

Full-scale field test study on the load-bearing characteristics of inclined anchor short pile foundation

Jun DUAN^a, Qiang XIE^{a,b*}, Yuxin BAN^c, Xiang FU^d, Yiqing ZHANG^e

^a School of Civil Engineering, Chongqing University, Chongqing 400045, China

^b State Key Laboratory of Safety and Resilience of Civil Engineering in Mountain Area, Chongqing University, Chongqing 400044, China

^c School of Civil and Hydraulic Engineering, Chongqing University of Science and Technology, Chongqing 401331, China

^d School of River and Ocean, Chongqing Jiaotong University, Chongqing 400074, China

^e State Grid Chongqing Electric Power Company Economic and Technical Research Institute, Chongqing 400014, China

*Corresponding author. E-mail: xieqiang2000@cqu.edu.cn

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ABSTRACT The inclined anchor short pile foundation, a novel composite foundation, has the advantages of less earth excavation, small construction workload and less environmental damage. Full-scale field tests were conducted on inclined anchor short pile foundation, and the pile top load–displacement curves, loading capacity of the inclined anchors, failure modes and load distribution regularities are analyzed. Compared with a single pile, the bearing capacity was improved by 29.41% under individual uplift load and 18.52% under individual horizontal load, indicating that the inclined anchors can effectively share load and improve the overall bearing capacity of the foundation. However, compared with uplift-only loading, the bearing capacity is reduced under combined uplift and horizontal loading, suggesting that horizontal loads diminish the uplift bearing capacity of inclined anchor short pile foundations. The short piles and inclined anchors work in coordination, and the load gradually spreads from the short pile to the inclined anchors as the load increases. The failure mode was also related to the applied load form, as the failure phenomenon under combined load integrated the characteristics of individual uplift and horizontal loading modes. The research findings provide significant support for the design and implementation of inclined anchor short pile foundations.

KEYWORDS inclined anchor short pile foundation, field full-scale test, load-bearing capacity, failure mode, distribution coefficient

1 Introduction

With the acceleration of global urbanization, power infrastructure construction is continuously expanding into mountainous areas [1]. When airflow passes through narrow canyons or valleys in mountainous areas, the limited space leads to a significant increase in wind speed [2], just like how wind behaves when blowing through narrow passages between tall buildings. The complex geological environment and weather conditions require that transmission line tower foundations must not only bear uplift load but also resist the action of horizontal

force [3,4]. For example, terminal towers and corner towers in mountain areas withstand the complex load imposed by cable tension and tensile forces generated by wind loads, as shown in Fig. 1. Similar force situations also occur in some foundations in construction engineering and offshore platform construction. This imposes higher requirements for the mechanical properties and economic efficiency of the foundations [5–9].

In mountainous terrain, the application of conventional excavated foundations and rock-socketed foundations faces significant challenges imposed by topographical constraints, which hinder effective mechanized construction [10–13]. Consequently, the miniaturization of foundation structures has emerged as a crucial direction

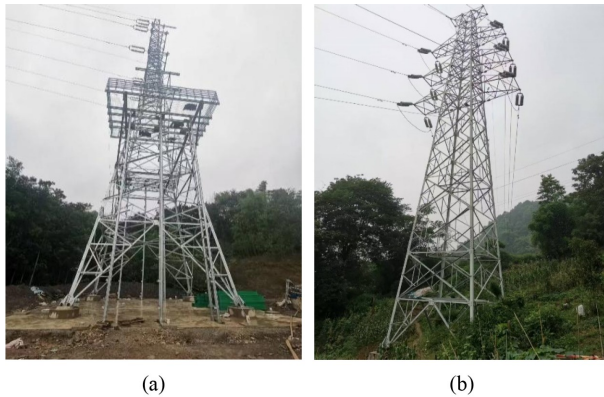


Fig. 1 Power grid infrastructure in mountainous areas: (a) terminal towers; (b) corner towers.

for the development and innovative breakthroughs in transmission line mechanized construction technology in complex mountainous environments [14]. Alternatively, rock anchor foundations are utilized for their distinct advantages, including their compact size that facilitates mechanized construction, reduces required foundation materials and stratum excavation, and delivers exceptional load-bearing capacity [15,16]. However, rock anchor foundations demand high integrity of the underlying rock mass and are only suitable for sites with favorable overburden conditions, limiting their applicability in complex geological settings [17].

To further improve the load-bearing capacity and facilitate fundamental lightweighting, various kinds of composite foundations have attracted researchers' attention [18–22]. Composite foundations combine the advantages of different foundation types to fully utilize their load-bearing capacities. For example, Aamer et al. [23] designed a new opening-bladed anchor pile, which provides a bearing area underneath the soil during uplift.

Sheng et al. [24] proposed a composite foundation that combines helical anchors with an expanded base to exploit the load-bearing capacities of both structures. Jiang et al. [25] developed a new prestressed uplift pile with semi-bonded composite anchors as the main reinforcement, which efficiently mobilizes the shaft friction of the lower pile body and improves its uplift capacity.

In the aspect of pile-anchor composition foundation, on the basis of a single drilled pile (Fig. 2(a)), Mao et al. [26] proposed a novel uplift pile and analyzed its load-bearing capacity and deformation characteristics through full-scale field tests and three-dimensional finite element numerical simulations (Fig. 2(b)). Sun et al. [27,28] further proposed a belled pile with inclined anchors embedded into pile bottom (Fig. 2(c)), and the load-sharing and static ultimate uplift capacity of pile-anchor foundations were studied. It is found that the displacements at which the pile and anchor reach their ultimate uplift states are not synchronized. Wang et al. [29] proposed a short pile inclined anchor foundation based on the conventional short pile direct anchor foundation (Fig. 2(d)), and they found that changing the inclination angle of the anchors can significantly enhance their uplift bearing capacity. These studies indicate that composite foundations offer distinct advantages over single foundations (Fig. 2(a)) in terms of bearing capacity, construction efficiency and cost-effectiveness with progressive shortening of the pile. However, in the existing combined foundation, the horizontal load is mainly borne by compression between the pile and stratum, and the horizontal load-bearing capacity of anchors has not been fully utilized.

To address this problem, an inclined anchor short pile foundation composed of a rock-socketed short pile in the

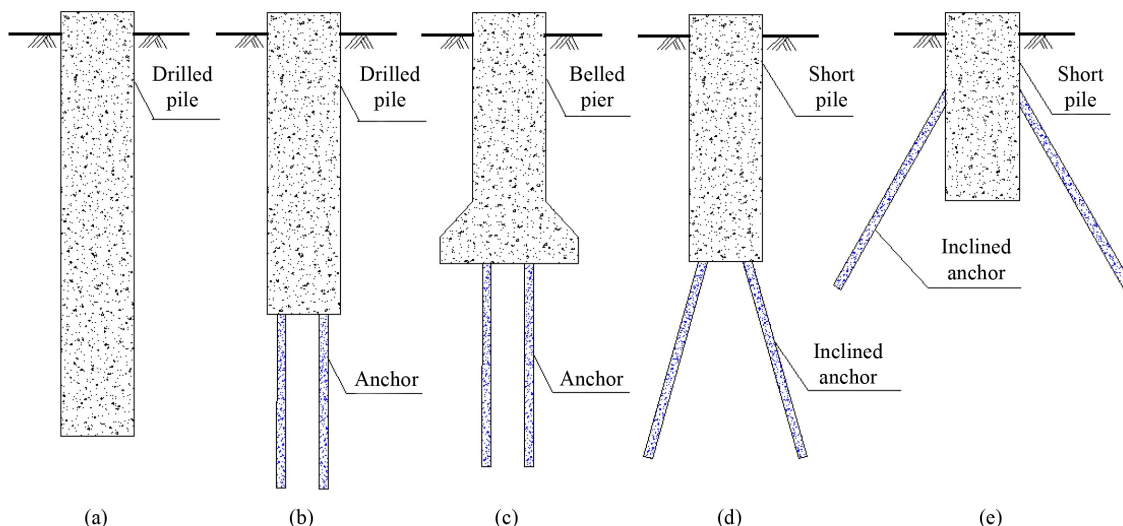


Fig. 2 Schematic of single pile foundation and several pile-anchor composite foundations: (a) single drilled pile foundation; (b) pile straight anchor foundation; (c) anchored pier foundation (belled pier); (d) short pile inclined anchor composite foundation; (e) inclined anchor short pile foundation.

shallow bedrock and anchors inclined towards the deep rock mass is proposed [30], as shown in Figs. 2(e) and 3(a). The load transfer path is shown in Fig. 3(b). The new combined foundation effectively transfers uplift or downward load to the bedrock through the side resistance and end resistance of the short pile and the anchoring force of the inclined anchors. It also further enhances the foundation's anti-horizontal load-bearing performance through the inclined anchors. Compared with conventional rock-excavated foundations, the inclined anchor short pile foundation leverages inclined anchorage and shortened pile lengths to optimize load distribution and stability. The novel foundation minimizes bedrock excavation, enables highly mechanized construction, and offers considerable advantages in safety, cost-effectiveness and environmental performance.

