

Numerical simulation of static load tests for evaluating the bearing capacity of expanded micropiles

Wenhui Zeng, Rongquan Fan, Jiahui Zhu, Min Xia*, Yu Mao, Wenjie Xu, Shijun Gao

Zeng, W., Fan, R., Zhu, J., Xia, M., Mao, Yu., Xu, W., Gao, Sh. 2026. Numerical simulation of static load tests for evaluating the bearing capacity of expanded micropiles. *Baltica* 39 (2) 148–158. Vilnius. ISSN 0067-3064.

Manuscript submitted 26 January 2026/Accepted 25 June 2026/Available online 15 September 2026
© Baltica 2026

Abstract. Based on in-situ static load tests of micropiles, a three-dimensional finite element model of the variable-diameter micropile was established using the software ABAQUS to investigate the bearing capacities of the straight, expanded-base, and double-expanded micropile under compressive, uplift, and lateral loading conditions. The results indicate that under compressive loading, the ultimate compressive bearing capacities of the expanded-base and double-expanded micropile were approximately 1.35 and 1.47 times that of the straight micropile, respectively. Notably, the enhancement in compressive bearing performance provided by the double-expanded micropiles configuration is not significantly greater than that of the expanded micropiles. Under uplift loading, the capacities of the expanded-base and double-expanded micropiles were approximately 1.64 and 2.0 times that of the straight micropile, respectively. These indicate that the expanded configuration significantly enhances uplift bearing performance. Under lateral loading, the capacity of the double-expanded micropile was approximately 1.1 times that of the straight and expanded-base micropile, suggesting that the contribution of the expanded section to improving lateral bearing performance is relatively limited.

Keywords: variable-diameter micropile; in-situ static load tests; uplift bearing capacities; compressive bearing capacities

✉ Wenhui Zeng, Rongquan Fan, Wenjie Xu

State Grid Sichuan Electric Power Company Economic and Technological Research Institute, Chengdu, Sichuan

Jiahui Zhu, Min Xia* (xiamin15@cdut.edu.cn),  <https://orcid.org/0000-0003-3621-3422>

State Key Laboratory of Geohazard Prevention and Geoenvironment Protection, Chengdu University of Technology, Chengdu, Sichuan

Yu Mao, Shijun Gao

Southwest Electric Power Design Institute Co., Ltd. Of China Power Engineering Consulting Group

*Corresponding author

INTRODUCTION

Micropiles are commonly referred to as root piles, mini-piles or pin-piles. Micropiles are similar to but exhibit key differences from conventional micropiles, such as larger percentages of reinforcements used and smaller diameters (≤ 300 mm) (Weaver, Morgenstern 1981; Cheng 2012). Micropiles have been widely used in the foundation design of transmission towers in mountainous areas (Liu *et al.* 2001). In traditional foundation designs, variable cross-sections (such as in expanded-base and pedestal piles) are often used to enhance the compressive and tensile bearing capacities of piles. This approach not only reduces material

costs and construction duration but also improves the pile bearing performance.

In terms of the compressive bearing mechanism of variable-diameter piles, extensive investigations have been conducted by researchers through a combination of numerical simulations and model tests, aiming to elucidate the enhancement mechanism of pile–soil interaction induced by the expanded base. Focusing on bearing performance in different soil types, Thottoth *et al.* (2024) developed a predictive model based on finite element analysis to quantify the contribution of the expanded section to the improvement of compressive bearing capacity in clay and sand. Beyond numerical simulations, experimental studies have also

confirmed these findings. Investigations on cement–mortar expanded-base precast piles demonstrated that the synergistic interaction between the expanded section and the core pile is the key factor governing the enhancement of overall compressive performance (Gao *et al.* 2024). At the theoretical level, Zhang *et al.* (2024) established a load-transfer analytical model for pre-bored grouted expanded-base precast piles and proposed a simplified method for calculating axial bearing capacity. Bao *et al.* (2019) further compared the bearing performance of expanded-base cast-in-place piles and uniform-diameter piles, pointing out that the pile–soil interface friction coefficient plays a critical role in mobilizing shaft resistance.

Transmission tower foundations are frequently subjected to uplift loads. Existing studies on the uplift performance of variable-diameter piles mainly focus on failure modes and the prediction of ultimate uplift capacity under different geological conditions. For sandy soils, a modified formula for estimating the ultimate uplift capacity of expanded-base piles was proposed and its applicability was verified (Sakr *et al.* 2025). In cohesive soils, a lower-bound finite element limit analysis method was employed to reveal the uplift failure mechanisms of expanded-base piles in soft and stiff clay layers (Majumder, Chakraborty 2021). For complex soil–rock composite foundations, uplift tests were conducted to elucidate the interlocking and shear interaction mechanisms between the expanded section and the surrounding soil–rock mass (Hu *et al.* 2023). Regarding the optimization of geometric parameters for the expanded section, Nariyelil *et al.* (2026) compared the performance of different expanded configurations in saturated clay and clayey sand, finding that a single expanded-base pile with a 45° enlargement angle exhibited the highest uplift efficiency. Further investigation on the bearing capacity gains from multiple enlargements indicated that the uplift capacity of double-expanded piles can reach up to seven times that of straight piles (Al-Bayati *et al.* 2023). From both theoretical and field-evidence perspectives on failure modes, Wang *et al.* (2007) pointed out that the failure of expanded-base piles is jointly governed by shaft friction and compressive – shear deformation of the soil surrounding the expanded base. Drawing on test results in soft soils, an ultimate state model characterized by elliptical local failure in the expanded section and power-function-type failure in the uniform-diameter section was established (Huang *et al.* 2011).

Given that transmission tower foundations are often subjected to lateral wind loads and inclined tensile forces generated by the tower – line system, studies on the associated complex loading mechanisms have increasingly become a research focus in recent years. The bending deformation characteristics and failure

patterns of expanded-base piles under lateral loading were visually demonstrated through model tests (Zhang *et al.* 2018). Concerning group pile effects, the length-to-diameter ratio and pile spacing are found to be key factors controlling the lateral bearing capacity and displacement of micropile groups in sand (Vakili *et al.* 2025). When the influence of load inclination is considered, physical modelling tests also confirmed a significant effect of cone angle on the bearing capacity of conical expanded-base piles under inclined loading (Goudar *et al.* 2026). To further enhance lateral performance, experimental studies revealed that micropile groups installed with a 15° inclination (battered piles) exhibited a 155% increase in lateral bearing capacity compared with vertical pile groups in soft clay (Panda, Borthakur 2025). At the microscopic damage-mechanism level, the controlling role of the expanded section size on pile failure modes under combined loading conditions was clarified by combining physical modelling and the material point method (Wang *et al.* 2026). In addition, addressing the nonlinear soil resistance and deformation characteristics of such variable-section special-shaped piles, a simplified method for calculating the lateral bearing capacity of expanded-base wedge piles based on the p–y curve approach was developed (Kong *et al.* 2016).

