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Effect of Pile Side Tandem-Type Cavities on the Settlement of Pile Under Vertical Load in Karst Area

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Abstract. In order to investigate the influence of tandem-type karst cavities on the lateral side of pile foundations on the settlement behavior and stability under loading conditions, this study was conducted within the context of the East Block Project of the Lianrong Village Resettlement Housing Project in Hangzhou Xianlin Street. Field vertical static load tests were performed on single piles, considering three representative single pile models under different working conditions. Theoretical modifications were applied to analyze the im-pact of lateral cavities on the pile body. The results indicate that under the influence of tandem small-sized cavities, the initial loading phase induces a steep settlement due to the presence of multiple cavities, followed by a more elastic settlement phase. A second steep settlement occurs at the final stage of loading. During the unloading process, the load-displacement curve of the pile exhibits a parabolic rebound trend, with residual deformation observed after complete unloading. Preconstruction treatment of tandem-type cavities ensures stable linear elastic behavior under smaller loads, although larger loads still disturb the surrounding soil. Penetration of single piles through lateral cavities triggers debonding at the pile-soil interface, leading to a redistribution of shear stresses around the cavity soil. This results in pile settlement and deflection, increasing the vertical displacement at the pile head and reducing the stability of the single pile.

Keywords. Karst area, tandem small caves, residual deformation, pile-soil interface

1. Introduction

The structural conditions of karst caves are highly unstable, and embedded piles are frequently utilized in typical karst regions. Even after grouting and stabilization treatments, the caves remain prone to uncertainty and potential collapse. Several scholars have investigated the load transfer mechanisms of monopiles traversing various forms of karst cavities, revealing that an increase in the number of cavities significantly

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amplifies the negative skin friction resistance of the monopile. Chen et al. [1] and Lei Yong et al. [2] have studied the bearing capacity of pile ends and the effects of cavities in karst areas, deriving formulas for the tensile strength of rock masses and shear failure strength. They subsequently proposed a method for calculating the safe thickness of the cavity roof. Gong Xianbing et al. [3] established a simplified mechanical model of piles in karst regions and formulated a potential energy function. By integrating the fundamental concepts of catastrophe theory, they explored the instability conditions of cavity roofs and conducted ultimate load research around bridge monopiles, developing a calculation method for the ultimate load at the pile tip. Hu Baixue et al. [4] comprehensively considered the softening and hardening characteristics of the soil surrounding the pile after construction treatment, taking into account the impact of residual material at the pile base on bearing capacity. They determined the vertical bearing capacity of single piles in karst areas using a load transfer model, combined with in-situ monitoring, and established the relationship between pile head settlement and load influence.

Regarding research on single piles penetrating karst cavities, most scholars agree that the pile tip plays a crucial role in the bearing capacity of single piles. It is essential for the pile to penetrate the karst cavity and be embedded into the cavity's base at a certain depth to maintain the pile's bearing capacity. Fan Jinzhao [5] equated the single-pile bearing capacity problem and, through correlation, recursively introduced the long-axis collapse failure mode of cavity-type monopiles and the conditions for generating ultimate bearing capacity. Yang Wei et al. [6] established empirical relational equations using grey correlation theory to explore the influence of various factors on bearing capacity. Su Guanfeng et al. [7] employed physical simulation tests to study monopiles under conditions of no cavity, single-layer, and multi-layer cavity rock strata. They found that the settlement of monopiles penetrating cavities is significantly greater than that of ordinary monopiles, with lower load-bearing capacity, and identified the pile-soil interface and the pile base control interface in karst areas as weak surfaces. Based on the load transfer method, Peng Ge [8] analyzed the influence of different cavity morphologies on pile head load, proposing a calculation method for pile head settlement control. The study revealed that controlling the width of various physical dimensions of the cavity is a critical factor affecting the pile's bearing capacity. When dealing with complex projects, Huang Ming et al. [9] used numerical simulation methods to investigate the vertical bearing capacity of single piles penetrating bead-like cavities in Chongqing bridges, exploring the influence of the thickness-to-span ratio of the cavity roof in karst areas. They observed significant attenuation in the unfilled portion of the cavity roof, with failure modes including punching shear and punching damage.