To date, studies on the inclined anchor short pile foundation are still relatively scarce. Gao et al. [31] established a numerical model of the inclined anchor short pile foundation, as shown in Fig. 3(a), and explored the effects of anchor position and free length on the uplift characteristics of the inclined anchor short pile foundation. Tian et al. [30] analyzed the load-bearing characteristics and failure mechanism of the pile-anchor node under uplift load through laboratory tests. In summary, existing studies are mainly limited to numerical calculations and laboratory tests, whereas systematic research on the load-bearing behavior of inclined anchor short pile foundations based on full-scale field tests is still lacking, which is essential for promoting the engineering application of this new foundation type.

Consequently, full-scale field tests on inclined anchor short pile foundations are conducted in this study based on an actual transmission line project. By applying individual uplift load, individual horizontal load, and combined uplift and horizontal load to the inclined anchor short pile foundation, the load–displacement curves, the failure modes, and the load distribution coefficients are analyzed. The load-bearing capacity, deformation characteristics, and load-transfer mechanisms of the inclined anchor short pile foundation are studied. The study aims to provide support for the design, construction, and

engineering application of the inclined anchor short pile foundation.

2 Full-scale test schemes

2.1 Test site

The field tests are conducted in Jieshi Town, Ba'nán District, Chongqing, China. The district is characterized by rugged mountainous terrain, steep slopes, deep valleys, and extensive exposed or shallow buried rock layers. The test site and on-site layout are shown in Fig. 4.

Field investigations and sampling are conducted to acquire *in-situ* geotechnical properties. The site is relatively flat with gentle slopes of a gradient of 3° – 5° . The surface is covered by clay, and the bedrock beneath the soil layer is mudstone and sandstone in sequence. Among them, the thickness of the soil layer is 0–2.0 m; mudstone is 3.0–9.8 m thick; sandstone is 1.9–12.1 m thick. Mudstone and sandstone are interbedded in some areas. The physical and mechanical parameters of the stratum are listed in Table 1.

2.2 Test pile design

To comparatively analyze the role of inclined anchors under different load conditions, five sets of inclined anchor short pile foundations are designed, and two single pile foundations without inclined anchors are also constructed as a comparison. The design parameters of the test piles and the applied load are listed in Table 2.

The inclined anchor short pile foundation consists of a drilled short pile and three inclined anchors. The construction detail is shown in Fig. 5. The three inclined anchors, denoted as $RPi-1$, $RPi-2$, and $RPi-3$ (where $i = 1, 2, 3, 4, 5$, indicating the corresponding pile numbers), are symmetrically positioned at 120° intervals in the horizontal plane. The angle between the pile body and the anchor bars is 30° . The connection node between the short pile and anchor bars is located 0.7 m below the

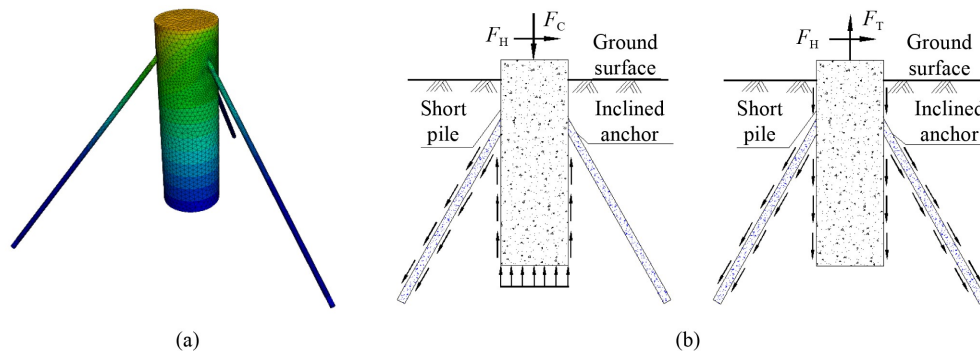


Fig. 3 Schematic of inclined anchor short pile foundation: (a) three-dimentional numerical model; (b) load transfer path.

ground surface. An anchor plate is installed at the inner end of each pile to improve anchorage performance. The short pile and single pile are all internally reinforced with longitudinal reinforcement, with a reinforcement ratio of 0.6%; the inclined anchor bars are composed of anchor bars and fine-grained concrete, with a reinforcement ratio of 8.6%.

2.3 Test pile construction

The key construction stages of the test piles include drilling, anchor bar and reinforcement cage fabrication, concrete pouring, and curing, as shown in Fig. 6.

First, the ground surface is leveled, and the center



Fig. 4 Test site and layout of the test piles.

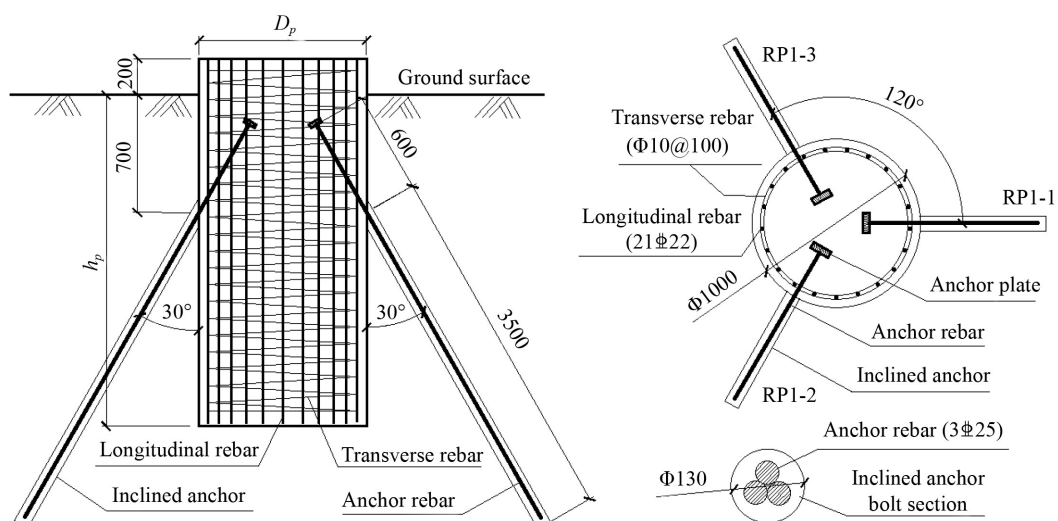
points of each test pile foundation and reaction abutment are determined (Fig. 6(a)). The pile hole above the pile-anchor connection node is excavated manually to the designed depth, and the bottom of the hole is trimmed flat (Fig. 6(b)). After locating the specific positions of the three anchor holes with a horizontal angle of 120° , a drilling rig is used to drill anchor holes with an inclination angle of 30° (Fig. 6(c)). After drilling to the designed depth, the drill is stabilized for several minutes, the anchor holes are cleaned, and then blocked with a woven bag and foam adhesive (Fig. 6(d)). The pile bore below the joint is subsequently excavated to the designed depth, the hole bottom is trimmed flat, and the residual blocking materials within the anchor bar holes are removed for hole inspection and acceptance. The drilling construction is then completed (Fig. 6(e)). During the excavation and construction process, the surrounding soil is not affected, and the sidewalls remain rough. Subsequently, the longitudinal and transverse reinforcement bars are bound together on-site with steel wire to form the reinforcement cage for the short pile. A strain gauge with an accuracy of 0.01 MPa is installed on the longitudinal reinforcement to measure the axial force of the short pile. The longitudinal reinforcement is extended 2.5 m above the ground surface for the application of uplift loading (Fig. 6(f)). HRB400 grade ribbed bars are used for all inclined anchors, and three ribbed bars are welded together to form an anchor bar. The inclined anchor bars are welded together with the anchor plate. A steel bar stress meter with an accuracy of 0.01 MPa is installed on one reinforcement bar of the anchor at 0.2 m away from the pile-anchor connection joint. Subsequent steel bar stress meters are arranged at intervals of 0.5 m along the anchor length to monitor the axial force distribution (Fig. 6(g)). Then, the reinforcement cage is

