Mechanism and Numerical Analysis of Micropile-Pressure-Type Anchor Composite Foundations Under Uplift Load

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Abstract. This study introduces a novel composite foundation designed to address the safety and convenience issues associated with the construction of traditional transmission tower foundations. The foundation incorporates micro piles and pressure-type anchor rods, connected to the upper tower via steel abutments. By using the finite element software ABAQUS to establish a model, this study delved into the load sharing effect mechanism of composite foundations under uplift loads and conducted case verification. The research results indicate that micro piles bear the main tensile force in the initial stage, while pressure type anchor rods gradually share more tensile force with increasing load. Furthermore, based on field test conditions, this study analyzed the effects of factors such as the depth of micro pile embedding in rock, soil elastic modulus, rock elastic modulus, and soil cohesion on the bearing capacity of various parts of composite foundations. The results indicate that the micro-pile pressure anchor composite foundation demonstrates an effective collaborative mechanism under uplift loads, with micro piles initially bearing the primary tensile force and pressure-type anchor rods increasingly sharing the load as the load increases, thereby enhancing the foundation's pull-out capacity. The tensile bearing capacity of the foundation is significantly influenced by the elastic modulus and cohesion of the surrounding rock and soil, with increases in soil elastic modulus enhancing the workability of the composite foundation and reducing uplift displacement. Furthermore, the load-sharing ratio of pressure-type anchor rods stabilizes initially and then decreases with increasing soil material parameters, while an increase in rock material parameters leads to a rising load-sharing ratio for the anchor rods, which slows down as the bearing capacity of the rock-embedded micro piles grows.

Keywords: Composite foundation; Pressure-Type Anchor; Micropile; Uplift bearing capacity; Numerical analysis

1 Introduction

Against the backdrop of rapid development of high-voltage transmission lines, traditional transmission line foundations face many challenges in complex terrains such as

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mountainous areas, such as low construction efficiency, severe environmental damage, and high costs. Existing research has proposed various types of foundations, including micro piles[1-2] and rock anchor foundations[3], but these studies mostly focus on single foundation types and lack in-depth exploration of composite foundation structures. In recent years, some scholars have proposed various new composite foundations, including straight column pile anchor composite foundation and excavation anchor composite foundation, and conducted a series of experimental and theoretical studies around these foundation types[4-5]. However, the pile diameter of the upper piles in these basic types is often larger, exceeding 1m, which fails to effectively solve the problem of manual operation at the bottom of the piles. At the same time, during construction in mountainous areas with steep slopes, due to the large pile diameter, extensive excavation and slope cutting are required, which not only increases the difficulty of construction, but also raises costs and may cause environmental problems. In addition, the substructure of these composite foundations often uses full-length bonded anchor rods, which have problems such as poor durability and susceptibility to cracking[6].

In response to these issues, this study proposes a novel micro-pile pressure anchor composite foundation. The foundation connects to the upper steel tower through a steel pier, combining the advantages of micro-piles and pressure-type anchors, aiming to enhance the stability and safety of the foundation while achieving mechanized construction and environmental protection. The diameter of micro-piles is relatively small, typically ranging from 0.1m to 0.4m, allowing their use in areas with spatial constraints. Pressure-type anchors, due to their mechanism of stress transfer through the compressed grouting body at the bottom, can better utilize the lateral resistance of the rock mass. By combining micro-piles with pressure-type anchors, the composite foundation can adapt to various conditions and has excellent load-bearing capacity.

On the basis of experiments, this study conducted numerical simulations of the pull-out bearing capacity of a micro pile pressure anchor composite foundation through finite element calculations. The effects of factors such as the elastic modulus of the rock and soil mass, foundation conditions, etc. on the ultimate pull-out bearing capacity, P-S curves of each part of the bearing capacity, and ultimate strength coefficient of the composite foundation were analyzed. Based on this, the load sharing effect and bearing mechanism of the composite foundation were further discussed.

2 Numerical Model

Establish a composite rock anchor foundation model in ABAQUS finite element software. The overall shape of the model is cylindrical, with a diameter of 8m and a height of 7.5m. Empirical calculations show that the size of the model has no significant impact on the calculation results of the bearing capacity; Using hexahedral C3D8 solid element to simulate direct anchored composite foundation and rock soil mass; The boundary conditions for rock and soil are set as lateral horizontal constraints, bottom fixed constraints, and upper free surfaces;, The model is shown in Figure 1.

