Rock-socketed Piles with Steel Tube under Lateral Load Analysis Based on Finite Element Method

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Abstract: Lateral bearing behaviors of large-diameter rock-socketed pile with steel tube was studied by finite element method. According to the calculation results of load-displacement curve, the lateral displacement curve and bending moment of pile, the influence of steel tube on lateral bearing behaviors of large-diameter rock-socketed pile was analyzed, and it was discussed that the influence of rock-socketed depth, pile diameter, steel tube rock-socketed depth, steel tube thickness and rock strength parameters on lateral bearing behaviors of large-diameter rock-socketed pile. The results show that the lateral bearing capacity of rock-socketed piles has been improved after considering steel tube; steel tube carries a part of lateral bearing capacity of rock-socketed pile, and it can effectively constrain the lateral displacement of the pile above the ground; rock-socketed depth and steel tube rock-socketed depth both have a critical rock-socketed depth, the influences of pile diameter, steel tube thickness and rock strength parameters on lateral bearing behaviors are different.

Keywords: Bridge engineering; Rock-socketed pile with steel tube; Lateral bearing capacity

1. Introduction

Besides bearing vertical loads, the pile foundation of bridge engineering also bear the horizontal loads which are cause by mooring line, ship impact, water flow, wind and earthquake. At present, scholars at home and abroad study a lot on the rock-socketed pile, while there is less research on the bearing behavior of large-diameter rock-socketed pile which is under the lateral load and the research on large-diameter rock-socketed pile with steel tube is little. It is necessary to erect steel tube when rock-socketed pile is constructed above water. Steel tube is a kind of construction technical measure, so steel tube should be embedded in a certain depth of rock, and after the construction, steel tube bears loads together with concrete. The stress of steel tube normally is not considered by the existing code. But, because of the comparative large flexural stiffness, the steel tube will bear the corresponding load under the effect of lateral bearing.

Based on the original bridge pile foundation date of Chongqing Orchard, the deformation mechanism of large-diameter rock-socketed pile with steel tube under lateral bearing was studied by finite element method in this paper .The influence of steel tube on lateral bearing behavior of large-diameter rock-socketed pile was analyzed , and it was discussed that the influence of rock-socked depth , pile diameter, steel tube rock-socketed depth , steel tube thickness and rock strength parameters on lateral bearing behavior of large-diameter rock-socketed pile.

2. FEM (Finite Element Method)

2.1. Finite Element Model

Modelling the finite element method by (the model sample of) the rock-socketed piles of Chongqing Orchard Harbor II Extension Project . The bridge adopts suspended verticle frame. Platform single frame structure adopts 4 rows of pile foundation, and the pile spacing is 8m. The front pile foundation is steel tube pile diameter 2200mm; Diameter of jacket is 2400mm, thickness 16mm. The last three row pile foundation are steel tubes with/whose pile diameter 2200mm , Diameter of jacket is 2200mm , thickness 16mm . The rock-socketed pile embed in no less than 5 times the length of the diameter of pile foundation .And the steel tubes also embed in moderately weathered rock a certain depth, and it should be compacted to avoid, the vertical displacement. The geologic condition of rock foundation is sand shale interbed.

By use of the finite element software ABAQUS, building the calculation model of the single rock-socketed pile with steel tube. For the symmetry of the model, three-dimensional finite model can be built just by half of the whole. But, in order to meet the requirement of numerical accuracy and satisfy the boundary conditions, twenty times of the pile diameter should be used as the horizontal effect/impact zone, which is under the pile base.

Rock-socketed pile diameter 2200mm, total pail length 21m, pile foundation length above the ground 10m. The pile shaft should be furnished by steel tube that length 12.75m, wall thickness 16mm, the length above ground 10m. Setting the foundation is moderately weathered rock. They are all homogeneous rock, whose properties are the same.

The unit of steel tube, concrete and rock foundation is C3D8R solid element. During the modelling, both of the top interfaces of the concrete pile and steel tube should have the same height. The mesh which is nearby the rock-socketed pile should be refined and the mesh which is away from should be sparse. The finite element model and mesh generation are shown in Figure 1. Applying the symmetric boundary condition on the symmetry plane of X and Z, let the bottom of foundation constrain the displacements on directions of X , Y and Z ,and let the side / profile of foundation constrain the displacements on direction of X and Y.