Table 1 Physical and mechanical parameters of each stratum

Stratum	Unit weight (kN/m ³)	Elastic modulus (MPa)	Poisson's ratio	Cohesion (kPa)	Internal friction angle (°)
Clay	19.0	3.5	0.25	21.8	18.3
Mudstone	25.1	812.0	0.30	385.0	29.7
Sandstone	24.7	5740.0	0.26	1439.0	36.1

Table 2 Design parameters of the test piles

No.	Buried depth, h_p (m)	Anchor bar length (m)	Pile diameter, D_p (m)	Anchor bar diameter (mm)	Rock-socketing depth (m)	Lithology	Applied load
RP1	2.0	3.5	1.0	130	2.0	mudstone	uplift
RP2	1.5	3.5	1.0	130	1.0	mudstone	horizontal
RP3	2.0	3.5	1.0	130	1.5	mudstone	uplift + horizontal
RP4	2.0	3.5	1.0	130	1.0	mudstone	uplift + horizontal
RP5	2.0	3.5	1.0	130	1.5	sandstone	uplift + horizontal
P1	2.0	—	1.0	—	2.0	mudstone	uplift
P2	1.5	—	1.0	—	1.0	mudstone	horizontal



placed into the pile hole, and the anchor bar is inserted and installed at the designed angle. During pouring, fine aggregate concrete is first poured into the drilled hole, followed by the pouring of C30 grade concrete for the short pile (Fig. 6(h)). Finally, the test pile is cured under natural conditions for 28 d (Fig. 6(i)).

2.4 Loading system

A large-span uplift and horizontal load-applying system of the inclined anchor short pile foundation is developed, as shown in Fig. 7.

The loading and monitoring system consists of two main beams (5000 mm × 650 mm × 500 mm, two pieces, with stiffeners), a perforated box-type secondary beam (850 mm × 750 mm × 250 mm, with stiffeners), a steel pad (diameter is 600 mm), jacks, five short beams (1700 mm × 250 mm × 50 mm, steel plates), concrete abutments, a reference beam, several displacement gauges, and monitoring equipment. The main bar of the test foundation extends 2.5 m above the ground surface and is connected to the perforated box-type secondary beam via nuts to ensure the transfer of uplift load. Considering the on-site geological conditions and the test load, the cast-in-place concrete abutments are embedded into the bedrock by 0.3 m. The uplift load is applied to the foundation main bar through the perforated box-type secondary beam via a 500 t jack. The uplift force is then

transferred sequentially from the short beam, main beam, and concrete abutment to the bedrock. The horizontal load is directly reacted by the concrete abutment and applied to the side of the test pile through a 100 t jack acting on the concrete reaction abutment via a load transfer cylinder. The reference beam is installed above the short pile, parallel to the main beam. During the loading process, displacement gauges are employed to measure the foundation displacement and ground heave at each loading stage. The bases of the displacement gauges are symmetrically mounted on the reference beam, with their pins positioned on the measuring plate. This measuring plate is rigidly connected to the short pile through reinforcement bars. When monitoring the vertical displacement of the pile top, the measuring plate is kept parallel to the top surface of the short pile; when measuring the horizontal displacement, the plate is arranged perpendicular to the pile top and oriented toward the applied horizontal load.

To fit the actual force-bearing characteristics of the tower foundation of mountainous transmission lines, the slow-sustained alternating uplift-horizontal load method was adopted in this test [28], and the specific loading scheme is shown in Fig. 8. During the loading process, both the uplift load and horizontal load adopted the load control mode, and the displacement stability principle was strictly followed. The specific loading parameters and procedures are as follows: first, an initial uplift load

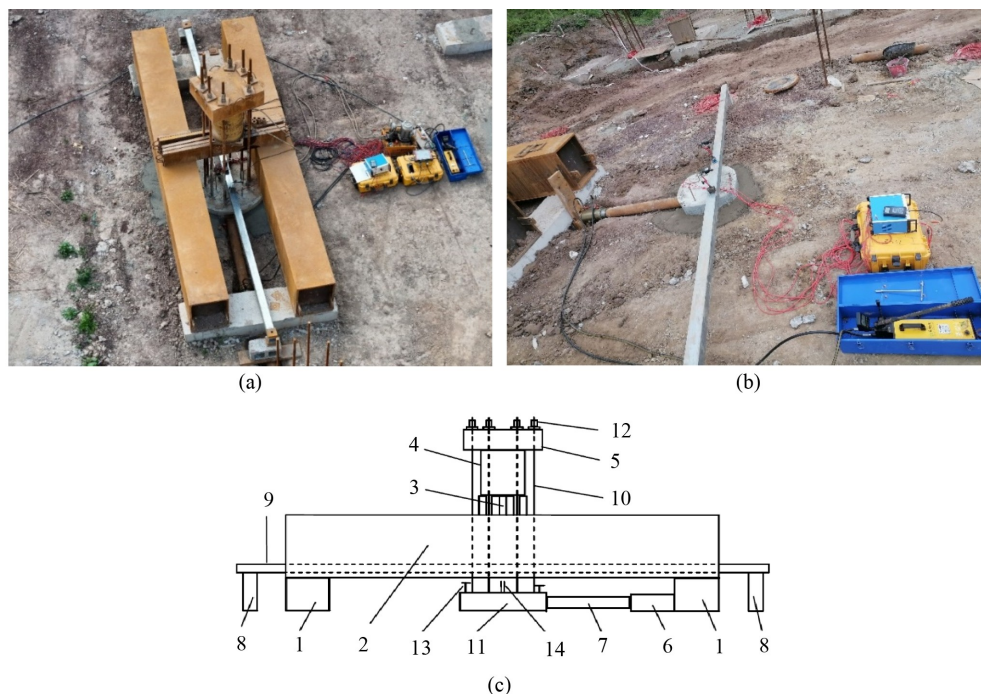


Fig. 7 The testing and monitoring system: (a) uplift + horizontal loading module; (b) horizontal loading module; (c) schematic diagram of the loading module (Note: 1: Concrete reaction abutment; 2: Rectangular main beam; 3: Short secondary beam; 4: 5000 kN hydraulic jack; 5: Perforated box-type secondary beam; 6: 1000 kN hydraulic jack; 7: Load transfer cylinder; 8: Reference beam abutment; 9: Reference beam; 10: Reinforcing bars; 11: Inclined anchor short pile foundation; 12: Nuts and shims; 13: Horizontal measuring plate; 14: Vertical measuring plate).

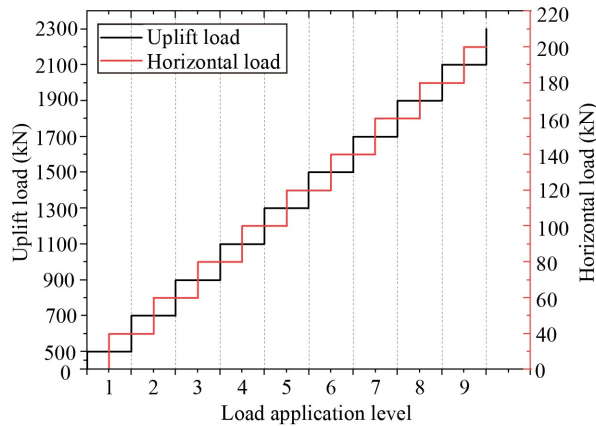


Fig. 8 Schematic diagram of the slow-maintained alternating uplift and lateral load application.

of 500 kN was applied to the test pile; after the displacement of the inclined anchor short pile foundation was stabilized, an initial horizontal load of 40 kN was applied; when the displacement under the horizontal load was stabilized, the next level of load loading was carried out. Among them, the subsequent increment of each level of uplift load was set to 200 kN, and the increment of each level of horizontal load was set to 20 kN. The alternating loading was performed until the end of the test. The above load grading scheme was determined by comprehensively considering the bearing characteristics of the test foundations, the actual test loading conditions and the requirements of relevant engineering specifications [32,33].