In summary, although micropile technology has become relatively mature in engineering practice, studies on variable-diameter micropiles under specific working conditions remain limited. First, existing research on micropiles for power transmission and transformation projects has mainly focused on soft soils or general cohesive soil regions (Borthakur, Das 2024), while investigations targeting complex geological environments such as high-altitude mountainous areas are still scarce. Studies on the uplift performance of rock-socketed micropiles under inclined loading remain particularly limited (Wang *et al.* 2025). Second, most existing studies on the bearing performance of variable-diameter piles have focused on large-diameter or conventional-diameter piles (Shubha *et al.* 2024), whereas research on the bearing characteristics of “variable-diameter micropiles” is still extremely limited.

In view of these gaps, this study established a three-dimensional finite element model using ABAQUS. Drawing on the analytical approach regarding the efficiency of multiple enlargements (Sakr *et al.* 2023), a comparative analysis is conducted on the bearing characteristics of the straight, expanded-base and double-expanded micropile, with an in-depth investigation of their failure mechanisms. The results are expected to fill the theoretical gap and provide a scientific basis for the optimized design of pile foundations in complex mountainous power transmission projects (Wang *et al.* 2024).

GEOLOGICAL CONDITIONS FOR *IN SITU* ENGINEERING

The study area lay within a structural denudation shallow hill-slope terrain, where the topography slopes from high in the north to low in the south. The test site was generally located in a trench area with a relatively gentle terrain, with slopes of approximately 1–2°. Borehole investigations revealed a relatively simple stratigraphy at the site, consisting mainly of Quaternary silty clay and the Mid-Jurassic Shaximiao Formation with highly and moderately weathered mudstone (Fig. 1).

METHODS

Design of variable-diameter micropiles

The tapering piles with varying cross-sections enhance the bearing performance of pile foundations. Variable-diameter single piles (including wedged, stepped, extruded pedestal, and expanded-base piles)

are commonly used in various engineering applications. Expanded-base piles are more commonly applied in the transmission tower foundation design than other types of variable-diameter single piles (Cheng 2012; Kong *et al.* 2016). In this study, we selected the expanded-base form for the micropile taper.

Based on the in-situ static load tests conducted by the research group, three types of micropiles were designed: straight, expanded-base, and double-expanded. The geometric configurations of the test piles are illustrated in Fig. 2. A total of nine test piles were designed, with three piles for each type subjected to compressive, uplift, and lateral static load tests, respectively. The specific parameters are summarized in Table 1.

Model establishment and parameter selection

In this study, the finite element analysis software ABAQUS was used to establish a three-dimensional model of the variable-diameter micropile. Both the pile and the surrounding soil were modelled using

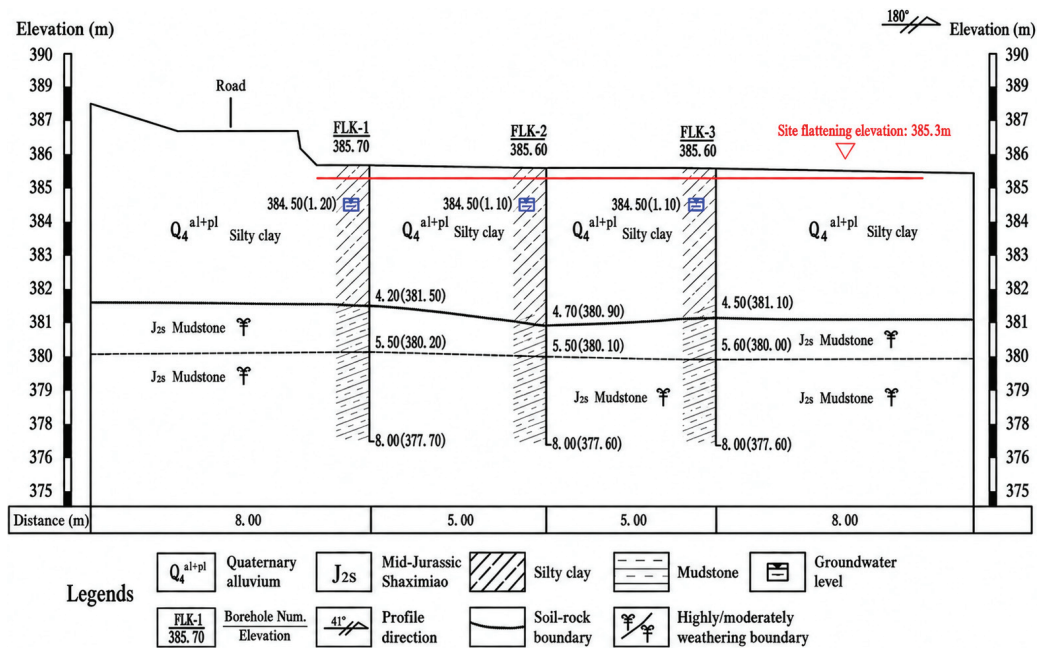


Fig. 1 Engineering geological profile of the site

Table 1 Design parameters of variable-diameter micropiles

Number of piles	Pile type	Diameter/Length (m)	Expanded size (m)	Expanded sections	Load
UM-1	Straight micropile	0.3/7	/	/	Compressive
UM-2	Straight micropile	0.3/7	/	/	Uplift
UM-3	Straight micropile	0.3/7	/	/	Lateral
VMA-1	Expanded-base micropile	0.3/7	0.6	Base	Compressive
VMA-2	Expanded-base micropile	0.3/7	0.6	Base	Uplift
VMA-3	Expanded-base micropile	0.3/7	0.6	Base	Lateral
VMB-1	Double-expanded micropile	0.3/7	0.6	Middle & Base	Compressive
VMB-2	Double-expanded micropile	0.3/7	0.6	Middle & Base	Uplift
VMB-3	Double-expanded micropile	0.3/7	0.6	Middle & Base	Lateral