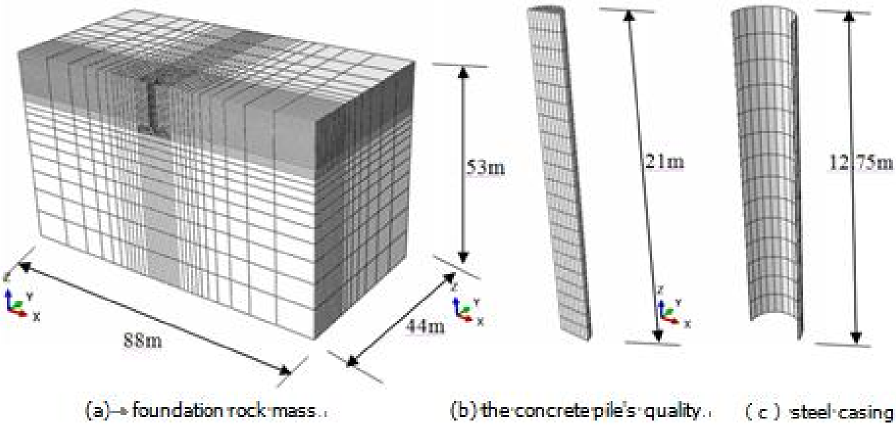

Figure 1. Finite element model and mesh

2.2. Material Constructive Model

The steel tube (in model) adopt elastic-intensive model, namely the slope of stress-strain curve is the elastic modulus E_s of steel before the steel stress reaching its yield stress f_y. When reaching the yield stress, the stress strain curve will simplify into a straight line with slop of 0.01ES .Supposing the density of steel tube ρ_s=7850kg/m^3, elasticity modulus Es=206GPa, the poison ratio of plastic stage v_s=0.3, yield strength f_y =235Mpa.

Pile shaft concrete adopts ductile damage model, concrete density $P_c = 2500Kg/m^3$, elastic modulus Ec=30Gpa, the poison ratio of plastic stage V_s=0.2, axial compressive strength f_c=20.1MPa, axial tension strength f_y=2.01Mpa.

Concrete uniaxial stress-strain relationship is defined by the following formulas.

Compression:

$$s = (1-d_c)E_c e \tag{1}$$

Among them, $d_c = \begin{cases} 1-\dfrac{r_c n}{n-1+x^n} & x \le 1 \\ 1-\dfrac{r_c}{a_c(x-1)^2+x} & x>1 \end{cases}$

$r_c = \dfrac{f_c}{E_c e_c}; n = \dfrac{E_c e_c}{E_c e_c - f_c}; x = \dfrac{e}{e_c}$.

Tension:

$$s = (1-d_t)E_c e \tag{2}$$

Among them, $d_t = \begin{cases} 1-r_t\left[1.2-0.2x^5\right] & x \le 1 \\ 1-\dfrac{r_t}{a_t(x-1)^{1.7}+x} & x>1 \end{cases}$;

$x = \dfrac{e}{e_t}; r_t = \dfrac{f_t}{E_c e_t}$.

In these formulas, α_c is the parameter values of descent segment part parameter of tension stress-strain curve, α_t is the parameter values of descent segment part parameter of compressive stress-strain curve: f_c , f_t respectively are compressive and tensile strength of concrete. ε_c and ε_t respectively are the corresponding peak strain of the compressive and tensile strength. d_c and d_t are the damage evolution parameters of uniaxial tension and compression.

Rock-foundation adopts Mohr –Coulomb Law, and according to the experimental data and the rock mass rating system of Chongqing region, the basic parameters of rock-foundation are as follows; elastic modulus E_r=3Gpa, poisson ratio v_r=0.3 , cohesive force c=400KBa , friction angle $\varphi = 30^\circ$, density ρ_r=2500 Kg/m^3 .

2.3. Interface Model

Besides the rock mass around pile, the concrete on pile and material of steel tube which are nonlinerity, the interaction between pile and rock are under considerations, pile and concrete are also considered during the infinite element modelling. In ABAQVS, through “contact pair” we achieve the setting of contact. The constitutive relation normal of interface adopts hard contact. Tangential Tangent adopts Coulomb Elastic –Plastic Friction model and it is modeled by penalty function method.

The interface element uses master-slave algorithm and there are three kinds of interface elements. First in the contact between steel tube and pile shaft concrete, the steel tube is main control surface and the concrete is subordination surface, friction coefficient 0.5. Second, in the contact between steel tube and stock mass, the steel tube is main control surface, and stock mass is subordination surface, friction coefficient 0.4. Third, in contact between concrete and stock mass, the concrete is main control surface and stock mass is subordination surface, friction coefficient 0.35.