The load shall be applied uniformly and continuously without impact excitation. The variation of each incremental load shall not exceed 10% of the graded load magnitude. The subsequent loading stage can only be initiated after the displacement stabilizes, which is defined as follows: the monitored displacement difference between two consecutive readings within one continuous hour is less than 0.1 mm. The failure criteria for test piles under uplift loading differ from those under horizontal loading. Under uplift load, structural failure is characterized by a continuous increase in vertical displacement without convergence. For horizontal loading, the ultimate design load is deemed reached when the horizontal displacement exceeds the threshold of 10 mm [34].

3 Test results

3.1 Effect of uplift load

3.1.1 Uplift load–displacement curves characteristics

Figure 9 shows the pile top load–displacement curves of the inclined anchor short pile foundation specimen RP1 and the single pile foundation specimen P1 under

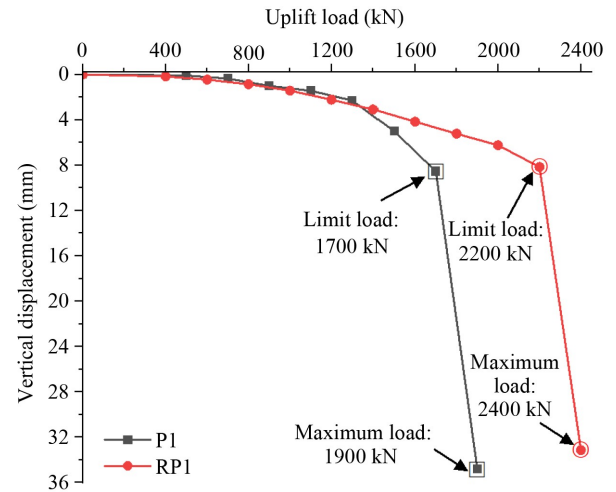


Fig. 9 Uplift load–displacement curves of P1 and RP1 foundations under the individual effect of uplift load.

individual uplift load, reflecting their displacement response characteristics. The single pile foundation P1 failed at an applied load of 1900 kN, with an ultimate bearing capacity of 1700 kN. In comparison, the inclined anchored short-pile foundation RP1 failed at 2400 kN, corresponding to an ultimate load of 2200 kN. Under the effect of individual uplift load, the inclined anchor increases the ultimate uplift bearing capacity by 500 kN, which is an increase of 29.41%. The inclined anchors can significantly improve the ultimate load-bearing capacity of the inclined anchored short-pile foundation.

The uplift load–displacement curve of two piles gradually increases with load. The curve can be divided into three stages: the initial elastic stage, the elastoplastic stage, and the rapid failure stage. In the initial elastic stage, both the short pile and the inclined anchor are in the linear deformation stage, with the pile top displacement increasing linearly with the increase in uplift load, and the slope of the curve remains essentially constant; When the uplift load gradually increases to a critical value, the increment in displacement begins to increase significantly under the same load increment. The slope of the load–displacement curve increases slightly, while the overall curve maintains a relatively gentle trend and is currently in the transition stage of the elastoplastic curve. In the third stage, the ultimate displacement corresponding to the ultimate load of pile RP1 is 8.16 mm. Thereafter, the displacement of the short pile increases sharply, exceeding five times the displacement at the previous loading level, which marks the termination of loading. The maximum vertical displacement reaches 33.13 mm.

3.1.2 Load-bearing of the inclined anchors

The total uplift load borne by three anchors in each loading level under uplift load, i.e., the vertical

component of the axial force of three anchor bar F_{Ry} , as well as the maximum axial force of each anchor, are extracted in Fig. 10 to investigate the effect of the inclined anchors. The evolution trends of RP1-1, RP1-2, and RP1-3 anchors are similar, and subtle differences are believed to be related to the interaction between inclined anchors and the surrounding stratum. Among them, the axial force value of RP1-1 anchors reaches 619 kN, indicating that the anchor bars yield and cause the anchor structure to fail due to excessive deformation. The vertical uplift load F_{Ry} exhibits an approximately linear variation trend within the ultimate load range, and it surges to 1157 kN at the failure moment.

3.1.3 Uplift failure mode

The failure modes of the surrounding stratum and the foundation under individual uplift load are shown in Fig. 11. Red lines indicate the distribution of the inclined anchors. Radial and circumferential cracks appear on the ground surface, with radial cracks occurring earlier than circumferential cracks.

During the loading process, the ground surface around

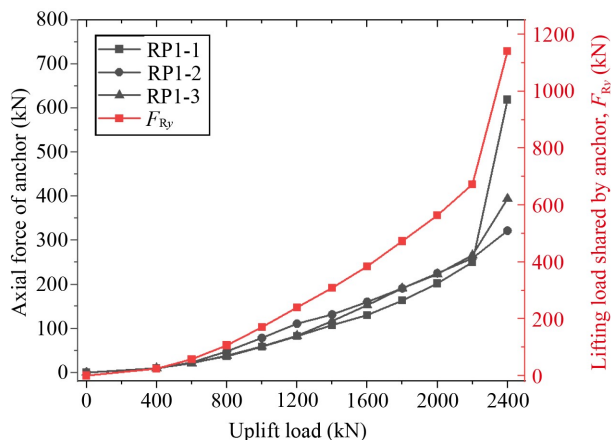


Fig. 10 Maximum axial force of each inclined anchor and the vertical component F_{Ry} of uplift load subjected by the whole anchor structure.

the inclined anchor short pile foundation begins to bulge slightly, and several fine cracks are observed. As the uplift load gradually increases, the cracks quickly expand radially outward. At the failure moment, when the loud sound of structural fracture is heard, radial cracks rapidly extend outward, intersecting and penetrating with the circumferential cracks to form a complete failure surface, as shown in Fig. 11(c). Significant ground heave and a rapid increase in foundation uplift displacement are observed. The main surface cracks are concentrated around the inclined anchors. Under the action of individual uplift load, the short pile first experiences contact surface failure, with a gradual increase in pile displacement. The inclined anchors squeeze the surrounding stratum upward, resulting in tensile failure of the upper ground and the formation of radial main cracks along the axis of the inclined anchors. Eventually, the anchor structure fails due to tensile damage, which in turn leads to the overall failure of the foundation. The foundation is excavated after failure, as shown in Fig. 11(b), and failure cracks are found on the inclined anchors. This is caused by the excessive deformation of rebars after yielding, leading to the cracking of the mortar wrapped around the inclined anchors.

3.2 Effect of horizontal load

3.2.1 Horizontal load–displacement curves characteristics

Figure 12 shows the pile top horizontal load–displacement curves of test piles RP2 and P2. The horizontal load–displacement curves of both foundations exhibit a gradual change pattern. Similarly, the curves can also be divided into three characteristic stages: the initial elastic stage, the elastoplastic stage, and the rapid failure stage. During the initial elastic phase, the horizontal load–displacement relationship exhibits near-linear behavior, demonstrating proportional growth between pile top displacement and applied horizontal load. In the elastoplastic stage, the pile top displacement increases non-linearly with the increase in horizontal load, and the

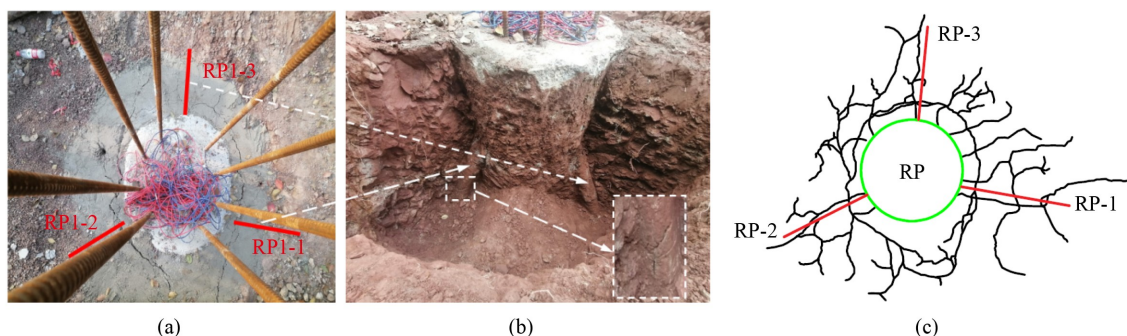


Fig. 11 Failure mode of inclined anchor short pile foundation under individual uplift load: (a) ground surface heave and cracking; (b) failure of inclined anchors; (c) sketches of surface cracks distribution.