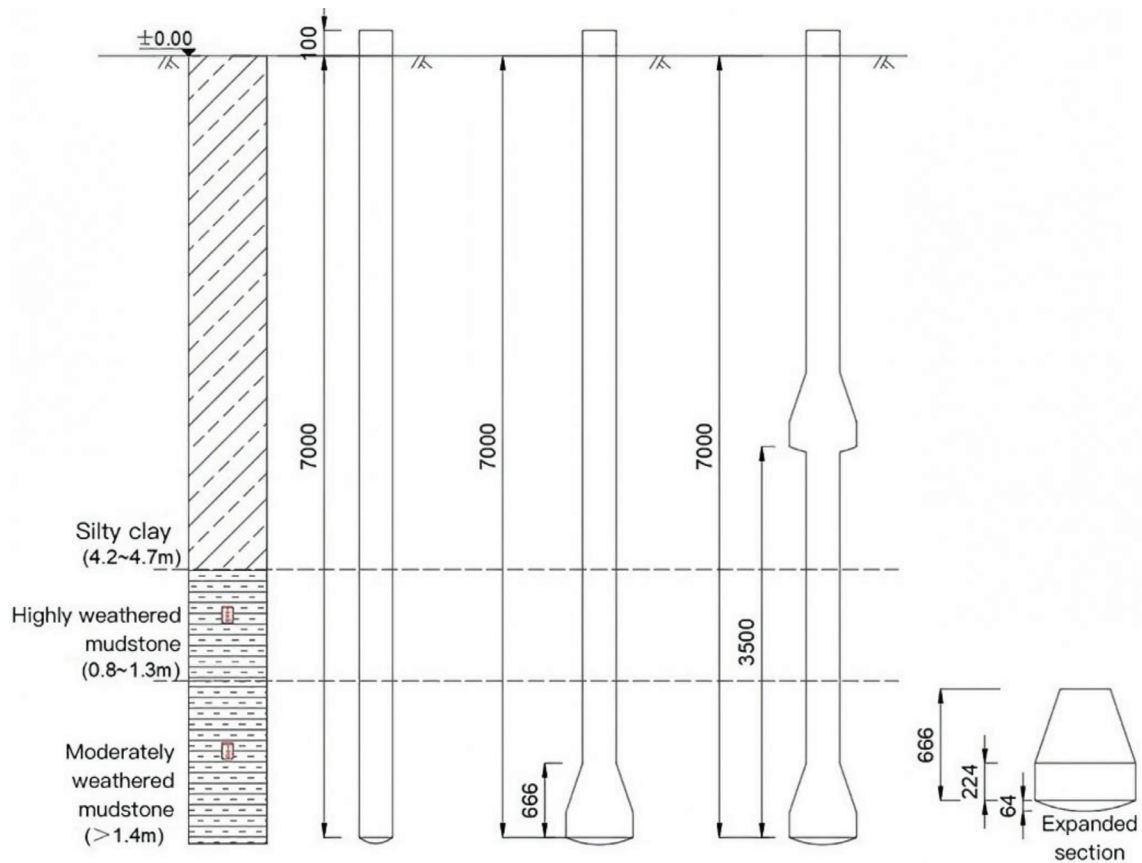


Fig. 2 Stratum structure of the test pile site and a schematic of the rock-socketed micropile

solid elements. To eliminate the influence of boundary effects, the dimensions of the soil domain were determined as follows: the length was set to 18 m (exceeding 20 times the pile diameter), the width to 9 m, and the soil depth to 22 m (greater than twice the pile length).

The model comprises two types of materials. The surrounding soil is treated as a homogeneous, horizontally stratified, and infinite elastic-plastic medium, for which the Mohr-Coulomb (MC) constitutive model is adopted. The pile is modelled as a homogeneous solid; due to its high strength, a linear elastic model is employed.

Based on the geotechnical investigation data from the test site and the preliminary survey of the substation, the physical and mechanical parameters of the foundation soil and the design parameters of the pile used in the numerical simulation are summarized in Table 2.

Pile-soil interaction contact settings

The pile-soil interaction was simulated using the surface-to-surface contact formulation. In this model, three specific contact interfaces were defined: pile-silty clay, pile-strongly weathered mudstone, and pile-moderately weathered mudstone. The contact pairs are categorized into master and slave surfaces. In accordance with the standard criterion where the material with higher stiffness serves as the master surface, the pile surface was designated as the master surface, while the surfaces of the surrounding soil and rock mass were assigned as slave surfaces.

Regarding the contact interaction properties, the normal behaviour was defined as “hard” contact. This formulation allows the transmission of normal pressure only when the surfaces are in a closed state, thereby preventing the penetration of slave nodes into the master surface during calculation. The tangential

Table 2 Piles, rock and soil material calculation parameters

Soil layer / Material	Density ρ /(g/cm ³)	Elastic modulus E/MPa	Poisson's ratio ν	Friction angle φ /(°)	Cohesion c /(kPa)
Silty clay	1.98	15	0.35	11.81	19.22
Strongly weathered mudstone	2.35	100	0.30	24.0	100
Moderately weathered mudstone	2.7	1100	0.28	30.0	150
Pile	2.5	30000	0.2	/	/

behaviour was defined using the penalty function method. Based on the properties of the geotechnical materials and preliminary trial calculations, the friction coefficients for the pile–silty clay, pile–strongly weathered mudstone, and pile–moderately weathered mudstone interfaces were determined to be 0.20, 0.35, and 0.45, respectively.

Boundary conditions and mesh settings

Normal constraints were applied to the lateral boundaries of the model, restricting displacements in the x- and y-directions, respectively. Fixed constraints were applied to the bottom of the model (restraining displacement in the x-, y-, and z-directions), while the top surface of the model remained free. Both the pile and the surrounding rock–soil mass was discretized using C3D8R elements (8-node linear hexahedral elements). The applied boundary conditions and the finite element mesh are illustrated in Fig. 3.

Reliability verification of the model

The in-situ static load tests were performed using the slow maintenance loading method specified in the Technical Code for Testing of Building Foundation Piles (JGJ 106-2014) with stepwise loading. Loading was applied in 150-kN increments for each pile type. At each load level, the pile-head displacement was recorded at 5, 15, 30, 45, and 60 minutes and subsequently at every 30 minutes. To accurately determine the ultimate bearing capacity of each pile type, the pile foundation was considered to have failed and the test was terminated when any of the following conditions were met: 1) the pile-head displacement

under the current load exceeded five times that under the previous load and the total displacement exceeded 40 mm; 2) the pile-head displacement was twice that under the previous load and did not meet the stability criterion after 24 hours; and 3) the total pile-head displacement exceeded 40 mm.