Numerical simulation is based on the following basic assumptions: 1) The model rock and soil mass are homogeneous and isotropic, without considering the influence of pore water; 2) The overall foundation has deformation coordination characteristics; 3) Not considering the internal damage of foundations such as anchor bar fracture and concrete fragmentation. The ideal elastic model is adopted for the foundation, and the Mohr Coulomb elastoplastic constitutive model is used for the rock and soil mass.

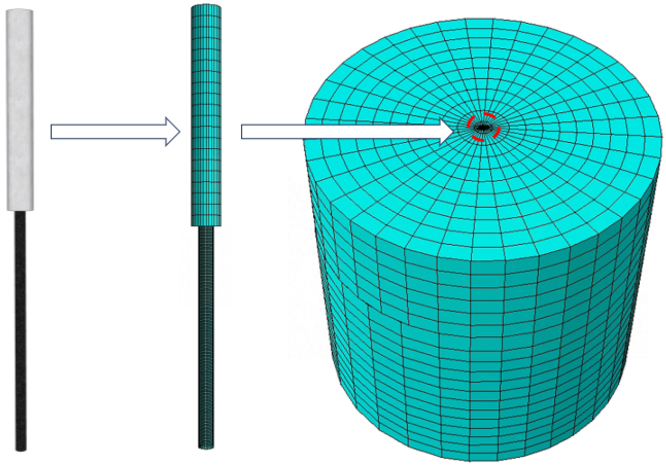

Fig. 1. Three dimensional and numerical models of composite foundations

The ideal elastic model is adopted for the foundation, and the Mohr Coulomb elastoplastic constitutive model is used for the rock and soil mass.

The contact surface between the micro pile foundation and the rock and soil mass on the upper part of the micro pile anchor composite foundation is set as a small sliding contact model in ABAQUS, using the principal subordinate contact algorithm, where the foundation surface is defined as the main surface, the rock and soil mass surface is defined as the subordinate surface, the normal direction is the hard contact, and the tangential direction is set with a friction coefficient of μ=tan (0.75 φ)[7].

For the pressure type anchor rod, there is a bonding effect between the anchor body and the rock mass at the interface. In ABAQUS, the above interface is divided into "cohesive" cohesive unit layers to simulate the bonding slip failure process of the interface. The bonding strengths are set to 3000kPa and 320kPa, respectively. Define damage evolution as fracture energy mode.[8]

3 Verification of Numerical Model

Prior to conducting numerical simulations, this study carried out field experiments in Shaoxing City, Zhejiang Province, as shown in Figure 2(a) for the composite foundation structure used in the field tests. The basic dimensions and material parameters of the numerical model should be consistent with those used in the field tests. Specific material parameters are presented in Table 1.

A 30mm upward displacement was applied to the top surface of the foundation to simulate the effect of an upward pull force.

Table 1. Numerical calculation of parameters values

Material	Elastic modulus (Mpa)	Poisson's ratio	Density ($kN \cdot m^{-2}$)	Cohesion (kPa)	Internal friction angle (°)
Silty clay	20	0.25	19.5	23	10
Strongly weathered rock	500	0.3	24.1	650	35
Foundation	30000	0.2	25	/	/

Figure 2(b) illustrates the P-s curves of the composite foundations ZY1 and ZY2 under uplift load. It can be seen from Figure 2(b) that the numerical simulation results of the P-s curve variations for the two types of composite foundations under uplift load match well with the field test results, demonstrating the feasibility of using the finite element model established in this paper to simulate the behavior of the composite foundation under uplift loads. The modeling method, the settings of the material constitutive models, and the material mechanical parameter values are reasonable.