deformation rate is significantly greater than that in the initial elastic stage. Under the same load level, the pile top displacement of the inclined anchor short pile foundation RP2 is smaller than that of the single pile P2. This trend becomes more pronounced as the horizontal load increases, indicating that the anti-horizontal load effect of the inclined anchors gradually comes into play during this stage. Subsequently, in the rapid failure stage, the pile top displacement increases rapidly with the increase in horizontal load, and a small increment in horizontal load results in a significant change in horizontal displacement. As shown in Fig. 12, the design load is 315 kN, which is 18.52% higher than the design value (245 kN) of the single pile's horizontal bearing capacity. The results indicate that the inclined anchors can significantly enhance the horizontal load-bearing capacity of the inclined anchor short pile foundation.

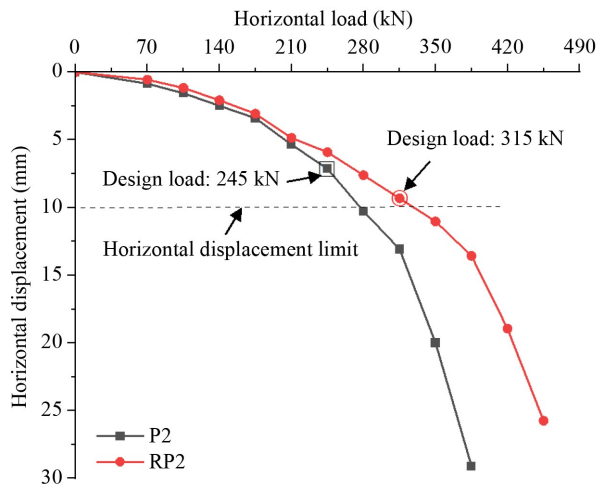


Fig. 12 Horizontal load-displacement curves of P2 and RP2 foundations under the effect of horizontal load.



3.2.2 Load-bearing of the inclined anchors

Figure 13 shows the maximum axial force of the three anchors and the horizontal component F_{Rh} borne by the entire anchor bar structure at each loading level under horizontal load. Under horizontal loads, the axial forces of inclined anchors RP2-2 and RP2-3 manifest as tension, while the axial force of RP2-1 manifests as compression (the horizontal load direction is marked by the white arrow in Fig. 14). For the convenience of data demonstration, the absolute values of the compressive axial force of anchor bar RP2-1 are plotted in Fig. 13. As the horizontal load increases gradually, the maximum axial force of each inclined anchor also increases. When the design horizontal load is reached, the inclined anchor does not yield, as the axial force exerted on it is less than 100 kN, which is below the yield strength of the anchor structure. When the horizontal load is small, the axial forces of the three anchors increase almost synchro-

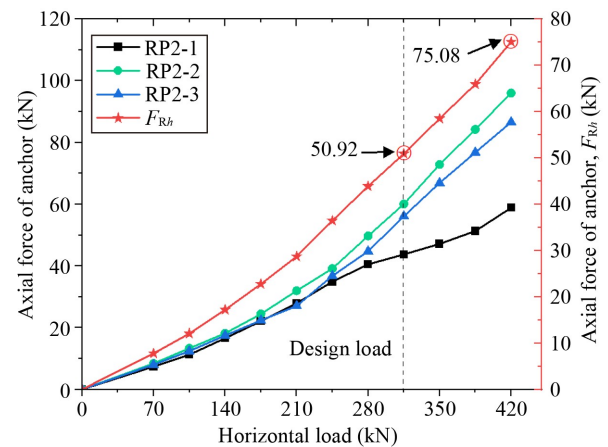


Fig. 13 Maximum axial force of inclined anchors and horizontal load borne by the whole anchor structure.

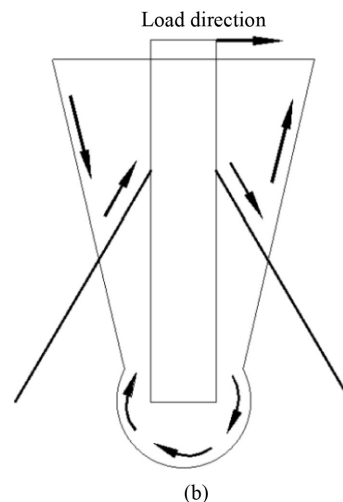


Fig. 14 Failure modes of RP2 pile and surrounding ground under individual horizontal load: (a) on-site failure situation of ground surface; (b) schematic of short pile-soil-inclined anchor interaction.

nously. However, there are certain differences in the axial forces of each anchor bar. Among them, the axial force of the compressed inclined anchor RP2-1 is always smaller than that of the other two bars. The axial force growth rate of RP2-1 anchor gradually slows down as the horizontal force increases. This phenomenon could be attributable to the fact that the surrounding rock mass of the RP2-1 anchor bearing is subjected to a portion of the axial force.

The total horizontal load shared by the whole anchor bar structure is 75.08 kN, which accounts for 17.87% of the applied horizontal load, indicating that the anchors play a significant role in enhancing the anti-horizontal load-bearing capacity of the inclined anchor short pile foundation.

3.2.3 Horizontal failure mode

The failure mode of RP2 is quite different from that of RP1 under uplift load. As shown in Fig. 14, under individual horizontal loading conditions, the inclined anchor short pile foundation RP2 exhibits a failure mode dominated by global rigid-body rotation, accompanied by pronounced displacement accumulation at the foundation base. The shallow surrounding stratum above the node mainly exhibits wedge-shaped failure, inverted wedge-shaped failure near the node, and planar rotational failure of the deep soil below the node, which is referred to as “rigid rotational failure accompanied by an inverted wedge shape”. At low horizontal load levels, the pile body and surrounding stratum remain in the elastic stage, accompanied by small pile-top displacement and rotation angle. As the load increases, the front stratum is compressed, forming a wedge-shaped failure zone. Meanwhile, the supporting effect of the inclined anchor gradually strengthens, causing the upper stratum to form

an inverted wedge-shaped failure zone. The deep stratum starts to rotate around the pile bottom. When approaching the design load, the pile top displacement and rotation angle increase sharply, long and wide stratum tension fractures are observed in front of the pile, while the stratum behind the pile is completely damaged by compression.

3.3 Effect of uplift and horizontal load

3.3.1 Load–displacement curves characteristics

Under the combined action of uplift and horizontal loads, the vertical and horizontal displacements of the pile top for RP3, RP4, and RP5 are shown in Fig. 15 at each loading level. The load–displacement curves of the foundations under uplift and horizontal load are also still gradual and can be divided into three stages: the initial elastic stage, the elastoplastic stage, and the rapid failure stage. During the initial loading stage, the load–displacement curves are approximately linear, with both the short pile and the inclined anchors in the elastic deformation stage. As the load continues to increase, the pile top displacement gradually increases, and the slope of the curve also increases slightly. The increase in the horizontal displacement of the pile top is mainly due to the increase in the vertical displacement of the pile top, as the nearby rock mass at the ground surface cannot provide sufficient restraint. The deformation of the surrounding stratum is relatively small. In the elastoplastic stage, as the vertical displacement of the pile top rapidly intensifies, the load level becomes increasingly difficult to sustain. When the pile fails, the horizontal displacement of RP3, RP4, and RP5 foundations also exceeded the 10 mm allowable displacement.