In the study of the effect of cavities on the lower side of piles, the calculation of pile side friction resistance can be performed using the triple-fold model. Chen Xin et al. [10] proposed a nonlinear combination algorithm suitable for analyzing the settlement of branch piles. Based on the load transfer method, they adopted a biplane model conforming to the mechanical configuration of the branch structure and proposed a nonlinear expression for the resistance and displacement at the branch end. Beyond the conventional transfer model, many studies focus on simplifying the calculation model to determine the theoretical value of pile settlement. Hu Chao and Liu Hongjun et al. [11-12] conducted research based on the pile-soil interaction mechanism under vertical loading, establishing a mathematical planning model for single pile settlement calculation using the soil load transfer method. Jin et al. [13] studied the nonlinear settlement response of monopiles under axial loading and performed settlement response analysis based on a layered Gibson foundation model. Liu Zhong et al. [14] utilized a bifurcated load transfer function, applied the load transfer method, and embodied the interaction characteristics of the soil-soil interface and pile-soil interface. They combined experimental and theoretical analyses of the pile-soil interface mechanism and conducted research on the vertical bearing performance and settlement characteristics of different types of monopiles. C. Knellwolf et al. [15] first introduced the load transfer method into pile research, using static equilibrium conditions at the neutral point of mooring resistance. They constructed a load-temperature coupled load transfer equation and employed a segmented folded load transfer model to provide a calculation method for the working and bearing deformation characteristics of the pile body under heat-force coupling. The analysis method was verified by comparing it with field test data. N. Plaseied et al. [16-17] improved Knellwolf's method based on the hyperbolic load transfer model of the pile and surrounding soil. Their model considered the gradualness of soil strain, although the location of the neutral point still required prior assumption.

Currently, research on the influence of cavity stability primarily focuses on the bearing capacity of the cavity roof thickness for single pile loads, but the impact of cavities on the pile side is not adequately reflected. Regarding research on the impact of single piles penetrating cavities, most scholars assume that the pile body passes exactly through the midpoint of the cavity, primarily focusing on the vertical settlement of the pile body while largely ignoring the transverse offset of the pile tip. Studies often examine the relationship between pile body settlement and various cavity physical factors, but the distribution of cavities in different directions is less frequently considered. In the study of the impact of cavities on the lower side of penetrating piles, the focus is mainly on the change characteristics of the ultimate bearing capacity of monopiles in the presence of side cavities and the stability of the cavity roof. However, there is less attention paid to the change characteristics of the vertical settlement and lateral offset of the pile body.

2. Experimental Background

This project pertains to the East Block of the Resettlement Housing Project in Lianrong Village, Xianlin Street, Hangzhou. The site exhibits a maximum thickness ranging from approximately 12.50 to 37.3 meters, predominantly composed of residual slope deposits. The shallow strata are characterized by gravelly clay and clay, ranging from soft to hard plasticity, underlain by greenish-gray limestone of the Xiyangshan Formation from the Upper Cambrian System. The bedrock has undergone varying degrees of weathering.

According to the geotechnical investigation report, the soil layers within the influence zone of the foundation pit excavation are distributed in the following sequence (table 1):

Table 1. Soil layer information.

Soil Layer	Layer Thickness (m)	Number of Test Blows n (Blows/30cm)	Depth of Burial at The Top of The Layer (m)	Elevation at The Top of The Layer (m)	Maximum Grain Size (mm)
Miscellaneous fill	0.50~3.10	/	/	/	/
Gravelly clay	2.90~13.00	21.3	0.50~3.10	6.64~17.68	60
Clay	2.10~12.90	25.9	4.80~13.80	2.74~11.18	30
Gravelly clay	1.00~17.80	6.9	9.10~25.20	-14.06~6.79	40
Cave	0.20~13.60	/	/	/	/

