized and became unstable due to the insufficient resistance of the pile-side soil, and increasing soil strength parameters significantly improved the ultimate bearing capacity of the pile foundation.

In this study, to examine the \( R \) of belled piles, a 3D FE belled pile model was constructed using ABAQUS FE software. The reliability of the numerical calculations was validated. On this basis, using numerical calculations and analysis, the bearing capacity of belled piles under vertical and oblique uplift loads were investigated.

2. Construction and validation of an FE model

2.1. Modeling

Considering the symmetrical nature of structures, foundations and loading conditions, an FE model for half of a pile foundation-ground foundation coupled system was constructed. Mesh generation was performed on the calculation model using 3D 8-node reduced-integration elements. Three degrees of freedom of the bottom boundary of the FE model were constrained; one or two degrees of freedom of the side boundary of the model were constrained; and only two degrees of freedom for the symmetric surfaces were constrained. A Mohr–Coulomb elastoplastic model was used to simulate the soil. A linear elastic model was used to simulate the pile shaft. To eliminate the effects of boundary conditions, a computational domain extending 20 times \( d \) in the radial direction and 1.5 times \( L \) in the depth direction was selected.

When constructing the model, it is only necessary to set master and slave surfaces, whereas an assumption on other contact states is not needed. In the calculation process, the contact state can be directly determined based on the normal stress at the pile–soil interface. When the normal stress at the interface is a tensile stress, there is relative separation between the pile and soil, and the frictional force at the interface disappears completely. When the normal stress at the interface is a compressive stress, the pile is in contact with the soil, and the frictional force at the interface is determined based on Coulomb's friction law:

\[
f_{\text{crit}} = \mu p
\]

where \( \mu \) is the interfacial coefficient of friction, and \( p \) is the normal contact stress at the interface.

When the shear stress at the interface is lower than the critical value \( f_{\text{crit}} \), the contact surfaces are bonded; when the shear stress at the interface is higher than \( f_{\text{crit}} \), the contact surfaces slip relative to one another. Discontinuity resulting from the transition of bonded contact surfaces to slipping contact surfaces often results in convergence failure in FE calculations. To solve this problem, an "elastic sliding" penalty stiffness function factor is introduced in ABAQUS using the penalty stiffness method, which allows for a minor “relative elastic slip” between bonded contact surfaces.
2.2. Model validation
To examine the reliability of the calculation model, the numerical calculation results were compared with experimental results from Huang et al [10]. The following parameter values were used in the numerical calculation: pile length \((L)\): 27 m; pile shaft diameter \((d)\): 0.45 m; height of the enlarged base \((L_1)\): 2 m; diameter of the enlarged base \((D)\): 0.8 m; and coefficient of friction between the pile and soil \((\mu)\): 0.2. The parameters of soil and pile are list in Table 1. The displacement loading method was used in the calculation. Steel plates were used to reinforce the pile top to ensure an even \(P\). Figure 1 compares the \(P\)–uplift displacement \((\delta)\) curves of the belled pile. As demonstrated in Figure 1, the experimental and calculation results are in relatively good agreement, thereby validating the reliability of the newly constructed model.

![Figure 1. Comparison between experimental and calculation results](image)

Table 1. Physical and mechanical parameters

| Parameters | SL1 | SL2 | SL3 | SL4 | SL5 | SL6 | SL7 | Pile |
|------------|-----|-----|-----|-----|-----|-----|-----|------|
| \(\gamma/(\text{kN/m}^3)\) | 18.0 | 17.4 | 16.6 | 16.8 | 19.6 | 19.3 | 19.4 | 25.0 |
| \(c/\text{kPa}\) | 0 | 2 | 12 | 16 | 15 | 36 | 5 | |
| \(H/\text{m}\) | 1.6 | 1.4 | 7.0 | 2.5 | 7.4 | 5.1 | 5.0 | |
| \(\varphi^o\) | 22 | 22 | 18 | 12 | 20 | 22 | 32 | |
| \(E/\text{MPa}\) | 10.0 | 8.0 | 15.0 | 21.0 | 32.0 | 40.0 | 100.0 | 28000.0 |
| \(\mu\) | 0.40 | 0.40 | 0.40 | 0.35 | 0.32 | 0.30 | 0.25 | 0.16 |

3. Analysis of factors affecting the vertical \(R\) of a belled pile

3.1. Analysis of the \(P–\delta\) curve during the vertical uplift process
To analyze the \(R\) of a belled pile under a vertical \(P\), FE calculations were conducted using the following parameter values: \(L=20\) m; \(d=0.8\) m; \(L_1=2.0\) m; and \(D=1.6\) m (i.e., diameter enlargement ratio \(D/d=2\)). The soil surrounding the pile was set to consist of two layers. The enlarged base was buried in the lower soil layer. See the parameters for layers SL3 and SL6 in Table 1 for the soil parameters. Figure 2 shows the calculated pile-top \(P–\delta\) curve of the belled pile. As demonstrated in Figure 2, the \(R\) of the pile-top increases as its \(\delta\) increases. The curve has a notable inflection point. The rate of increase in \(R\) decreases significantly beyond the inflection point of the curve.
3.2. Analysis of the effect of the elastic modulus $E$ on the soil during the vertical uplift process

Figure 3 shows the $P$–$\delta$ curves calculated using the following conditions: the $E$ ($E_b$) of the soil surrounding the enlarged base: 40 MPa; the $E$ ($E_c$) of the soil surrounding the pile shaft: 5, 10, 20 and 30 MPa. As demonstrated in Figure 3, the slope of the straight-line section before the inflection point of the $P$–$\delta$ curve of the belled pile gradually increases as $E_c$ increases. Under the same $P$, as $E_c$ increases, the $\delta$ of the pile top decreases, although to an increasingly smaller extent. This finding suggests that the effect of $E_c$ on the $R$ and $\delta$ of the pile decreases as $E_c$ continuously increases beyond a certain value.