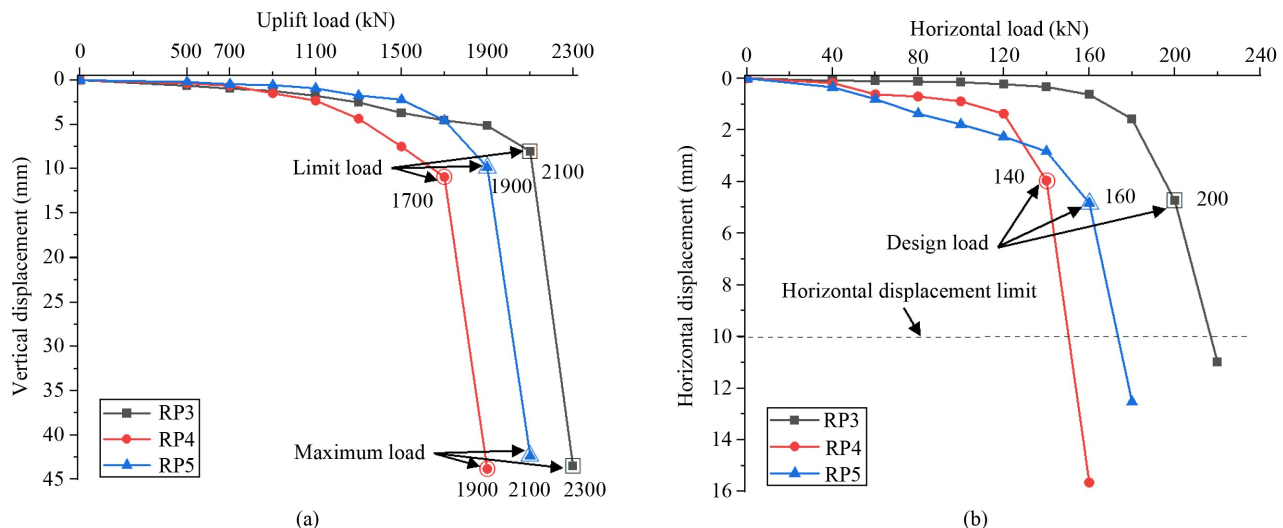


Fig. 15 Load–displacement curves of test foundations under the joint effect of uplift and horizontal load: (a) uplift load–vertical displacement relationship; (b) horizontal load–horizontal displacement relationship.

The ultimate uplift load of test foundation RP3 (with a rock socketing depth of 1.5 m in mudstone) is 2100 kN, which is higher than that of test pile RP4 (with a rock socketing depth of 1.0 m in mudstone). Thus, the rock socketing depth of the short pile exerts a positive effect on improving the bearing capacity of the inclined anchored short-pile foundation. The ultimate uplift load of test pile RP5 (with a rock socketing depth of 1.5 m in sandstone) is slightly lower than that of test pile RP3 (with a rock socketing depth of 1.5 m in mudstone). The reason is further discussed in Subsection 4.1 combined with the failure mode.

Compared to RP1 foundation subjected to individual uplift load, the uplift bearing capacity of the RP3 foundation is lower, indicating that the horizontal load can reduce the uplift bearing capacity of inclined anchor short pile foundations to a certain degree.

3.3.2 Load-bearing of the inclined anchors

Figure 16 reflects the maximum axial force of each

anchor and the uplift load borne by the whole anchor structure under the combined uplift and horizontal load. In Fig. 16, the upper x -axis represents the applied horizontal load, and the lower x -axis represents the applied uplift load. For example, the marking of 60 on the upper x -axis indicates that the current combined loading condition is an uplift load of 700 kN and a horizontal load of 60 kN.

The evolution of the anchor axial force is closely related to the relative position between the inclined anchor and the applied loads. For the three foundations investigated, the axial forces of the anchors located in the front stratum are considerably greater than those in the rear stratum. For the front-stratum anchors (RP3-1, RP4-1, and RP5-1), tensile effects are superimposed by both the uplift load and the horizontal load. However, for the anchors in the rear stratum, the tensile force induced by uplift load is periodically reduced by the compressive force induced by the horizontal load. This explains why the axial forces of anchors RP3-1, RP4-1, and RP5-1 are

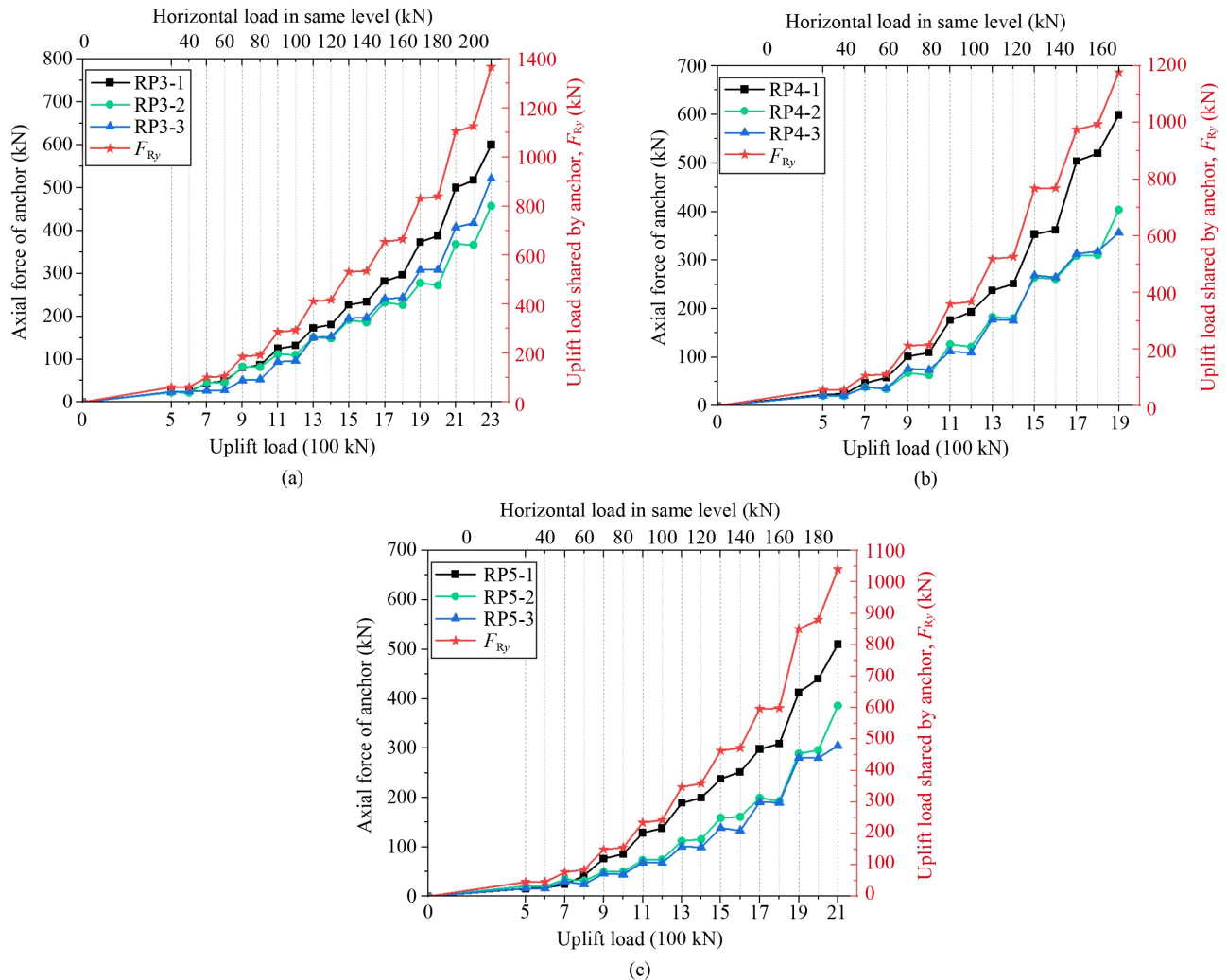


Fig. 16 Axial force of each anchor and the vertical component F_{Ry} of the whole anchor structure under combined uplift and horizontal load: (a) RP3; (b) RP4; (c) RP5.

greater than those of the other anchors, and the differences among them become more pronounced as the load increases. Furthermore, the axial force characteristics of the three anchors vary significantly at each loading level. Consequently, due to the aforementioned load superposition effect, the axial forces of anchors RP3-1, RP4-1, and RP5-1 continue to increase at each loading level; in contrast, the other anchors occasionally experience a decrease in axial force when the horizontal load increases during a single uplift loading period.