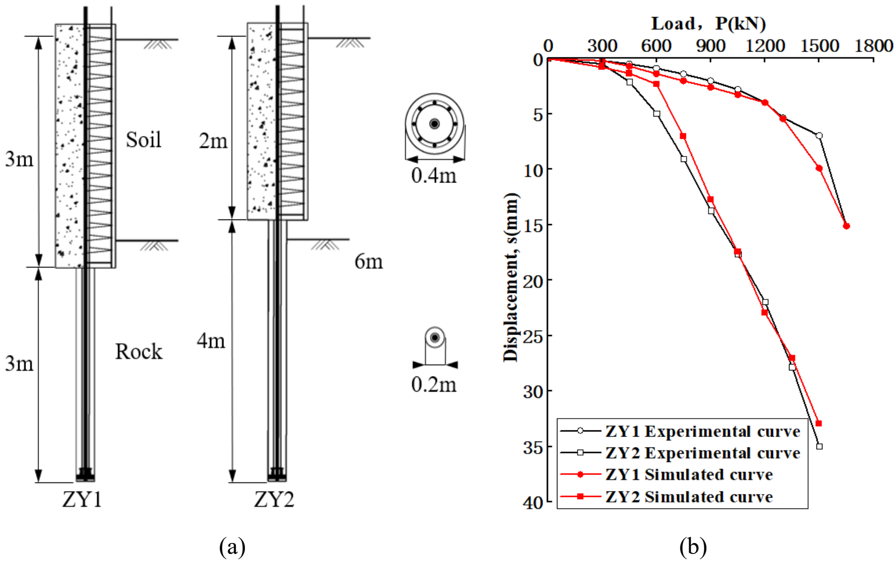

Fig. 2. Graphic design drawing of composite foundation and Comparison of P-S curves

4 Analysis of Pull-out Bearing Characteristics of Composite Foundation

The stress cloud map of the composite foundation and surrounding rock and soil mass obtained by numerical calculation is shown in Figure 3. By extracting the internal forces of each part of the composite foundation in ABAQUS, the axial force distribution diagram of the composite foundation can be drawn as shown in the Figure 4. From the axial force distribution diagram, it can be seen that the stress of the pressure type anchor rod is negative, that is, the grouting body is compressed at the bottom. At the initial stage of loading, the lower pressure type anchor rod begins to bear the tensile load, and as the upward load increases, the axial force of the anchor rod continues to increase. After the axial force of the upper micro pile increases to a certain extent, it stops increasing and even decreases. It can be seen that the load level at which the axial force of ZY1 micro pile decreases is consistent with the load when the load displacement curve suddenly changes. It can be considered that at this time, the micro pile has reached the ultimate pull-out state, and the lateral friction resistance of the pile body has been fully exerted. In the axial force distribution diagram of ZY2, the axial force of the micro pile remains relatively stable during the loading process. This phenomenon indicates that the pull-out bearing capacity of micro piles with a depth of 2 meters without rock embedding is lower than 450kN. Therefore, when the first level load is applied, their lateral friction resistance has been fully exerted.

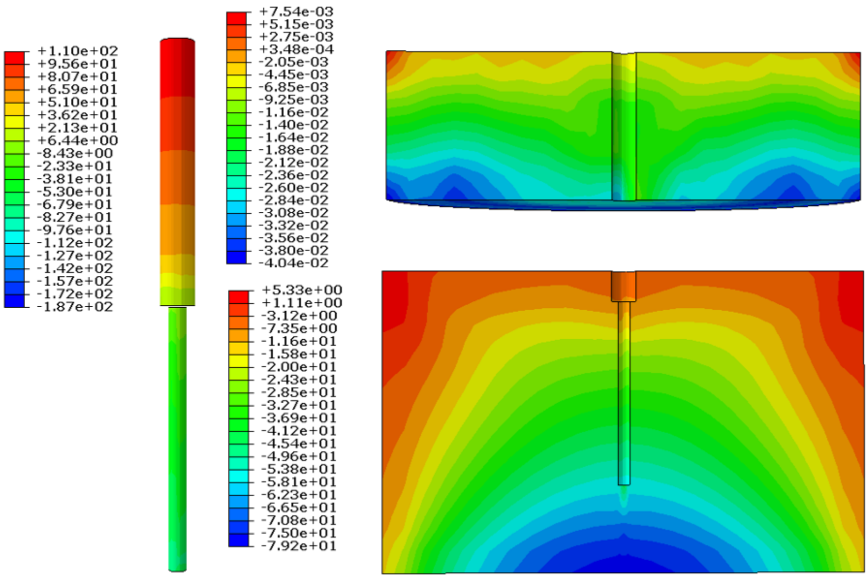

Fig. 3. Stress cloud map for numerical calculation of composite foundation and rock soil mass

The composite foundation is composed of a combination of micro piles and pressure type anchor rods, and its bearing mechanism can be described by the distribution of resistance between these two structures at different stages. Figure 5 shows the distribution of resistance between micro piles and anchor rods at different loading stages in the uplift static load test of composite foundation.