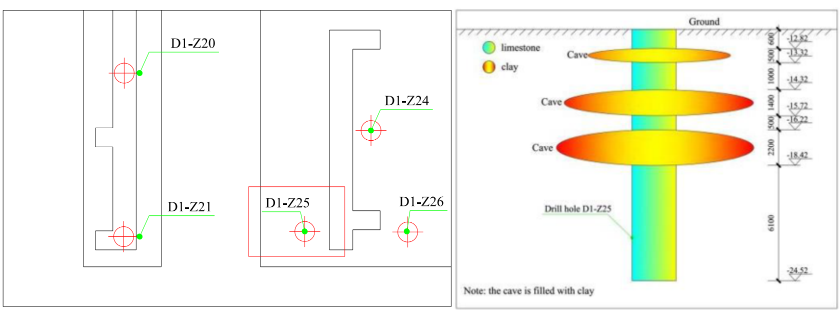
A total of three pile locations and piles were selected for this test, and the distribution patterns of the pile cavities are shown in table 2.

Table 2. Table of distribution of experimental differences

Pile Position	Number of Caverns	Cavern Condition	Cavern Height	Cavern Filling	Cavern Distributio n
D1-25	3	Strong unilateral development	0.5m\1.4m\2 .1m	Gravelly clay, moderately weathered greywacke	Tandem Cave
D2-38	2	Strong bilateral development	0.9m \0.7m	Gravelly clay, moderately weathered limestone	Tandem Cave
D5-30	2	Strong unilateral development	1m \0.9m	Gravelly clay, moderately weathered greywacke	Tandem Cave

3. Field Trial Design

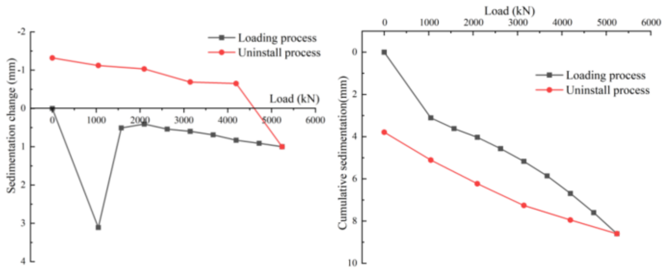
In order to determine the settlement behavior of single piles potentially affected by tandem small karst cavities during in-situ vertical static load tests, three representative single pile models were selected for a comprehensive study on the relationship between loading and settlement.



(a) Pile situation (b) Cave situation

Figure 1. D1-Z25 Drill hole surveys.

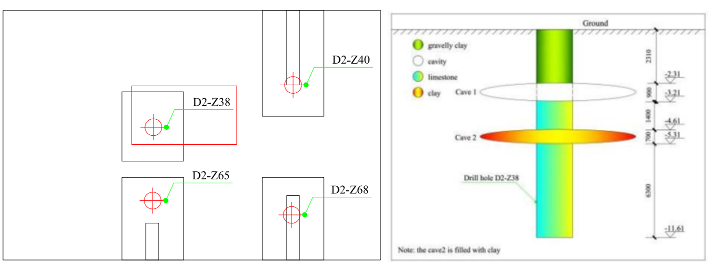
D1-Z25 drilled hole survey is shown in figure 1, at the junction of the clay layer is estimated to exist a small 0.5m cave, and two 2m small caves, in the pile adjacent to the Z21 pile sampling did not find the existence of caves, Z24, Z26 piles were found to have a similar to the existence of this pile of the tandem cave, judgement of the D1-Z25 cave for the development of the side of the pile body is strongly developed, the caves for the rock layer of a single cavern. Arranged in strings at the junction of rock layer and upper side clay layer, affecting the stability of single pile.



(a) Cascading changes (b) Cumulative change

Figure 2. D1-Z25 pile settlement change pattern diagram.

By D1-Z25 in the in-situ vertical static load test can be seen, as shown in figure 2 back-end curve in line with the line elasticity stage, gradually reach the demand of bearing capacity, the same in the static load test in the front section, the project pile only in the process of the primary loading, there is a short period of large displacement steeply up to 3.1mm, judged to be the pile-soil interface in the process of the work of the soil body backlash in the course of the single pile. Due to the small cavern is located in the end of the pile produced by the impact of figure 2, rebound amount is larger 4.81mm, after the engineering treatment, the soil still exists in a certain cavity, but the cavern stability is the first to be undermined, the primary loading process can make the monopile return to a stable state both, the settlement cumulative amount of up to 8.6mm.