At the failure moment, the total vertical component F_{Ry} values of the three anchors are 1367, 1177, and 1039 kN,

accounting for 59.43%, 61.94%, and 49.48% of the total uplift force, respectively. RP3-1 and RP4-1 enter the yielding stage (the yield load of three HRB 400 welding rebars is about 588 kN), while all anchors of RP5 do not enter the yielding stage, as RP5 failed due to node failure (Fig. 17(c)).

3.3.3 Comprehensive failure mode

The overall failure of the foundations, local failure and cracks distribution sketches on the surrounding ground of each foundation are shown in Fig. 17. The failure mode

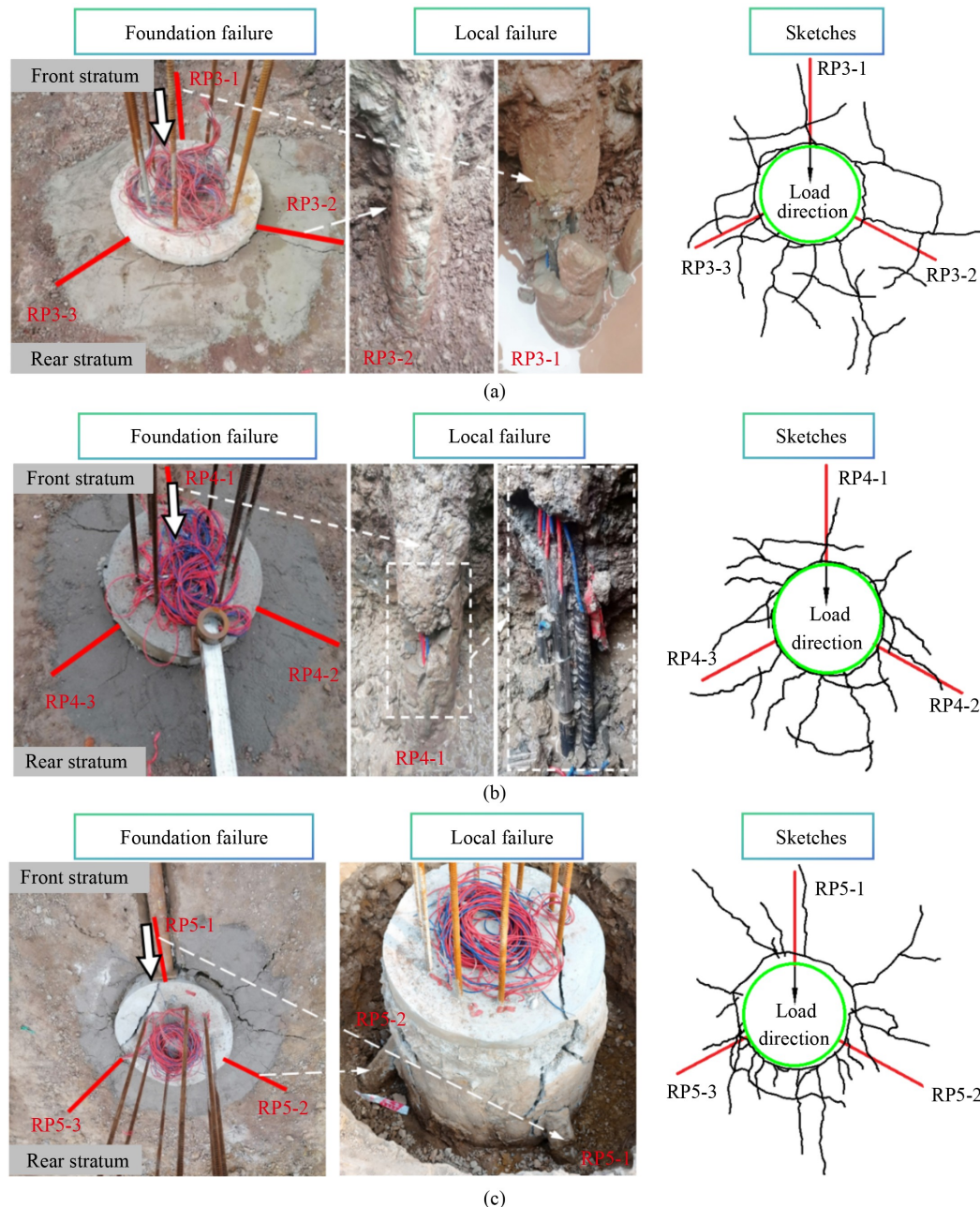


Fig. 17 Failure of the inclined anchor short pile foundation and surrounding ground surface under combined uplift and horizontal load: (a) RP3; (b) RP4; (c) RP5.

induced by the combined action of uplift and horizontal loads is a combination of the above two failure modes, which is much more complex than that induced by a single loading factor.

During initial loading, an increasing number of radial and circumferential cracks are being observed, with radial cracks typically appearing before circumferential ones.

Under the effect of uplift load, the surrounding ground surface begins to slightly heave and crack, rapidly expanding radially in different directions. Meanwhile, subjected to horizontal loading, the short pile and inclined anchors rotate, causing compression of the stratum in front of the pile with noticeable local bulging. The rear stratum separates from the structure to form circumferential cracks, which intersect and coalesce with the radial cracks. Consequently, a fan-shaped failure zone develops on the ground surface, while a shear slip surface forms within the underlying stratum.

As the load increases, the continuous interaction among stratum, short pile and inclined anchors promotes the foundation deformation and failure process: the separation between stratum and pile enables rotation of short pile, as well as vertical displacement; the short pile exerts compressive forces on the rear stratum; meanwhile, the inclined anchors experience an increase in axial force magnitudes to limit the displacement of short pile, and the anchor bar yield as axial stress passes its yield stress; the deformation of inclined anchors further promote the surrounding stratum being compressed and uplift. Ultimately, this phenomenon leads to a progressive deformation and failure mechanism. Compared with the situation of an individual load factor, the final vertical and horizontal displacements are greater.

4 Discussion

4.1 Failure-dominant factor

The failure-dominant controlling factor varies significantly among the specimens, owing to differences in loading conditions and stratum properties.

The final failure mode of the specimens embedded in mudstone (RP1, RP2, RP3, and RP4) is governed by overall pile–rock interfacial bond loss. For RP2 (subjected only to horizontal loading), significant pile rotation occurs, and the horizontal displacement increases sharply after reaching the design load. For RP1 (pure uplift loading), as well as RP3 and RP4 (combined uplift and horizontal loading), anchor bar yielding and overall pile pull-out further contribute to the final failure. The sharp increase in measured displacements at the ultimate stage, accompanied by obvious yielding of the anchor bars, is consistent with this failure mechanism.

For sandstone-socketed specimens (RP5), the failure

mode is dominated by local joint splitting and structural connection damage, rather than rock–pile bonding failure. The tested sandstone stratum features high brittleness and well-developed fractures. Preferential splitting failure initiates at the structural connection instead of overall pullout (Fig. 17(c)), which leads to a lower ultimate uplift capacity compared with that of mudstone (Fig. 15(a)). The interfacial resistance degrades rapidly under tensile loading, inducing severe stress concentration at the joint. The measured strain data reveal abnormal strain concentration at the connector at the early loading stage, while the overall pile displacement remains limited before the joint splitting occurred.

4.2 Effects of inclined anchors

The inclined anchor short pile foundation consists of two distinct structural components: the short pile and the inclined anchors. To clarify the load-bearing mechanism of this foundation type, a load distribution coefficient α is defined as follows:

$$\alpha = \frac{F_{Ry}}{P_T}, \quad (1)$$

where F_{Ry} denotes the vertical component of the resultant axial force of the three inclined anchors, and P_T represents the uplift load value of the inclined anchor short pile foundation. Meanwhile, $\beta = 1 - \alpha$, which represents the load distribution coefficient corresponding to the load borne by the short pile.

Figure 18 shows the evolution regularities of load distribution coefficients α and β in each loading level. The load distribution coefficient α gradually increases, while β gradually decreases. The inclined anchors and the short pile work together to resist the uplift load.