3. Lateral Bearing Behavior of Large-Diameter Rock-socketed Pile with

Through comparative study between rock-socketed pile without steel tube model and rock-socketed pile with steel tube model, we can get the lateral bearing behavior of large-diameter rock-socked pile with steel tube, including that pile top is in Free State and the lateral load is enforced on the pile top.

3.1. Load-Displacement Curve of Pile Top

Load-Displacement curves of pile with steel tube and pile without steel tube are shown in Figure 2. The foundation of pile without steel tube is damaged under the 800KN lateral bearing , while the 2000KN lateral bearing loads on and bring no damage on the pile with steel tube .Compared with pile without steel tube ,the lateral bearing capacity of stock-socketed pile with steel tube gets a corresponding rise . As Figure 2, the lateral bearing in 2000KN is a kind of slow deformation curve.

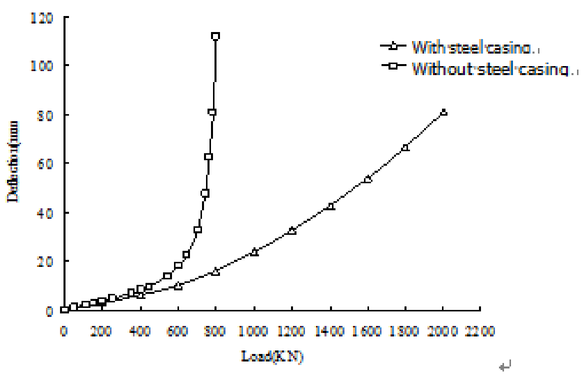

Figure 2. Lateral load-displacement curves

3.2. Lateral Displacement of Pile

From Figure 3 and Figure 4 we can get conclusions as follows. The bigger lateral bearing is on pile, the bigger lateral displacement will be, And when various stepwise loadings are on pile top, the lateral displacement is maximum .The lower height of load point is, the minor lateral displacement will be , because the free segment pile length which is above the ground (Depth=0) is comparatively long, so when the load effect reaches on the ground , the lateral displacement is tiny .When the lateral displacement quantity of rock-socketed segment is very small, the clamping effect of rock-socketed pile is dramatically. Under the consideration of the stress of steel tube, the lateral displacement of pile which is above the ground can be restrained effectively by rock-socketed pile with steel tube.