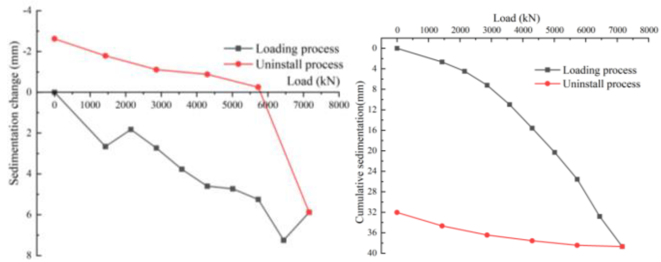


(a) Pile situation (b) Cave situation

Figure 3. D2-Z38 Drill hole surveys.

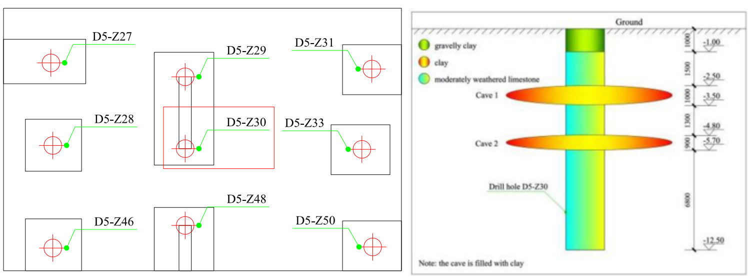
D2-Z38 borehole survey situation is shown in figure 3 above, in the soil layer junction is estimated to exist a 1m small cavern, and a 0.7m small cavern, in the pile adjacent to the Z40 sampling found that a single cavern exists, Z65 piles found that the existence of tandem caverns, judgement of D2-Z38 cavern for the pile body on both sides of the development of a strong, the cavern for the string-like arrangement in the rock layer and the upper layer of the junction of the clay, affecting the Stability of single pile.

D2-Z38 in the process of in-situ vertical static load test, the cumulative displacement increment during loading at all levels is larger, such as figure 4, the initial settlement of 2.6mm, and in the eighth level of loading appeared in the second settlement curvature changes in the settlement of the point for settlement steeply up to 7.2mm, initially determined as the soil bearing capacity is weak, resulting in a large settlement between the various levels of load, a cumulative total of 38.7mm, the soil still maintains a certain degree of continuity at this time, able to support the pile to achieve the bearing capacity requirements. Currently, the soil body still maintains a certain degree of continuity, and can support the pile body to achieve the bearing capacity requirements. In the process of load gradually increasing, the original continuity of soil body is destroyed to form a new stable state, so there is a certain degree of displacement steeply as shown in figure 4, the rebound rate is only 17.2%, the stability of single pile is affected.



(a) Cascading changes (b) Cumulative change

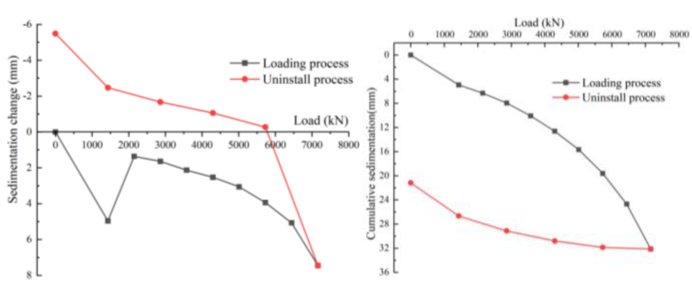
Figure 4. D2-Z38 pile settlement change pattern diagram.



(a) Pile situation (b) Cave situation

Figure 5. D5-Z30 Drill hole surveys

D5-Z30 borehole survey this situation is shown in figure 5 above, in the soil layer junction is estimated to exist two 1m small caverns, in the pile adjacent Z28, Z29, Z33 probe holes have no caverns exist, Z48 probe holes exist string of bead-like caverns, judgement of D5-Z30 caverns for the pile side of the development of a strong, caverns in strings arranged in the bedrock layer and the upper layer of the junction of the clay, affecting the single pile The holes are arranged in strings at the junction of bedrock layer and upper clay layer, affecting the bearing capacity of single pile.