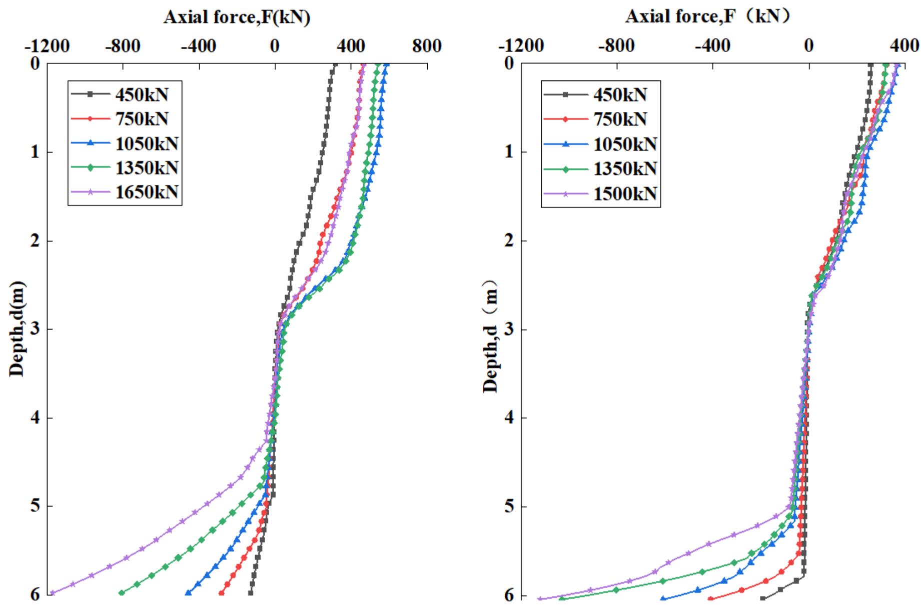

Fig. 4. Axial force curves of ZY1 and ZY2

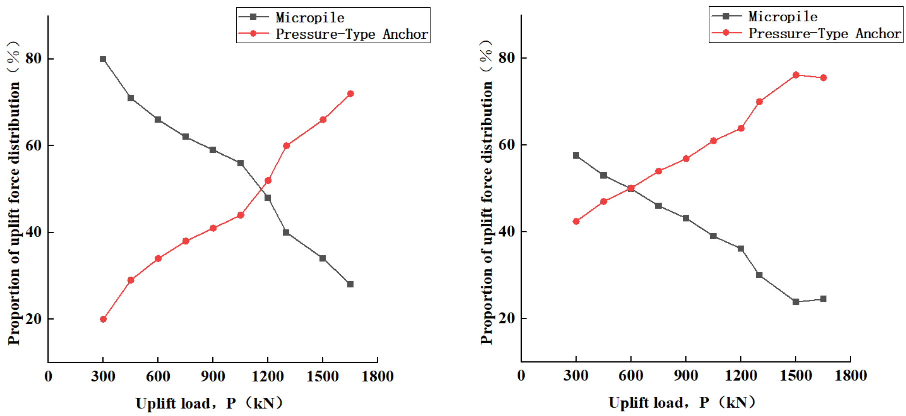

Fig. 5. Resistance distribution of upper and lower structure members in composite foundation during loading process of ZY1 and ZY2

Analysis of the graphical data reveals that in the initial stage of loading, micro piles and anchor rods jointly bear the uplift load, with micro piles bearing a greater proportion of the uplift force than anchor rods. At this point, micro piles share 80% and 60% of the uplift force, while pressure type anchor rods share 20% and 40% of the uplift force. With the increase of uplift load, the bearing capacity of pressure type anchor rods gradually comes into play, and the proportion of anti uplift force they share continues to rise. When the upward pulling load reaches a certain critical value, the proportion of anti pulling force shared by the anchor rod begins to exceed that of the micro pile. When the composite foundation experiences overall failure, the micro pile reaches its ultimate pull-out state. At this point, the proportion of resistance shared by the pressure type anchor rod reaches 72% and 75%, while the proportion shared by the micro pile decreases to 28% and 25%. The main reason is that in the early stage of upward pulling, the anchor bars of pressure type anchor rods elongate significantly due to their high elastic modulus, but the displacement of micro piles is small, which limits the displacement of the anchor rods; In the later stage of loading, the lateral friction resistance of the micro pile reaches its maximum, and the displacement increases, while the anchor rod limits the displacement of the micro pile. This collaborative working mechanism enables the composite foundation to more effectively exert its anti pull ability.