Based on the in-situ static load tests conducted by the research group, the bottom-expanding pile was selected as a case study. The loading steps in the numerical simulation were configured in accordance with the load grading standards employed in the field tests. The displacement values of the pile top at different loading stages were extracted and compared with the data obtained from the full-scale field tests. The comparative load-displacement curves are presented in Fig. 4, thereby verifying the reliability of the numerical model.

It can be observed that the load-displacement curves of the pile obtained from the numerical simulation and field tests exhibit good agreement under various loading conditions. Specifically, under uplift loading, the ultimate uplift bearing capacities derived from the numerical simulation and the field test were 1150 kN and 1100 kN, respectively. Under compressive loading, the corresponding ultimate compressive bearing capacities were 1620 kN and 1540 kN, respectively. Under horizontal loading, the ultimate horizontal bearing capacities were 168 kN and 158 kN. The relative errors for these three loading scenarios were 4.5%, 5.2%, and 5.7%, respectively. Despite certain discrepancies between the numerical and experimental results, the trends of the load-displacement curves are highly consistent. Therefore, the finite element analysis method using ABAQUS employed in this study is considered reasonable and reliable.

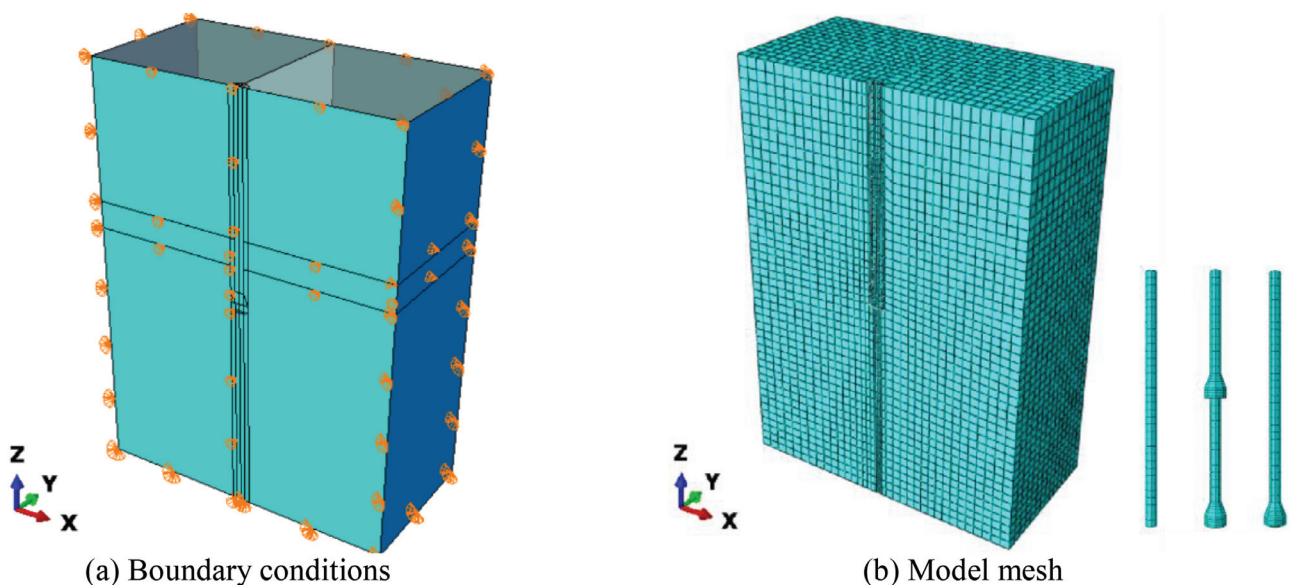
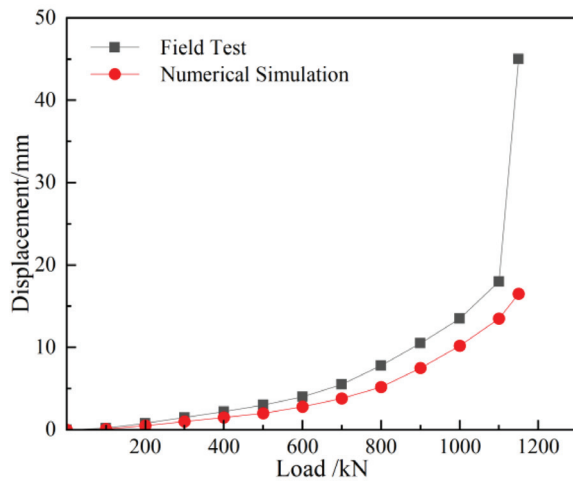
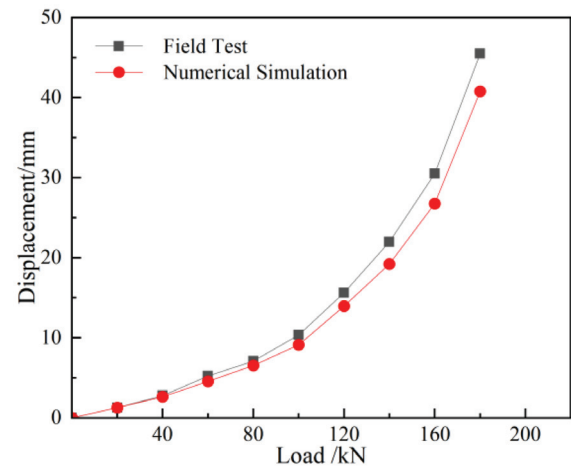


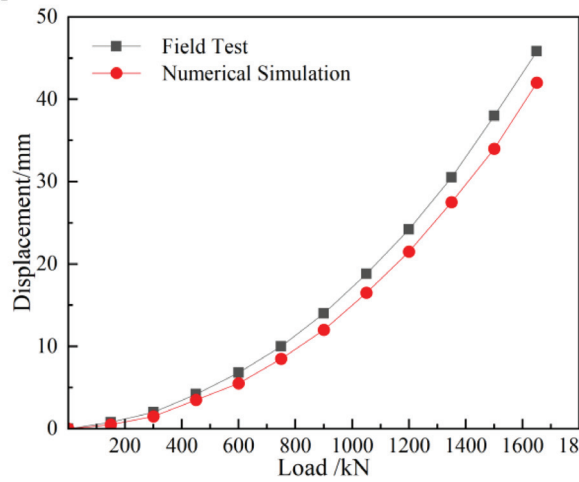
Fig. 3 Finite element calculation model: (a) boundary conditions, (b) model mesh



(a) Uplift load-displacement curves



(b) Lateral load-displacement curves



(c) Compressive load-displacement curves

Fig. 4 Comparison of load-displacement curves based on numerical simulation and field test results: (a) uplift load-displacement curves, (b) lateral load-displacement curves, (c) compressive load-displacement curves