(a) Cascading changes (b) Cumulative change

Figure 6. D5-Z30 pile settlement change pattern diagram.

D5-Z30 in the 1st stage loading process, the settlement cumulative increment appeared instantaneous increment, in the 2nd~6th stage loading process, the settlement cumulative increment was relatively stable and there was no steep drop in the loading stage, but from the 7th stage loading, the settlement cumulative increment of the monopile began to increase in gradient, and the pile was still able to maintain stability, and the 2nd curvature change point of settlement appeared in the 8th stage loading see figure 6, the rebound rate of single pile was controlled at 34.0%, probably due to the existence of multiple holes in the initial loading process, which reached a new stable state after the initial stage loading, and the subsequent existence of new holes in the soil layer, which gradually increased the cumulative increment of settlement to a cumulative total of 32.1mm.

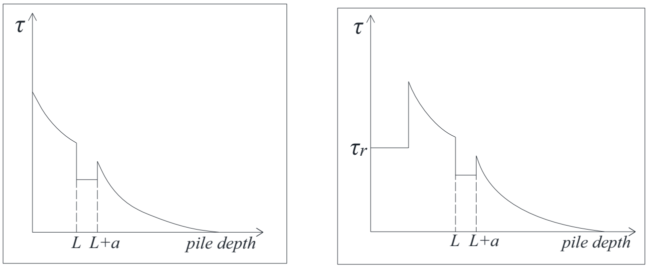
In summary, the settlement change rule of D1-Z25 pile is more stable in the loading process, and the settlement amplitude of D2-Z38 and D5-Z30 piles is larger, therefore, the solution holes of D1-Z25 piles are handled more perfectly in the construction treatment process, which has a smaller effect on the soil homogeneity, while D2-Z38 and D5-Z30 piles still have a second curvature point in the loading process of the 5th post-stage loading and the settlement curvature change of D2- Z38 piles has a second curvature point, and the settlement curvature change of D2- Z38 piles has a second curvature point in the loading process of the 5th post-stage loading. Z38 piles have the strongest change in settlement curvature, D5-Z30 piles have a more obvious change in settlement curvature, and D1-Z25 piles have a less obvious change but relevant changes can be seen, indicating that the tandem cave side penetration piles can maintain stable linear elasticity when subjected to smaller loads after completion of the pre-construction treatment, but when subjected to larger loads, tandem cavities can still disturb the soil body.D1-Z25 and D5 D1-Z25 and D5-Z30 piles have three curvature settlement changes, which to a certain extent can indicate that the instability of pile-soil interface shows three stages of damage characteristics, which may be caused by the initial disturbance, the disturbance triggered by the treatment of the cavern, and the disturbance suffered by the soil body at the interval of the tandem cavern.

4. Results and Discussion

When tandem cavities are present on the lower side of a karst cave, Ma Zhongliang [18] employed a load transfer model utilizing a transfer function for analysis. It was assumed that the presence of soil around the pile would lead to interface failure and debonding effects due to pile movement, resulting in a redistribution of shear stresses around the soil cavity, as illustrated in figure 7. This scenario closely aligns with the analysis of a single pile penetrating multiple cavities. The relationship between the shear stress and shear displacement of the pile body and the surrounding rock mass is expressed as follows:

$$\tau(z)=\begin{cases} ks(z),\ \text{Elastic stage} \\ \tau_r,\ \text{Plastic stage} \\ \psi\tau(L+a/2), z=L\sim L+a \end{cases} \tag{1}$$

where L represents the vertical spacing between the pile head and the cavity, a denotes the height of the cavity, and ψ is the attenuation coefficient of shear stress during the existence of the cavity.



(a) Without considering the debonding effect (b) Considering the debonding effect

Figure 7. Characteristics of Shear Stress Distribution Along the Pile Body without and with Debonding Cavity at the Interface [18].