5 Parameter Analysis

To investigate the influence of different rock and soil properties on the pull-out bearing capacity of composite foundations and the sharing ratio of various parts of composite foundations, this study designed three different working conditions through simulation methods for analysis. They are the exploration of the influence of soil elastic modulus, rock elastic modulus, and soil cohesion. Each study controlled for Poisson's ratio υ, severity, and internal friction angle φ to remain constant, while changing other variables. The specific parameters for each study group are shown in the table 2.

Table 2. Parameters of models for different groups

Research group	Number	Soil elastic modulus (MPa)	Rock elastic modulus (Mpa)	Soil cohesion (kPa)
Exploration into the Influence of Soil Elastic Modulus	TM-1	10		
	TM-2	20		
	TM-3	30	500	23
	TM-4	40		
Exploration of the influence of rock elastic modulus	YM-1		200	
	YM-2		400	
	YM-3	20	600	23
	YM-4		800	
Exploration of the Influence of Soil Cohesion	TN-1		500	10
	TN-2	20		20
	TN-3			30
	TN-4			40

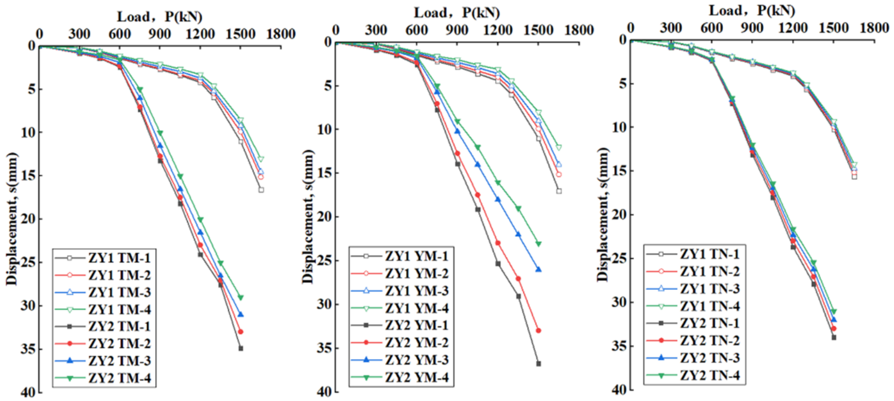

Fig. 6. P-S curves of uplift bearing of the composite foundation under varied elastic modulus of soil, elastic modulus of rock and cohesion of soil

Figure 6(a) shows the P-S curve obtained by numerical calculation when the elastic modulus of soil varies within the range of 10 to 40 MPa. The results indicate that as the elastic modulus of the soil increases, the trend of the load displacement curve of the composite foundation remains consistent, but the uplift displacement under the same load gradually decreases, indicating an improvement in its working performance. When the elastic modulus of the soil increased from 10 MPa to 40 MPa, the displacement corresponding to the ultimate load of ZY1 decreased by 5.09%, 11.90%, and 21.43%, respectively, while the displacement corresponding to ZY2 decreased by 4.35%, 21.12%, and 32%, respectively. This suggests that the soil elastic modulus has a relatively minor impact on ultimate bearing displacement when micro piles are embedded in rock, compared to non-embedded scenarios.

Figure 6(b) shows the P-S curve of the elastic modulus of the rock mass varying within the range of 200 to 800 MPa. It can be seen that as the elastic modulus of the rock mass increases, the change trend of the P-S curve gradually transitions from steep deformation to gradual deformation. Meanwhile, as the elastic modulus of the rock mass increases, the uplift displacement under the same load gradually decreases, indicating an improvement in its working performance. When the elastic modulus of the soil increased from 200 MPa to 800 MPa, the displacement corresponding to the ultimate load of ZY1 decreased by 9.4%, 18.18%, and 29.55%, respectively, while the displacement corresponding to ZY2 decreased by 9.02%, 29.41%, and 37.25%, respectively. This indicates that compared to non embedded rock, the influence of the elastic modulus of the rock mass on the ultimate bearing displacement is relatively small when micro piles are embedded in rock.