NUMERICAL SIMULATION RESULTS ON BEARING CHARACTERISTICS OF EXPANDED MICROPILES

Compressive bearing capacities

Compressive load-displacement curves

The compressive load-displacement ($Q-s$) curves for the straight, expanded-base, and double-expanded micropile are presented in Fig. 5. It can be observed that under identical loading conditions, the settlements of the expanded micropile are significantly smaller than those of the straight micropile, indicating the superior bearing performance of the variable-diameter designs. The $Q-s$ curves obtained from the finite element simulation for both the variable-diameter and straight micropiles exhibit no distinct inflection points, characterizing them as the gradually varying type. In accordance with the *Technical Code for Testing of Building Foundation Piles* (JGJ 106-2014),

for a curve exhibiting gradual variation, the load corresponding to a settlement of 40 mm is adopted as the ultimate bearing capacity. Consequently the ultimate

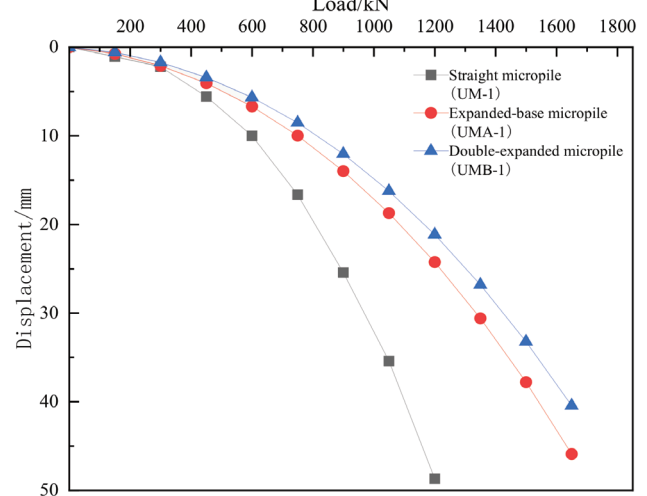


Fig. 5 Comparison of compressive load-displacement curves of different pile types

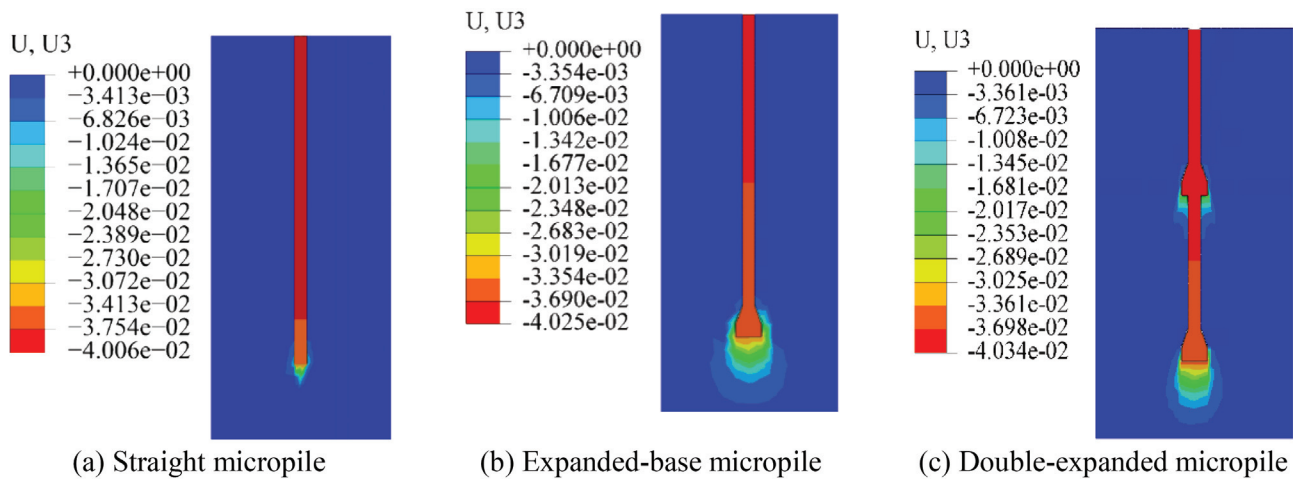


Fig. 6 Displacement of micropile and soil around pile under compressive load: (a) straight micropile, (b) expanded-base micropile, (c) double-expanded micropile

mate compressive bearing capacities derived from the $Q-s$ curves for the straight, expanded, and double-expanded micropiles are determined to be 1200 kN, 1620 kN, and 1775 kN, respectively. The capacities of the expanded piles are approximately 1.35 and 1.48 times that of the straight pile, respectively. Notably, the enhancement in compressive bearing performance provided by the double-expanded micropiles configuration is not significantly greater than that of the expanded micropiles.

Vertical displacement of the pile and surrounding soil

To visually compare the displacement of the pile and surrounding soil for the straight, expanded-base and double-expanded micropiles at the ultimate failure state under compressive loading, displacement contours corresponding to a pile top settlement of $s = 40$ mm were extracted. The results are presented in Fig. 6.

It can be observed that all three pile types underwent varying degrees of compressive deformation under compressive loading. The straight micropile exhibited the largest deformation, followed by the expanded micropile, with the double-expanded micropile showing the least. This indicates that the design of the expanded sections effectively enhances the stiffness of the pile body and reduces its deformation. For all three pile types, the displacement of the surrounding soil occurred primarily at the pile toe and expanded sections. The extent of the influence zone of the soil at the pile toe followed the order: expanded-base micropile > double-expanded micropile > straight micropile. Specifically, the soil displacement beneath the pile toe of the straight micropile exhibited a distribution pattern characterized by larger values at the centre and smaller values at the edges. In contrast, the soil displacement beneath the pile toe for the expanded-base and double-expanded micropiles

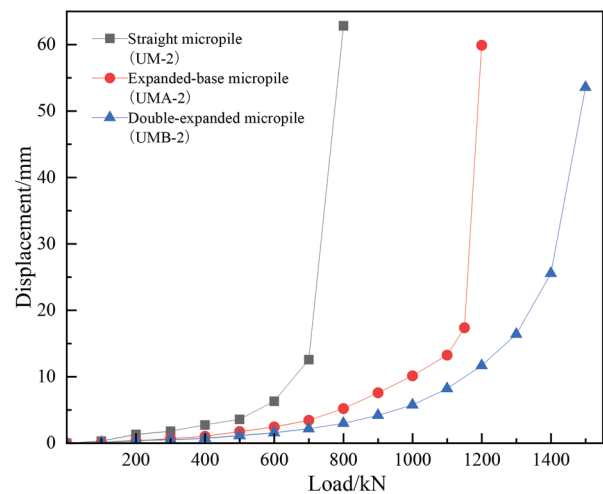


Fig. 7 Comparison of uplift load-displacement curves of different pile types

was basically uniformly distributed, and the displacement contours presented an "elliptical" shape. At the ultimate load displacement, the maximum vertical displacement of the soil surrounding the straight micropile was less than that surrounding the single and double-expanded micropiles. From the soil deformation characteristics, it is evident that the presence of the expanded sections mobilizes a larger volume of soil to participate in sharing the upper load. Simultaneously, this design enhances the pile stiffness and minimizes compressive deformation, thereby promoting the improvement of the compressive bearing capacity of the expanded micropile.

