Study on the Influence of Karst Size on the Vertical Bearing Capacity of Pile Foundation

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Abstract: Based on the actual project, this paper studies the vertical bearing characteristics of bridge pile foundation in karst area by Marc numerical simulation. The results show that the vertical ultimate bearing capacity of pile foundation has a negative correlation with the size of karst cave. With the increase of span, the bearing capacity of pile foundation and its sub-bearing capacity decrease. When the span of karst cave is 2m × 2m, the ratio of pile side resistance to pile end resistance is 3 : 1. When the cavern span is increased to 12m × 12m, the ratio of pile side resistance to pile end resistance is 9 : 1. Therefore, it is necessary to fully consider the influence of the size of the karst cave on the bearing characteristics of the pile foundation during the construction, and make corresponding engineering disposal measures according to the influence degree of different influencing factors, so as to improve the design and construction effect of the pile foundation.

1. Introduction.
With the extension of highway infrastructure work to the mountainous area, in order to reduce the damage to the mountain ecological environment and avoid landslides and other disasters caused by large excavation, it is inevitable to build a large number of highway bridges in mountainous areas. There are many problems in the construction of highway bridges in karst areas, the influencing factors are extremely complex, the topography and geomorphology along the highway vary greatly, and the engineering and hydrogeological conditions are complex. Therefore, the bearing characteristics of bridge pile foundation under special geological conditions have always been the focus of scholars’ discussion1-3.

At present, scholars at home and abroad have made an in-depth analysis of the bearing characteristics of bridge pile foundation under the steep slope karst terrain geological conditions. Based on the static load test of pile foundation, Feng Zhongju and others discussed the bearing characteristics of pile foundation, and obtained the optimization method of pile foundation design and calculation under different topographic and geological conditions4-6. Zhao Minghua et al established the punching failure mechanism of karst cave floor at the end of pile in karst development area by means of limit analysis principle of theoretical calculation, which provided design reference for bridge...
pile foundation located in karst area\cite{7,8}. Wang Huabin et al analyzed the influence of karst cave roof thickness in karst development area by numerical simulation, and obtained the formula for calculating the safe thickness of karst cave roof\cite{9,11}. Qin Su et al carried out reliability analysis on the stability of karst cave roof by interval analysis theory and structural non-probabilistic reliability measurement method, and obtained the corresponding stability calculation formula\cite{12}.

Based on the bridge pile foundation in the karst development area on the steep slope of Guangna Expressway in Yunnan Province, Marc finite element software is used to analyze the influence degree of different size of karst cave under the pile on the vertical bearing characteristics of the bridge pile foundation. The research results have guiding significance for the design and construction of the pile foundation.

2. General situation of relying on engineering.
This paper relies on the project for the Guangnan to Nasa section of the expressway network S19 from Guangnan to Xingjie in Yunnan Province, which is located in Guangnan County, Wenshan Prefecture, Yunnan Province, and is a section in the planning of the expressway network in Yunnan Province. It is an important channel between Yunnan Province and Guangxi Province, and is of great significance to the construction of highway network in Southwest China. The traffic location is shown in Fig.1 below.

![Fig 1. the site location](image)

After considering the geological conditions, the relationship between pile position and karst, the left 4# pile foundation of Wuchaku No.5 Bridge with typical topographic geological conditions is selected as the specific supporting project for the study. The length of the pile is 23m, the diameter of the pile is 1.8m, the thickness of silty clay in the upper soil layer is 21m, the middle weathered limestone thickness is 24m in the lower bearing layer, the rock-socketed depth of the pile foundation is 2m, and the depth of the underlying karst cave is 26m.

3. Overview of numerical simulation.

3.1. Model establishment and parameter selection.
In this paper, the Marc finite element software is used to simulate the left 4# pile foundation of Wuchaku No.5 Bridge, and the modeling is carried out based on the general situation of the actual project. In order to meet the boundary condition of 8D (D is pile diameter), the diameter of pile is 2m, the length of pile is 24m, the thickness of silty clay in the upper soil layer is 28m, and the thickness of limestone in the lower part is 23.5 m, in which the rock-socketed depth of the pile foundation is 1.5m. By comparing the field investigation data and references\cite{13}, the material parameters of pile body and the surrounding soil model are shown in Table 1. The elastic constitutive relation of pile and the Mohr-Coulomb constitutive relation of soil are used for calculation and analysis. In this example, it is considered that the karst cave is 2m below the bottom of the pile, the slope is 45°, and the size of the karst cave is 6m × 6m × 6m, as shown in Fig.2.
Fig 2. 45° overall section view of the model

| Tab 1. Model material parameters |
|---------------------------------|
| name of the material | Modulus of elasticity $E$ (MPa) | poisson's ratio $\mu$ | cohesive force $c$ (kPa) | angle of internal friction $\phi$ (°) | bulk density $\gamma$ (kN/m$^3$) |
| pile | 30×103 | 0.20 | — | — | 25.0 |
| miscellaneous fill | 10 | 0.25 | 4.5 | 16.2 | 16.0 |
| silty clay | 35 | 0.25 | 18 | 18 | 19 |
| moderately weathered limestone | 850 | 0.25 | 15 | 25 | 23.0 |

3.2. Computational scheme design.
In order to further analyze the vertical bearing characteristics of bridge pile foundation in steep slope karst development area, the design of the following working conditions is carried out based on the actual project of Guangnan Expressway, as shown in Table 2.