In the initial elastic stage, the increase of load distribution coefficient α is relatively small, around 10%. The short pile bears the main load, which is transferred to the surrounding stratum through the short pile; the load-bearing role of the inclined anchors is not yet fully exerted. As the load increases, the load-bearing performance of the inclined anchors gradually comes into play, and the load distribution coefficient α also increases continuously. In the elastoplastic stage, the short pile still bears the main load, while the inclined anchors gradually exert their uplift and horizontal load resistance, gradually enhancing the load-bearing capacity of the inclined anchor short pile foundation. In the failure stage, the load distribution coefficient α increases sharply and eventually stabilizes at approximately 50%. The load distribution coefficient α of the inclined anchors under uplift and horizontal load is significantly higher than that under individual uplift load, indicating that the anchors have a certain capacity to resist horizontal loads. At this point, the short pile reaches its ultimate load-bearing capacity,

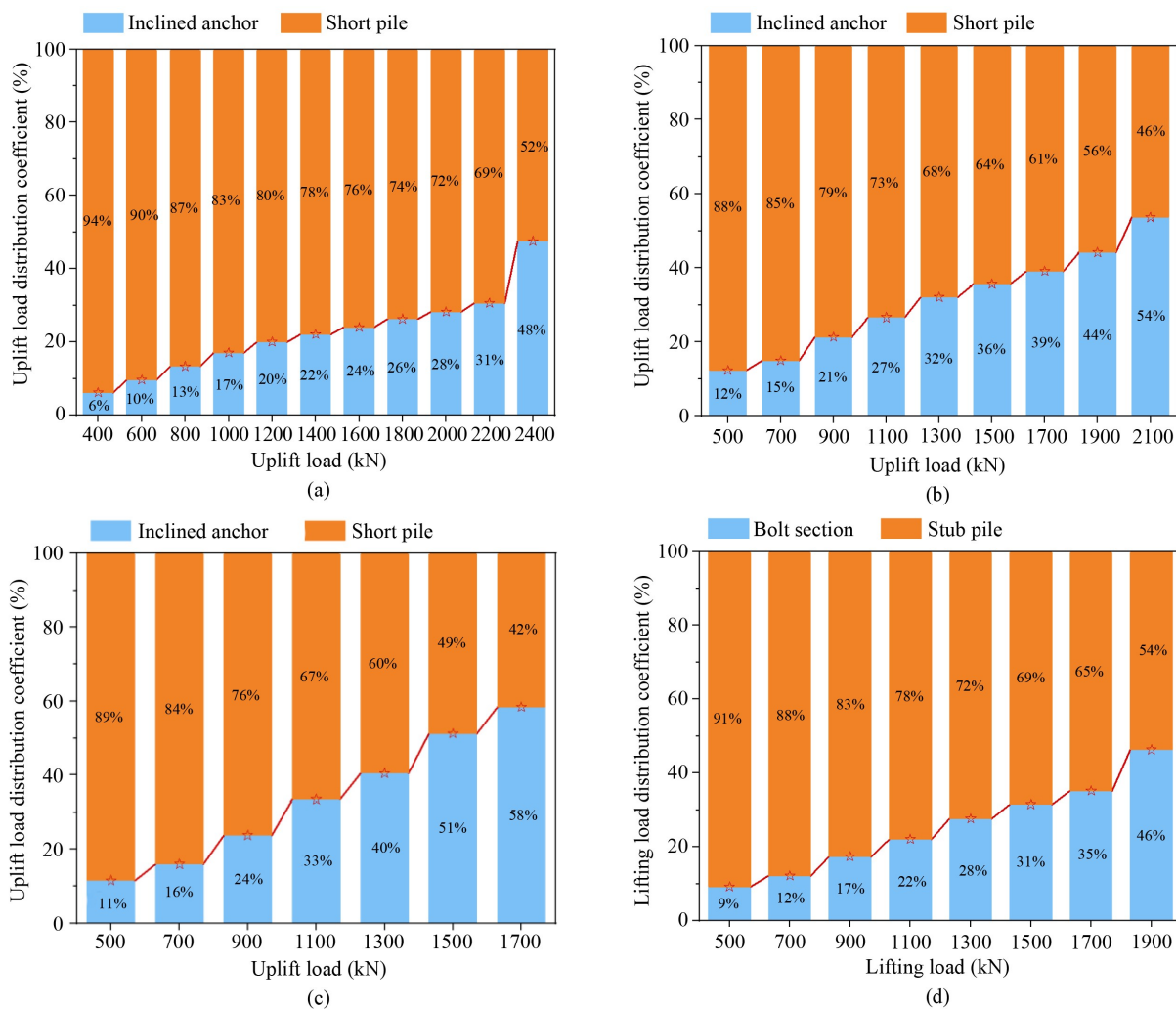


Fig. 18 Load distribution proportion of the short pile and inclined anchor under combined uplift and horizontal load: (a) RP1; (b) RP3; (c) RP4; (d) RP5.

with a significant increase in pile displacement, leading to material yielding or fracture of the pile body. The inclined anchors bear a greater load until the entire foundation fails.

The inclined anchors demonstrate load redistribution capability through soil-anchor interaction, achieving both stress diffusion and force transmission, which collectively improve the global bearing performance of the short pile foundation system. The interaction between the short pile and the inclined anchors is crucial for the overall load-bearing performance, as they work together to improve the load-bearing capacity and stability of the inclined anchor short pile foundation.

It can be seen from Figs. 18(b) and 18(c) that when the mudstone embedding depth increases from 1.0 to 1.5 m, the maximum load distribution coefficient of the anchor bolts decreases from 58% to 54%, indicating that the load distribution coefficient of the anchor bolts tends to decrease with the increase of rock embedding depth. Under the same rock embedding depth, the maximum load distribution coefficient of the inclined anchor bolts

in the sandstone-embedded test pile RP5 is 8% lower than that in the mudstone-embedded test pile RP4, as shown in Figs. 18(b) and 18(d), suggesting that the load distribution coefficient of the anchor bolts decreases with the increase of rock mass strength. The main reason is that the bond strength of mudstone is lower than that of sandstone, and the lateral friction resistance of the short pile is relatively small, which results in a higher load borne by the anchor bolts.

5 Conclusions

With the rapid development of mountain power grid construction, inclined anchor short-pile foundations for transmission towers inevitably bear complex uplift and horizontal loads in steep and fragmented rock terrain. However, their load-displacement responses, failure mechanisms and pile-anchor synergistic behaviour under combined loading remain poorly understood, limiting reliable engineering design. Accordingly, full-scale field

tests were conducted under three typical loading conditions, the internal force distribution, failure modes, and load distribution regularities between inclined anchors and short pile components were studied to reveal the interaction mechanism. The main conclusions are presented as follows.

1) Compared to single pile foundations, inclined anchors can significantly enhance the bearing capacity under individual uplift and horizontal loads, with increases of 29.41% and 18.52% in the ultimate uplift and horizontal bearing capacities, respectively. However, under combined uplift and horizontal loads, the bearing capacity is decreased. Meanwhile, part of the inclined anchors yielded, highlighting their crucial role in resisting complex combined load conditions.

2) The failure mode of the inclined anchor short pile foundation is highly related to the load type and stratum conditions. Under individual uplift load, the failure mainly manifested as contact surface failure of the short pile and tensile failure of the inclined anchors. Under individual horizontal load, the foundation undergoes rigid rotation. Under the combined effect of uplift and horizontal load, the failure mode is the most complex, with radial cracks and fan-shaped failure surfaces forming on the ground surface. In mudstone strata, failure is predominantly governed by overall debonding at the pile-rock interface, manifesting as a typical integrated pullout failure with full mobilization of shaft friction, while the anchor reaches yield state. In sandstone strata, stress concentration at the anchorage connection, triggering preferential joint splitting failure before the rock mass achieves its ultimate anti-uplift capacity.

3) The load-bearing mechanism of the inclined anchor short pile foundation relies on the synergistic interaction between the short pile and inclined anchors under the test conditions. At the initial loading stage, the short pile bears most of the external load, and the contribution of inclined anchors is relatively small. With the increase of external load, the load-bearing role of inclined anchors is gradually mobilized, and the load distribution coefficient α increases continuously. When approaching failure, inclined anchors can undertake approximately 50% of the total load, effectively redistributing and transferring load from the short pile to the anchors. This synergistic load transfer mechanism significantly improves the overall bearing capacity and stability of the foundation under the test parameters and geological conditions adopted in this study.

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Competing interests The authors declare that they have no competing interests.

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