Uplift bearing capacities

Uplift load-displacement curves

The uplift load-displacement ($Q-s$) curves for the straight, expanded-base, and double-expanded micropile are illustrated in Fig. 7. It is evident that under

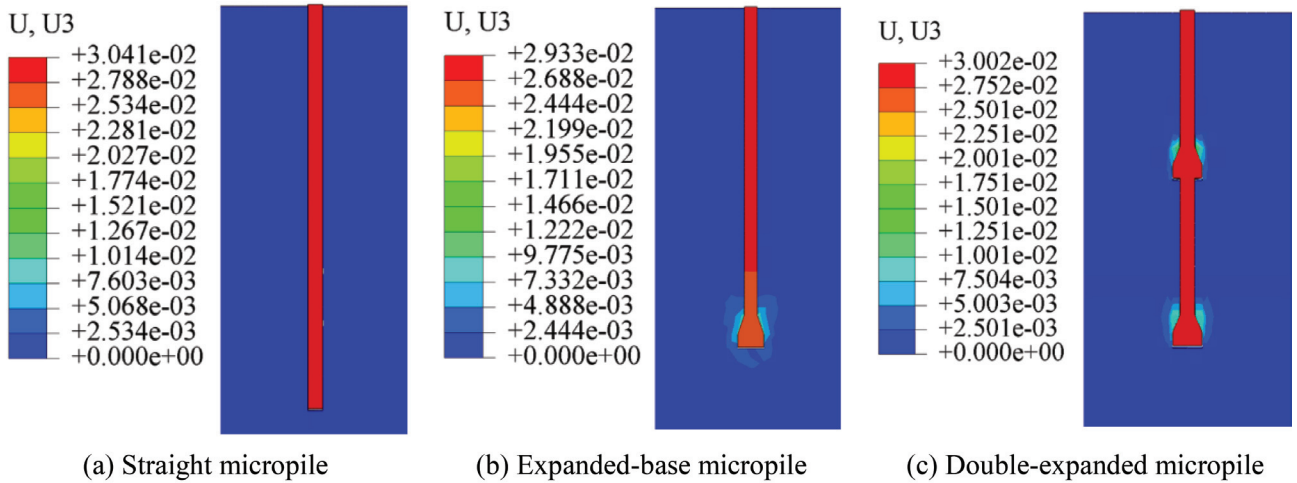


Fig. 8 Displacement of pile and soil around pile under uplift load: (a) straight micropile, (b) expanded-base micropile, (c) double-expanded micropile

identical loading conditions, the uplift displacements of the expanded micropiles are significantly smaller than those of the straight micropile, demonstrating the superior uplift bearing performance of expanded designs. The $Q-s$ curves for all three pile types exhibit distinct inflection points, characterizing them as the steeply varying type. The ultimate uplift bearing capacities for the straight, expanded-base, and double-expanded micropile are 700 kN, 1150 kN, and 1400 kN, respectively. Consequently, the capacities of expanded micropiles are approximately 1.64 and 2.0 times that of the straight micropile, respectively. These indicate that the expanded configuration significantly enhances the uplift bearing performance.

Vertical displacement of the pile and surrounding soil

Similarly, adopting the pile top uplift displacement as the reference criterion, the displacement contours of the pile and surrounding soil for the straight, expanded-base, and double-expanded micropiles were extracted at a displacement of $s = 30$ mm. The results are illustrated in Fig. 8.

It is evident that the double-expanded micropile, owing to the presence of expanded sections, possesses the increased pile stiffness, which significantly reduces the tensile deformation of the pile body. Compared with the straight micropile, the soil surrounding the expanded micropiles undergoes significant displacement. The displacement contours of the surrounding soil exhibit an elliptical shape, which aligns with the elliptical failure mode of long piles. This indicates that the presence of expanded sections effectively mobilizes a larger volume of surrounding soil to resist the applied uplift load, thereby enhancing the ultimate uplift bearing capacity of the expanded micropile.

Lateral bearing capacities

Lateral load-displacement curves

The lateral load-displacement curves for the straight, expanded-base and double-expanded micropile are presented in Fig. 9. It can be observed that under identical loading conditions, the lateral load-displacement curves at the pile top for the straight micropile and the expanded-base micropile essentially coincide. In contrast, the lateral displacement of the double-expanded micropile is significantly smaller than those of the straight and expanded micropiles. This indicates that the presence of the expanded section contributes to the enhancement of the lateral bearing capacity of the micropile, but the degree of improvement is dependent on the position of the expanded section.