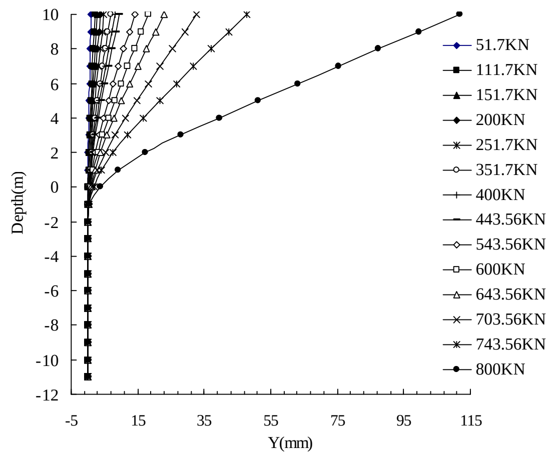

Figure 3. Lateral displacement curves of pile without steel tube

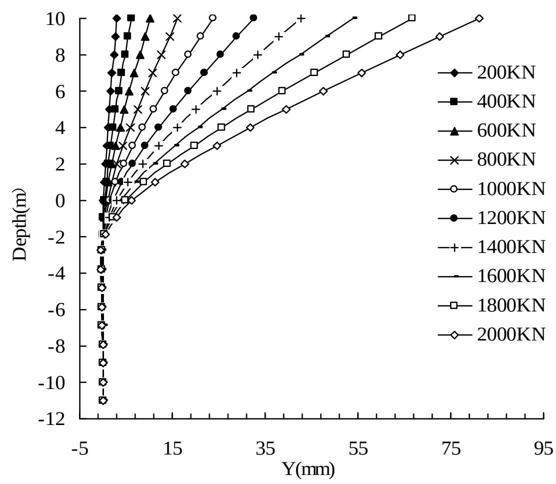

Figure 4. Lateral displacement curves of pile with steel tube

3.3. Bending Moment

Bending moment is the main stress of rock-socketed pile under the lateral bearing. We can get the bending moment distribution graphs of pile with steel tube and pile without steel tube which is in different socketed depth under various stepwise loadings respectively in Figure 5 and Figure 6. Weather the pile with steel tube or not, the bigger lateral bearing is, the bigger bending moment will be. As the rock-socketed depth increases, the bending moment of rock-socketed pile shaft which is under various stepwise loadings is going to smaller and smaller. But when the rock-socketed depth is 6m, the bending moment of pile shaft remains unchanging. And the bending moment achieves its maximum on the place of ground. Considering the steel tube, the bending moment increases on the segment of steel tube, and it changes suddenly on the place of the segment which is below the steel tube, but the effect which is brought by steel tube is not very obvious on the pile that the dept is less than 6m.

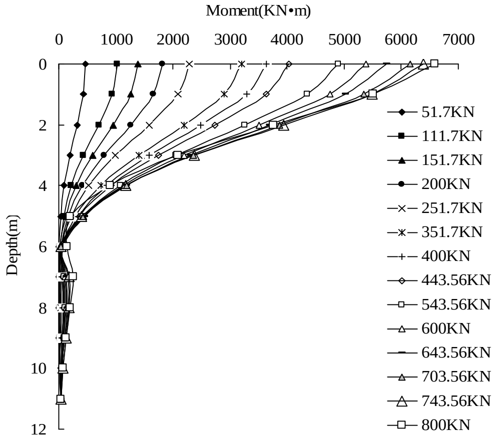

Figure 5. Moment curves of rock-socketed pile without steel tube

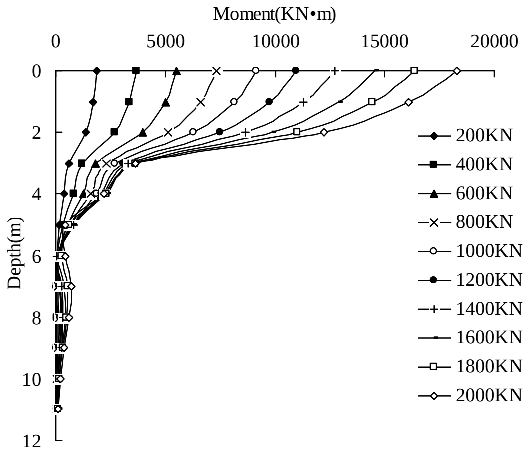

Figure 6. Moment curves of rock-socketed pile with steel tube

4. The Influence Factor Analysis of Lateral Bearing Behavior

4.1. The Influence of Rock-socketed Depth on Lateral Bearing Behaviours

Different situations of different rock-socketed depths are calculated by use of finite element method. From the result, we can see that the influence of lateral bearing of rock-socketed on the depth of rock –socketed pile with steel tube is not obvious.

In Table 1, the different lateral displacement of pile top in different rock-socketed depths and the lateral displacement under the lateral bearing which is in 2000KN are shown . The result show that, as the rock-socketed depths increase, the lateral displacement of pile top is going to decrease, but the reduced amplitude is relatively small. When the rock-socketed depths increase from 4D to 7D, the lateral displacement of pile top only have a 0.142mm decline. Rock-socketed pile with steel tube has a critical rock-socketed depth. When rock-socketed pile depth exceeds the critic depth, the effect will not obvious if only rely on increasing rock-socketed depth to improve the lateral bearing capacity of pile foundation.

Table 1. Lateral displacement of pile top of different rock-socketed depths

Rock-socketed length	3D	4D	5D	6D	7D
Horizontal displacements of the pile tops /mm	81.644	81.33	81.238	81.189	81.188