3.3. Analysis of the effect of the angle of internal friction ($\phi$) of the soil during the uplift process

Calculations were performed based on a $\phi$ of 15°, 20° and 25°. Figure 4 shows the calculated $P$–$\delta$ curves. As demonstrated in Figure 4, at a relatively small $\delta$, changes in $\phi$ have almost no impact on the $P$–$\delta$ curve of the belled pile. However, as $\delta$ increases, the $P$–$\delta$ curve begins to exhibit different trends at different $\phi$ values. $\phi$ has a slightly larger impact on the $R$ of the belled pile when it has a relatively large value.
3.4. Analysis of the cohesion (c) uniformity of the soil during the vertical uplift process

To analyze the effect of the uniformity of the soil on the R of a belled pile, it was assumed that the c uniformity of the soil changes linearly with depth, conforming to the following equation:

\[ c = c_0 + kz \]  \hspace{1cm} (2)

where \( c_0 \) is the cohesion of the foundation surface soil (kPa); \( k \) is the coefficient of variation of cohesion along the soil layer (kPa/m); and \( z \) is the depth of the foundation (m).

FE calculations were performed with respect to a nonuniform soil using various \( k \) values. Figure 5 shows the \( P-\delta \) curves of the belled pile under various \( k \) values. As demonstrated in Figure 5, the ultimate \( R \) of the belled pile increases as \( k \) increases; additionally, the larger \( \delta \) is, the more significantly it affects \( R \).

![Figure 5. Effect of \( k \) on \( P \) under vertical loading](image)

4. Analysis of factors affecting the oblique \( R \) of a belled pile

4.1. Analysis of the \( P-\delta \) curve during the oblique uplift process

To analyze the \( R \) of a belled pile under an oblique \( P \), calculations were performed using the following parameter values: \( L=20 \) m; \( d=0.8 \) m; \( D/d=2 \); \( L_1=2 \) m; \( \phi \) of the soil: 20°; \( c=12+kz \) (c changes non-uniformly); \( E=40 \) MPa; Poisson’s ratio (\( \mu \)): 0.3. When applying an oblique \( P \) to the top of the belled pile, the initial \( \theta \) with respect to the vertical direction was set to 0°, 15°, 30°, 45°, 60° and 75°. \( \theta \) was assumed to remain unchanged in the calculation. Figure 6 shows the oblique \( P-\delta \) curves of the belled pile under various \( \theta \) values. As demonstrated in Figure 6, as \( \theta \) increases, the \( P \) of the belled pile decreases. At the same \( \delta \), the maximum \( P \) occurs during the vertical uplift process.

![Figure 6. Curves of \( P \) versus \( \delta \) under oblique loading](image)

4.2. Analysis of the effect of the \( E \) of the soil during the uplift process

Calculations were performed with respect to a soil with a nonuniform changing \( c \). The \( E \) (\( E_s \)) of the soil was set to 20, 40 and 60 MPa. Figure 7 shows the effect of the \( E_s \) of the soil on the oblique \( R \) of the belled pile under various \( \theta \) values. As demonstrated in Figure 7, the effect of the \( E_s \) of the soil on the \( P-\delta \) curve is essentially the same under various \( \theta \) values. In other words, for a belled pile, \( E_s \) not only affects its ultimate \( R \) but also affects its \( \delta \). \( E_s \) affects belled and uniform-section belled piles differently.
Figure 7. Effect of $E_s$ on $P$ under oblique loading

4.3. Analysis of the $\phi$ of the soil during the oblique uplift process

Figure 8 shows the effect of the $\phi$ of the soil on the oblique $P-\delta$ curve under various $\theta$ values. As demonstrated in Figure 8, the $\phi$ of the soil has the same impact on the oblique $P-\delta$ curve under various $\theta$ values. In all cases, $P$ increases as the $\phi$ of the soil increases; however, the effect of the $\phi$ on the soil is insignificant.

Figure 8. Effect of $\phi$ on $P$ under oblique loading
4.4. Analysis of the effect of the c uniformity of the soil during the oblique uplift process

Calculations were performed using the following parameter values: c of the soil: 12+kz; \( \theta \): 0°, 45° and 75°. Figure 9 shows the effect of \( k \) on the oblique \( P-\delta \) curve under various \( \theta \) values. As demonstrated in Figure 9, as \( \theta \) increases, the effect of \( k \) on the oblique \( P \) gradually weakens.

![Figure 9. Effect of \( k \) on \( P \) under oblique loading](image)

5. Conclusions

(1) A load is gradually transferred from the top of a belled pile to its tip. The function of the enlarged base of a belled pile is realized only after the effect of the pile-side frictional resistance has been fully engaged. The \( E_c \) of the soil surrounding the pile shaft only affects the straight-line section of the \( P-\delta \) curve and has an insignificant impact on the section of the \( P-\delta \) curve beyond the inflection point.

(2) When \( \delta \) remains unchanged, the \( R \) of a belled pile increases as \( k \) increases. \( \varphi \) has an insignificant impact on the \( R \) of the pile shaft.

(3) As \( \theta \) increases, the oblique \( R \) of a belled pile foundation decreases, i.e., the \( R \) of a belled pile is the highest under a vertical load and the lowest under a horizontal load.

(4) The \( R \) of a belled pile increases as \( E \) and \( \varphi \) increase under various \( \theta \) values. \( E \) has a more significant impact than \( \varphi \). As \( \theta \) increases, the effect of \( k \) on the \( R \) of a belled pile foundation gradually weakens.

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