(1) size change of karst cave.

| Tab 2. Calculation condition of karst cave size change |
|-----------------------------------------------|
| slope $\alpha$ (°) | pile diameter $D$ (m) | pile length $L$ (m) | cavern span (m×m) | karst cave height (m) |
|-----------------|-----------------|-----------------|-----------------|-----------------|
| 45              | 2               | 24              | 0×0、2×2、4×4、6×6、9×9、12×12 | 6               |

In the case of the change of the size of the karst cave under piles, the vertical bearing capacity of the pile foundation is analyzed. Taking the slope of 45° as an example, the vertical bearing capacity, lateral friction resistance and partial bearing capacity of pile foundation with different karst cave span are studied respectively.

4. Analysis of vertical bearing characteristics of pile foundation under changing size of karst cave under pile

4.1. Analysis of vertical bearing capacity of pile foundation.
(1) variation of karst cave span.

The comparison of P-S curve and bearing capacity reduction of pile foundation under different cave spans is shown in Fig 3. and Fig 4.
From Fig 3. and Fig 4., it can be found that there is an obvious negative correlation between the ultimate bearing capacity of pile foundation and the span of karst cave. The variation range of pile bearing capacity of karst cave span 0m~12m is 14.07 MN ~ 10.09 MN. The reduction of ultimate bearing capacity is 22.17%, 31.71%, 36.80%, 41.98% and 44.51%, respectively (based on the absence of karst). With the increase of the span of the karst cave under piles, the growth rate of the decreasing amplitude of the ultimate bearing capacity decreases gradually. This is because when the span of the cave increases, the soil layer under piles is seriously missing, and there is a stress diffusion phenomenon at the bottom of the pile. When the span of the karst cave increases to the range larger than the stress diffusion angle, the resistance at the end of the pile decreases greatly. Therefore, the ultimate bearing capacity of pile foundation is sensitive to the change of karst cave span.

4.2. Lateral friction resistance of the pile

(1) variation of karst cave span.

When the span of karst cave changes, the distribution law of lateral friction resistance of pile foundation under the load of 30MN is shown in the following figure:

According to figure 5., under different karst cave spans, the pile lateral friction reaches the peak within the range of the bearing layer. In the overburden layer, the pile lateral friction gradually increases with the increase of depth, but the variation range is small. In addition, the change law of pile lateral friction under different spans is roughly similar. This is because the upper load is jointly borne by the pile end resistance and the pile side friction. The increase of the span of the underlying karst cave under the pile causes the serious loss of the soil layer. The bearing capacity of the pile end is greatly reduced, the relative displacement of the pile and the pile side friction increases. Because of the difference of the rock and soil, the pile side friction in the bearing layer is far greater than the side friction in the covering layer.
4.3. Proportion analysis of partial bearing capacity. 

(1) variation of karst cave span. 

The distribution of pile side frictional resistance and pile end resistance with the span of karst cave and the corresponding proportion of pile side frictional resistance and pile end resistance are shown in the following figure:

Fig 6. variation law of the resistance at the lower end and the resistance at the side with the change of the cave height

Fig 7. The ratio of resistance at the lower end and resistance at the side of cave span

From Fig.6 and Fig.7, under the upper load, with the increase of the span of the karst cave under piles, the proportion of lateral friction resistance of the pile foundation of the same slope increases from 72.5% to 88.9%, and the proportion of the pile end resistance decreases accordingly. The results show that with the increase of the span of the karst cave, the lateral friction resistance of the pile plays a major role gradually, and the reason is that the soil layer at the end of the pile is seriously missing with the increase of the span of the karst cave under piles. When the range of the cave span increases beyond the stress diffusion angle, the pile end resistance decreases due to the diffusion effect of the soil at the end of the pile. And when the span of karst cave is more than 2m, the reduction rate of pile side frictional resistance and pile end resistance is relatively smooth.

5. Conclusion.
The main results are as follows:

(1) There is an obvious negative correlation between the ultimate bearing capacity of pile foundation and the span of karst cave under piles; with the increase of span, the bearing capacity and partial bearing capacity of pile foundation decrease, and the lateral friction resistance of the pile plays a major bearing role gradually. When the span of karst cave is 2m × 2m, the pile side frictional resistance: pile end resistance is 3:1; when the span of the karst cave increases to 12m × 12m, the pile end resistance reaches 9:1.

(2) The large karst cave under the pile with the size larger than 6m × 6m × 6m should be paid attention to in the design and construction. It is suggested to increase the pile length so that the pile foundation can be embedded into the stable rock stratum through the karst cave, so as to ensure the stability of the pile foundation.

(3) The important engineering suggestions are as follows: the karst cave under piles with the size greater than 6m × 6m × 6m should be treated specially in the construction. For the pile foundation of the bridge located in the karst development area, the approximate size of the karst cave and the relevant stratum conditions should be first detected by the method of deep geophysical exploration.

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