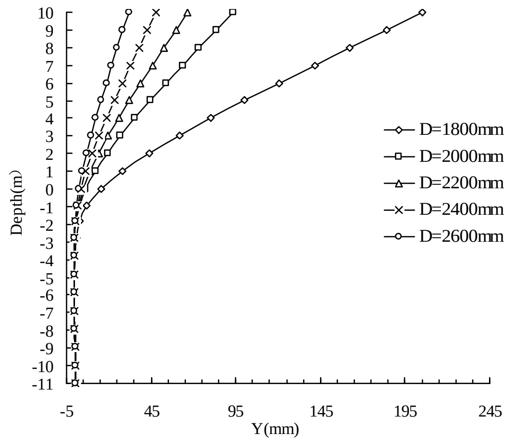

Figure 7. Lateral displacement curves of different pile diameters

4.2. The Influence of Rock-socketed Pile Diameter on the Lateral Bearing Capacity

To draw a more accurate conclusion, using finite element method to calculate out the situation/results of the rock-socketed pile diameter which are between 1800mm to 2600mm, and the diameter is changed from 1800mm to 1674mm under 2000KN lateral load. The lateral displacement curves with different pile diameter are shown in Figure 7. And the figure also shows that the load capacity is significantly influenced by pile diameter. The lateral bearing capacity increases with the increase of pile diameter. And the conclusion can be made that the pile diameter has significant influence on lateral bearing of rock-socketed pile. So, during the actual design the demand of bearing capacity and cost need to be considered comprehensively to confirm a proper pile diameter.

4.3. The Influence of Rock-socketed Pile with Steel Tube Depth on Lateral Bearing Capacity

Loading 2000KN lateral bearing on different rock-socketed pile with steel tube depth can get lateral displacement curves as Figure 8. From this figure, we can get that the pile top lateral displacement decreases as the rock-socketed pile with steel tube depth is increasing. Pile top displacement decreases 30% when the depth is increased from 2.75m to 5.5m, and from this we can know that after 2.75m increase, the lateral bearing capacity is significantly improved. But when the depth is increased from 5.5m to 8.25m, the lateral displacement of pile top is only decrease 2%. So, it can't get an obvious effect if only rely on increasing the depth of rock-socketed pile with steel tube to improve the bearing capacity of pile foundation. To decide a proper depth, both the optimal stress of pile foundation and economic benefit should be considered during the actual construction process. As the depth increase, the difficulty in construction also increases, at the same time the cost increases too. And when the depth of rock-socketed pile with steel tube exceeds its critic rock-socketed depth, it is difficulty to improve the bearing capacity.

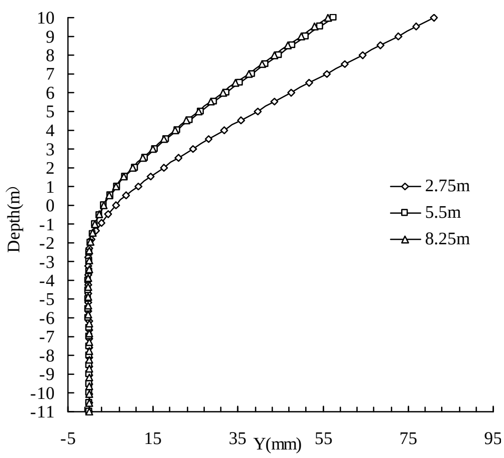

Figure 8. Lateral displacement curves of different steel tube rock-socketed depths

4.4. The Influence of Steel Tube Thickness

Figure 9 shows the lateral displacement curves with different steel tube thickness under 2000KN lateral bearing. The state shows that lateral bearing are significant influenced by steel tube. As the steel tube thickness, the pile top displacement is going to decrease. Above all, we can conclude that the increase of steel tube thickness can improve the capacity to withstand bending deflection of pile shaft, and the thicker steel tube is the better effect will get.