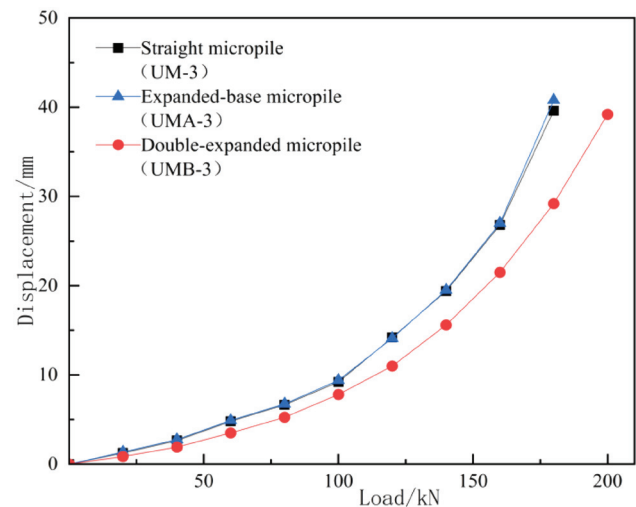


Fig. 9 Comparison of horizontal load-displacement curves of different pile types

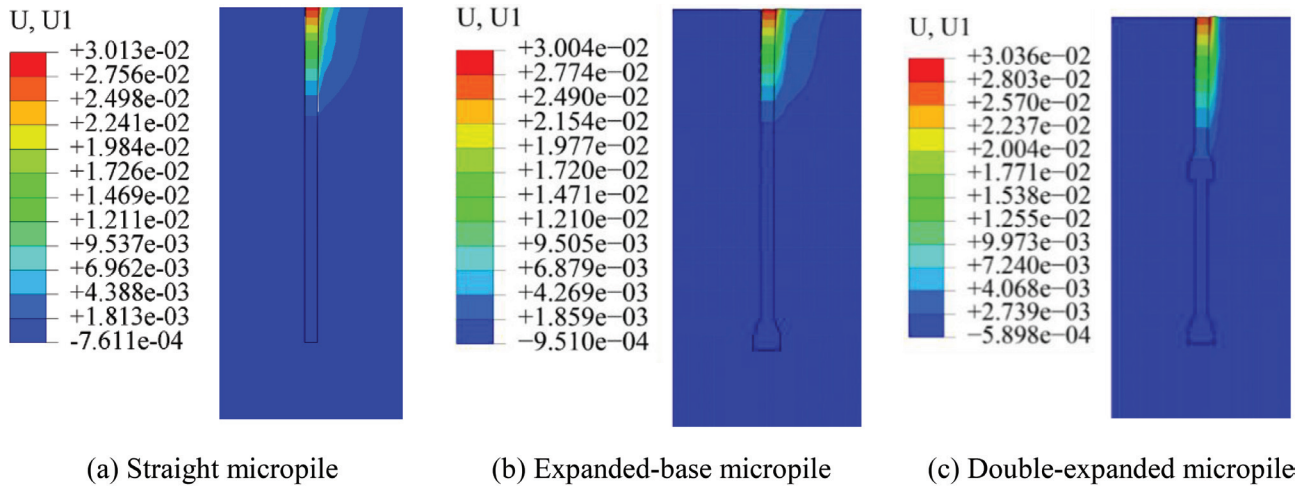


Fig. 10 Displacement of micropile and soil around pile under horizontal load: (a) straight micropile, (b) expanded-base micropile, (c) double-expanded micropile

Furthermore, the load-displacement ($Q-s$) curves obtained from the finite element simulation exhibit no distinct inflection points, characterizing them as the gradually varying type. The ultimate lateral bearing capacities for the straight, expanded-base, and double-expanded micropile are 165 kN, 165 kN, and 182 kN, respectively. The capacity of the double-expanded micropile is approximately 1.1 times that of the straight and expanded-base micropile, suggesting that the expanded section offers limited improvement to the lateral bearing performance.

Displacement of the pile and surrounding soil

To visually compare the displacement of the pile and surrounding soil for the straight, expanded-base and double-expanded micropile at the ultimate failure state under lateral loading, displacement contours corresponding to a pile top displacement of $s = 30$ mm were extracted. The results are illustrated in Fig. 10.

It is evident that the displacements of the pile and surrounding soil for all three pile types are primarily concentrated in the upper portion of the pile shaft, while the displacements in the middle and lower sections are negligible. Under lateral loading applied at the pile top, significant soil heave was observed around for all three pile types. When the lateral displacement of the pile top reached 30 mm, the maximum soil heave displacements for the straight, expanded-base, and double-expanded micropile were 11.7 mm, 12.1 mm, and 13.1 mm, respectively. Regarding the extent of soil disturbance, the vertical and horizontal ranges for the straight micropile were 2.13 m and 1.21 m, respectively. For the expanded-base micropile, these ranges were 2.17 m and 1.17 m, respectively. In contrast, the double-expanded micropile exhibited a vertical disturbance range of 2.89 m and a significantly reduced horizontal disturbance

range of 0.46 m. The soil disturbance zones for the straight and expanded-base micropiles are essentially consistent, whereas the horizontal disturbance range of the double-expanded micropile is notably smaller. This indicates that the middle-expanded section mobilizes more surrounding soil to participate in resisting the upper lateral load. However, the fact that the middle-expanded section is not fully engaged in resisting the lateral load limits the improvement in the single-pile bearing capacity. This further confirms that the influence of the expanded section on lateral bearing performance is closely correlated with its design position.

DISCUSSION AND CONCLUSIONS

In this study, based on full-scale field tests, three-dimensional numerical simulations of expanded micropiles under compressive, uplift, and lateral loading conditions were conducted using the finite element software ABAQUS. The bearing characteristics of the straight, expanded-base, and double-expanded micropiles under different loading scenarios were comparatively analyzed. The following conclusions were drawn:

(1) Under compressive loading, the $Q-s$ curves for all three pile types exhibited no distinct inflection points. The ultimate compressive bearing capacities of the expanded-base and double-expanded micropiles were approximately 1.35 and 1.47 times those of the straight micropile, respectively. The expanded sections effectively mobilized additional soil resistance, thereby enhancing the compressive performance of the pile foundation. At the ultimate load, all three pile types primarily exhibited local shear failure.

(2) Under uplift loading, the $Q-s$ curves for all three pile types exhibited distinct inflection points. The ultimate uplift bearing capacities of the expand-

ed-base and double-expanded micropiles were approximately 1.64 and 2.0 times those of the straight micropile, respectively. The displacement contours revealed that the soil deformation around the expanded micropiles formed an elliptical shape, consistent with the elliptical failure mode of long piles. The expanded sections further mobilized lateral soil resistance, significantly improving the uplift bearing capacity of the pile foundation.

(3) Under lateral loading, the $Q-s$ curves for all three pile types exhibited no distinct inflection points. The load-displacement curves for the straight and expanded-base micropiles essentially coincided, indicating no significant increase in the ultimate lateral bearing capacity. The double-expanded micropile showed a lateral capacity approximately 1.1 times that of the other two types. For all three piles, soil disturbance and plastic failure were concentrated in the upper shaft, consistent with the behaviour of flexible piles. The disturbance zones for the straight and expanded-base piles were similar, whereas that for the double-expanded pile was notably smaller. This indicates that the middle-expanded section mobilizes more surrounding soil to resist the upper lateral load. However, the middle-expanded section is not fully engaged in resisting the lateral load, resulting in a limited improvement in the bearing performance of the micropile.

ACKNOWLEDGMENTS

This study was supported by the Science and Technology Project of State Grid Corporation of China (SGZB0000TGJS2401067). The authors thank the Editor and the reviewers for their comments which greatly improved the quality of the manuscript.