The load transfer function for the pile side, considering the debonding effect at the pile-rock interface, is derived as follows [18]:

$$\tau(z)=\begin{cases}\tau_r, 0\le z<H_1\\ \dfrac{P_{H_1}\eta}{C}\left[\dfrac{\cosh(\eta H)-\alpha}{\sinh(\eta H)}\cosh(\eta z-\eta H_1)-\sinh(\eta=-\eta H_1)\right](H_1\le z<L)\\ \psi\dfrac{P_{H_1}\eta}{C}\left\{\dfrac{\cosh(\eta H)-\alpha}{\sinh(\eta H)}\cosh\left[\eta\left(L+\dfrac{a}{2}-H_1\right)\right]-\sinh\left[\eta\left(L+\dfrac{a}{2}-H_1\right)\right]\right\}(L\le z<L+a)\\ \dfrac{P_L+a\eta}{C}\left\{\dfrac{\cosh(\eta H)-\alpha}{\sinh(\eta H)}\cosh\left[\eta(z-L-a)\right]-\sinh\left[\eta(z-L-a)\right]\right\}(L+a\le z\le H)\end{cases} \quad (2)$$

This load transfer function indicates that when the pile body is in the elastic stage, the region below the cavity remains in the elastic deformation stage. Even if the upper part of the pile body enters the plastic stage due to the influence of the cavity, the area below the cavity can remain in the elastic stage. The cavity in the pile body has a relatively small impact on the soil below the cavity. Therefore, in the study of single piles penetrating lateral cavities, since cavities predominantly appear near the interface of the bedrock layer and are close to the bedrock, the influence of cavities located in the upper clay layer on the pile body is limited and can be neglected to some extent.

Based on field test results and the theory of lateral cavities, when considering the debonding effect at the interface between the lateral cavity and the pile body, the number of debonding occurrences during the loading process is related to the equivalent height of the cavity and the spacing between cavities. Under the premise of excluding initial loading conditions, if the debonding effect occurs only once during the penetration of a single pile through tandem lateral cavities, the theoretical model is modified accordingly.

$$\tau(z)=\begin{cases}\tau_r,(0\le z<H_1)\\ \dfrac{P_{H_1}\eta}{C}\left[\dfrac{\cosh(\eta H)-\alpha}{\sinh(\eta H)}\cosh(\eta z-\eta H_1)-\sinh(\eta z-\eta H_1)\right]\\ (H_1\le z<L_1)\\ \psi\dfrac{P_{H_1}\eta}{C}\left\{\dfrac{\cosh(\eta H)-\alpha}{\sinh(\eta H)}\cosh\left[\eta\left(L_1+\dfrac{a_1+a_2+\beta\Delta H}{2}-H_1\right)\right]-\sinh\left[\eta\left(L_1+\dfrac{a_1+a_2+\beta\Delta H}{2}-H_1\right)\right]\right\}\\ (L_1\le z<L_1+a_1+a_2+\Delta H)\\ \dfrac{P_{L_1+a_1+a_2+\Delta H}\eta}{C}\left\{\dfrac{\cosh(\eta H)-\alpha}{\sinh(\eta H)}\cosh\left[\eta(z-L_1-a_1-a_2-\Delta H)\right]-\sinh\left[\eta(z-L_1-a_1-a_2-\Delta H)\right]\right\}\\ (L_1+a_1+a_2+\Delta H\le z\le H)\end{cases} \quad (3)$$

5. Conclusion

The stability of single piles is significantly influenced by the presence of karst cavities on the pile side in karst areas. Through theoretical and experimental studies, the following three conclusions are drawn: (1) After pre-construction treatment of tandem cavities, the pile can maintain a stable linear elastic state under smaller loads. However, under larger loads, it still induces disturbances in the surrounding soil. (2) The penetration of a single pile through lateral cavities triggers debonding at the pile-soil interface, leading to a redistribution of shear stresses around the cavity soil. This results in pile settlement and deviation, increasing the vertical displacement at the pile head and reducing the stability of the single pile. (3) Existing engineering treatment methods are insufficient to completely eliminate the impact of cavities on the stability of single piles. Therefore, further optimization of design and construction techniques is necessary for pile foundations in karst areas to ensure engineering safety.

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