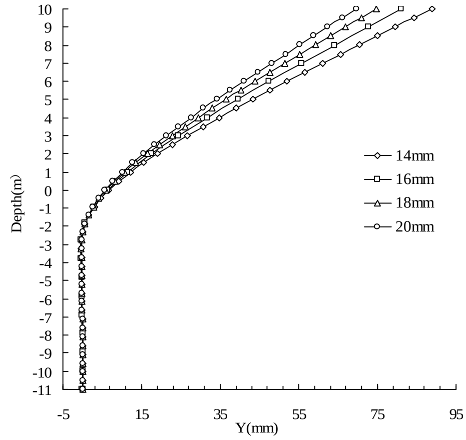

Figure 9. Lateral displacement curves of different steel tube thickness

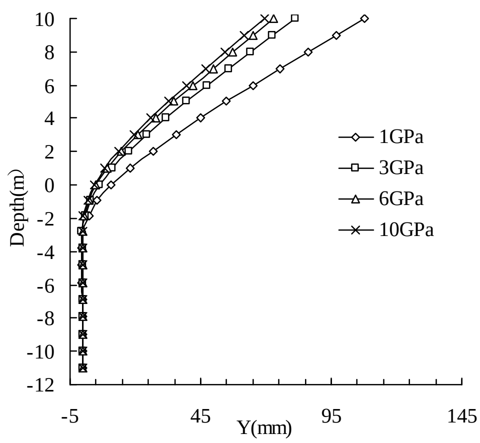

Figure 10. Lateral displacement curves of different rock elastic modulus

4.5. The Influence of Rock Strength Parameters

Figure 10 to Figure 12 are the lateral displacement curves of pile shaft which are under 2000KN lateral bearing in different rock elastic modulus , cohesive forces and internal friction angles . From Figure 10 to Figure 12 we can get that under a certain bearing, the displacement of the pile top and the pile shaft segment will decrease with the increase of rock elasticity modulus, cohesive forces and internal friction angles, but the lateral displacement of pile which is below the steel tube remains almost the same. The lateral displacement of pile with steel tube can be controlled effectively by the increase of rock elasticity modulus, cohesive force and internal friction angle, and the lateral bearing capacity can be improved by increase of these factors. While, improving the rock elasticity modulus and cohesive force are more efficient ways to improve the lateral bearing capacity of pile foundation than improving the rock internal friction angles.

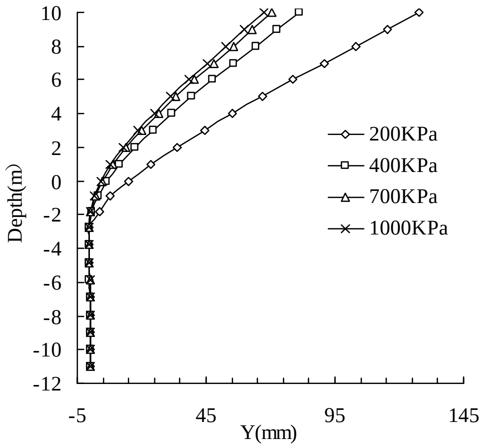

Figure 11. Lateral displacement curves of different rock cohesive force

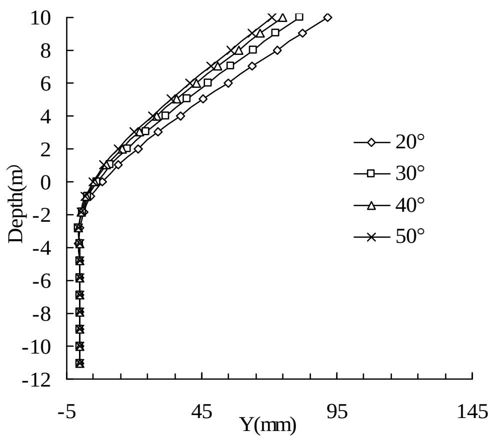

Figure 12. Lateral displacement curves of different internal friction angle

Conclusions

It is analyzed for the lateral bearing behavior of large-diameter rock-socketed pile with steel tube of bridge by using of nonlinear finite element method, and it can get following conclusions:

(1) The load-displacement curve of large diameter rock-socketed pile with steel tube under lateral bearing is slow deformation curve . Compared with rock-socketed pile without steel tube, the lateral bearing of rock-socketed pile with steel tube is significantly improved and the steel tube can restrain the pile above ground effectively.

(2) The lateral displacement of pile top decrease as rock-socketed depths is increasing, but the decreasing range is small. There is critic rock-socketed depth of pile. When rock-socketed pile depth exceeds the critic depth, the effect will not obvious if only rely on increasing rock-socketed depth to improve the lateral bearing capacity of pile foundation.

(3) The pile diameter has a significant influence on the lateral bearing capacity of rock-socketed pile with steel tube. With the increment of the diameter of rock-socketed pile, the lateral bearing capacity increase. So, during the actual design, the demand of bearing capacity and cost should be considered comprehensively to confirm a proper pile diameter.

(4) Rock-socketed pile with steel tube exists a critic rock-socketed depth . And when the rock-socketed depth exceeds the critic rock-socketed depth, it is difficulty to improve bearing capacity of pile foundation if just rely on increasing the depth of rock-socketed pile with steel tube.

(5) The withstand bearing deflection capacity of pile shaft is influenced by steel tube and the thicker steel tube is , the lager withstand deflection capacity will be.

(6) In the rock strength parameter , rock elasticity modulus and cohesive force have more significant influence on the lateral bearing capacity of rock-socketed pile with steel tube than internal angle. We can control the lateral displacement of pile segment with steel tube by improving the rock elasticity modulus, cohesive force and internal friction angle.

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