Figure 6(c) presents the P-S curve of the numerical calculation results for soil cohesion of 10-40kPa. The results show that with the increase of soil cohesion, the load displacement curve trend of the composite foundation remains consistent, but the uplift displacement under the same load gradually decreases, indicating an improvement in its working performance. When the soil cohesion increased from 10 kPa to 40 kPa, the displacement corresponding to the ultimate load of ZY1 decreased by 2.9%, 5.9%, and

8.6%, respectively, while the displacement corresponding to ZY2 decreased by 3%, 5.6%, and 9%, respectively. This indicates that the influence of soil cohesion on the ultimate bearing displacement of micro piles is basically the same when they are not embedded in rock and when embedded in rock.

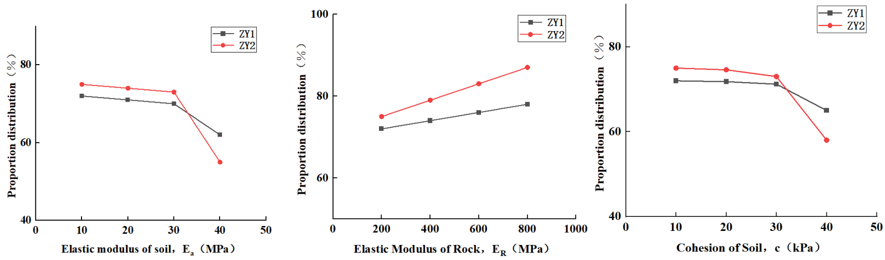

Fig. 7. The proportion of load borne by the pressure-type anchor at the limit.

Next, we will explore how the parameters of rock and soil properties affect the load sharing ratio between micro piles and pressure type anchor rods when they reach failure. The variation of the sharing ratio of pressure type anchor rods under ultimate load is shown in the Figure 7.

Through image analysis, it can be observed that as the soil material parameters increase, the proportion of pressure type anchor rods initially remains relatively stable, and then shows a downward trend. Specifically, the proportion of ZY2's share has decreased significantly. This phenomenon can be attributed to the fact that changes in soil material parameters mainly affect micro piles, while the bearing performance of lower pressure type anchor rods is relatively strong. When the soil parameters initially increase, their potential for anti pull bearing capacity is not fully released. With the enhancement of the bearing capacity of micro piles, the potential of pressure type anchor rods is gradually realized, leading to a decrease in their sharing ratio.

Furthermore, as the material parameters of the rock mass increase, the proportion of pressure type anchor rods shows an upward trend, with the slope of ZY2 being particularly significant. This may be because the increase in the elastic modulus of the rock mass mainly affects the substructure. In the case of ZY1, due to the embedded micro piles in the rock mass, when the bearing capacity of the pressure type anchor rod increases, the bearing capacity of the micro piles also increases synchronously, so the increase in the sharing ratio of the pressure type anchor rod is relatively slow.

6 Conclusion

The micro pile pressure anchor composite foundation exhibits a good collaborative working mechanism under uplift load. In the initial stage of load, micro piles bear the main tensile force, and as the load increases, pressure type anchor rods gradually share more of the tensile force. This composite effect improves the basic pull-out bearing capacity.

The elastic modulus and cohesion of rock and soil have a significant impact on their tensile bearing capacity. The increase in soil elastic modulus improves the workability of composite foundations and reduces uplift displacement. The increase in the elastic modulus of the rock mass changes the trend of the P-S curve, transitioning from steep deformation to gradual deformation.

An increase in soil material parameters initially stabilizes, then reduces, the load-sharing ratio of pressure-type anchor rods. The increase in rock material parameters leads to an increase in the load sharing ratio of pressure type anchor rods, and the growth of the sharing ratio slows down when the bearing capacity of rock embedded micro piles increases.

Based on the outcomes of numerical simulation parameter analysis, several refinements can be implemented to optimize the design parameters of composite foundations. Notably, the material properties of the soil and rock mass significantly influence the performance and uplift displacement of the composite foundation. Therefore, it is essential to conduct thorough geological surveys prior to construction, strategically selecting environments with more favorable geological conditions for foundation building.

To fully harness the pull-out load-bearing capacity of both micro-piles and pressure-type anchors, the lengths of these components should be adjusted according to the soil and rock mass parameters during the design phase. This adjustment aims to ensure that the ultimate pull-out capacities of these two structural elements are equal, allowing for a simultaneous failure mechanism.

Furthermore, theoretical calculations and numerical simulation results should be utilized as the starting point for an iterative design process. Continuous refinement of the design parameters, guided by feedback from subsequent simulations, is crucial until an optimal design is achieved that balances safety, cost, and performance effectively.

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