Conflicts of Interest

The authors have no competing interests to declare that are relevant to the content of this article. The authors declare that no artificial intelligence (AI) technologies were used in the article preparation.

REFERENCES

- Al-Bayati, A.W., Al-Neami, M.A., Rahil, F.H. 2023. Experimental work on the effect of under-reamed pile geometry on the pullout capacity of sand. *International Journal of Engineering* 36(9), 1645–1651.
- Bao, X.H., Ye, R.H., Zhou, Y. 2019. Experimental and finite element analysis on bearing capacity characteristics of expanded-base cast-in-place piles. *Chinese Journal of Underground Space and Engineering* 15(S1), 136–143 [In Chinese].
- Borthakur, N., Das, M. 2024. Predicting micropile group capacity in soft cohesive soil by artificial neural network. *Indian Geotechnical Journal* 54, 1–14.
- Cheng, Y.F. 2012. *Application of Micropile Foundations in Transmission Line Engineering*. Beijing: China Electric Power Press [In Chinese].
- Gao, X.J., Wang, J.B., Bao, J.X., Duan, P.H., Zhou, T.H., Zhu, X. 2024. Experimental research on bearing behaviors of cement mortar-expanded precast piles. *International Journal of Civil Engineering* 22(2), 259–270.
- Goudar, S., Ronad, H., Kamatagi, A., et al. 2026. Behaviour of single tapered belled and straight bored piles under inclined load: A comparative study using PLAXIS 3D. *Geotechnical and Geological Engineering* 44, 35.
- Hu, Z.B., Qu, S.Y., Wang, Q.K., Guo, Y.J., Ji, Y.K., Ma, J.L. 2023. Pullout behaviour of belled piles under axial and oblique pull in soil-rock composite ground: An experimental study. *International Journal of Civil Engineering* 21(4), 569–582.
- Huang, M.S., Wang, X.J., Wu, J.B. 2011. Unified calculation mode for ultimate bearing capacity of expanded-base uplift piles with different lengths. *Chinese Journal of Geotechnical Engineering* 33(1), 63–69 [In Chinese].
- Kong, G.Q., Zhou, L.D., Yang, Q. 2016. Theoretical analysis of lateral bearing capacity of expanded-base wedge piles based on p-y curve method. *China Journal of Highway and Transport* 29(6), 179–185, 206 [In Chinese].
- Liu, Z.C., Jiang, Y.S., Gong, W.M. 2001. Discussion of the Design Method of Large Diameter Belled Pile's Bearing Capacity According to Settlement. *Journal of Southeast University (Natural Science Edition)* 31(4), 49–53 [In Chinese].
- Majumder, M., Chakraborty, D. 2021. Uplift capacity and failure mechanism of under-reamed piles in clay based on lower bound finite element limit analysis. *National Academy of Science Letters* 44, 1–5.
- JGJ 106-2014. Technical code for testing of building foundation piles. Beijing: Ministry of Housing and Urban-Rural Development of the People's Republic of China [In Chinese].
- Nariyelil, A.J., Cyrus, S., Abraham, B.M., Balakrishnan, S. 2026. Experimental analysis of uplift behavior in under-reamed piles: A comparative study in saturated clay and clayey sand. *Indian Geotechnical Journal* 56(3), 1462–1477.
- Panda, A., Borthakur, N. 2025. An experimental study on the lateral load-carrying capacity of batter micropile groups in soft clayey soil. In: Chatterjee, K., et al. (eds), *Foundation Engineering*. Singapore: Springer, 347–358.
- Sakr, M., Nazir, A., Azzam, W., GamalEldin, I. 2023. Group efficiency of tension double under-reamed piles in sand. *Indian Geotechnical Journal* 53(1), 11–28.
- Sakr, M., Nasr, A., Khaffaf, M., Basha, A. 2025. Behavior of under-reamed piles under inclined uplift loads in sand. *International Journal of Geo-Engineering* 16(1), 1–12.

- Shubha, M., Venkatesh, S.V., Srilakshmi, G. 2024. A review on under-reamed piles. In: Krishna, A.M., *et al.* (eds), *Deep Foundations for Infrastructure Development in India*. Singapore: Springer, 275 pp.
- Thottoth, S.R., Das, P.P., Khatri, V.N. 2024. Prediction of compression capacity of under-reamed piles in sand and clay. *Multiscale and Multidisciplinary Modeling, Experiments and Design* 7(3), 2289–2305.
- Vakili, A.H., Khajeh, A., Shalchian, M.M., Tajari, R. 2025. Experimental analysis of the influential parameters on lateral resistance of micropile groups in sand. *Results in Engineering* 27, 105663.
- Wang, Q.K., Hu, Z.B., Guo, Y.J., Ji, Y.K., Zhu, B.L., Ma, J.L. 2024. Investigation on uplift behavior of rock-socketed belled piles in horizontal and inclined ground using 1-g model test and 3D numerical method. *Rock Mechanics and Rock Engineering* 57(5), 3371–3391.
- Wang, Q.K., Hu, Z.B., Chen, H.N., Zhu, B.L., Zhang, J., Yang, Y.X. 2025. Experimental Investigation on the Pullout Performance of Rock-Socketed Micropiles under Oblique Loads. *Journal of Geotechnical and Geoenvironmental Engineering* 151(10).
- Wang, W.D., Wu, J.B., Xu, L. 2007. Experimental study on bearing behaviors of expanded-base uplift piles in soft soil area. *Chinese Journal of Geotechnical Engineering* 29 (9), 1418–1422 [In Chinese].
- Wang, Z., Zhang, Y.L., Dong, D.F., Zhu, D.H., Zhao, Y.M. 2026. Physical modeling and material point method analysis of belled piles under combined uplift-lateral loading: Effects of enlarged base dimensions. *Geotechnical and Geological Engineering* 44(2), 81.
- Weaver, J.S., Morgenstern, N.R. 1981. Pile design in permafrost. *Canadian Geotechnical Journal* 18(3), 357–370.
- Zhang, H., Wang, Z., Liu, W.Z., Zhao, Y., Zhou, T.H. 2024. Bearing characteristics and simplified calculation of a reamed precast concrete pile with prebored grouting. *International Journal of Civil Engineering* 22(5), 859–875.
- Zhang, L., Zhang, R., Cheng, D.Y. 2018. Bearing behavior of expanded-base piles with different failure modes under lateral load. *Chinese Journal of Underground Space and Engineering* 14(4), 1016–1023 [In Chinese].