Study on Vertical Bearing Characteristics of Bridge Pile Foundation in Karst Area Considering the Size

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Abstract. By using finite element software, the influence of different karst cave span on the bearing characteristics of bridge foundation is analyzed. It is found that when other conditions are certain, with the increase of karst cave span, the ultimate bearing capacity presents a decreasing trend, and the lateral friction of pile drops steeply within the range of karst cave and decreases to a greater extent, showing a certain degree of depth effect, and the end resistance proportion also increases. The results show that when the span of the karst cave is more than 9m, the lateral friction resistance within the range of the karst cave of the pile body drops sharply. The research results can further deepen and perfect the design of pile foundation in karst development area and guide the construction, which has certain theoretical significance and engineering application value.

1. Introduction
With the in-depth development of China’s transportation infrastructure construction and the continuous expansion of urban scale, the engineering practice of a large number of highways under construction or planning to cross the steep slope karst development area is becoming more and more common. Because of its high bearing capacity, good stability, small and uniform settlement and other advantages, pile foundation has been widely used in the engineering construction of steep slope karst development areas [1-5].

Due to the lack of soil on the side of pile and the existence of pile body cavity, the bearing characteristics of pile foundation in steep slope karst area are different from those in general areas. At present, many scholars at home and abroad have mainly studied the bearing characteristics of pile foundations in different steep slope karst development areas by means of theoretical analysis, experimental research and field detection [6-10].

Sun yingxia et al. adopted dimensional analysis method and combined with numerical simulation to put forward the change rule of appropriate identification of karst cave stability index, so as to obtain the influence degree of each key parameter on karst cave stability [11].

Zhang junneng et al. used the finite element software DIANA to conduct stage analysis, simulated the gradual plastic deformation and displacement field characteristics of foundation soil during the continuous expansion of karst cave, and summarized the failure mode and mechanism of roof during the development of karst cave [12].
In order to explore the influence rule of underlying karst on bearing characteristics of pile foundation, Xie Shumeng conducted orthogonal numerical simulation test on surrounding rock types by using FLAC3D finite difference software, and discussed the influence of 4 main factors on bearing characteristics of karst cave roof thickness, span, height of karst cave and bedrock types\(^{[13]}\).

Luan Juan et al. carried out finite element numerical simulation by using the contact analysis of pile-soil interface in MIDAS FEA, and calculated and analyzed the influence of loess gully topography and steep slope on the bearing capacity of pile foundation, and summarized the influence rules of slope and slope distance on the ultimate bearing capacity of pile foundation\(^{[14]}\).

However, the above studies are only limited to the analysis of the influence of single factor of karst cave or steep slope on the bearing characteristics of pile foundation, and there are few studies on the comprehensive analysis of the interaction between steep slope and pile foundation, and few theoretical research achievements on the bearing characteristics of pile foundation in the karst development area of steep slope, so it is difficult to effectively guide engineering practice.

In order to deeply explore the bearing characteristics of bridge pile foundation in steep slope karst development area, relying on Guangnan highway in Yunnan Province, this paper studied the effects of karst cave size and steep slope on the bearing characteristics of pile foundation by using Marc finite element numerical simulation software. It has certain theoretical significance and engineering application value to further deepen and perfect the design of pile foundation in the karst development area of steep slope.

2. General situation of the study area

In this paper, the study area is the Guangnan to Nasa section of highway, the highway is located in Guangnan County, Wenshan Prefecture, Yunnan Province, meanwhile through complex geological environment, and there are low mountain and hilly landforms formed by structure and denudation. There are slope skirt formed by slope accumulation at the foothills, valley and basin geomorphology formed by alluvial alluvial deposition in front of the mountain, as well as karst depression, peak forest, peak cluster, slope valley and so on formed by carbonate dissolution. The topographic map of the study area is shown in Fig.1.

![Figure 1. Topographic map of the study area](image)

In order to reduce the influence of steep slope and karst adverse engineering geology on the bearing characteristics of pile foundation, after the comprehensive analysis of the field geological prospecting data, the relevant references and the relative position relationship between pile foundation, karst cave and steep slope, the typical no.5 pile foundation of Wuchaku No. 3 Bridge is selected for research, as shown in Fig.2.
3. Finite element numerical simulation

In order to explore the influence of bearing characteristics of bridge pile foundation in steep slope karst development area, Marc finite element software was used to design numerical simulation experiment.

3.1. Establishment of finite element model

Space considerations

Through the actual stress analysis of the bridge pile foundation of Guangna highway, the finite element calculation model is established. The pile diameter is 2.0 m, the pile length is 24 m, and the layer thickness is divided as shown in Fig. 3.

3.2. Model constitutive and parameter selection

In the model, the pile adopts the ideal elastic constitutive model, the foundation soil adopts the elastoplastic model, and the slightly weathered rock adopts the elastic model for analysis. The yield criterion is Mohr-Coulomb. According to the field investigation and geological survey report, the strata in the region where the pile is located are divided into: miscellaneous fill, silt clay, moderately weathered limestone and so on. The calculation parameters of various materials are shown in Table 1.

Table 1. Material parameters

| Material name                  | Elastic modulus $E$ (MPa) | Poisson's ratio $\nu$ | Cohesive $c$ (kPa) | Internal friction angle $\phi$ (°) | Bulk density $\gamma'$ (kN·m$^3$) |
|--------------------------------|--------------------------|-----------------------|--------------------|-----------------------------------|-----------------------------------|
| Pile (concrete)                | $3.0 \times 10^4$        | 0.20                  | —                  | —                                 | 25.0                              |
| Miscellaneous fill             | 10                       | 0.25                  | 4.5                | 16.2                              | 16.0                              |
| Silt clay                      | 35                       | 0.25                  | 18                 | 18                                | 19                                |
| Moderately-weathered limestone | 850                      | 0.25                  | 15                 | 25                                | 23.0                              |
3.3. Boundary conditions and calculation conditions

The bearing capacity of pile foundation is affected by many factors due to the fact that the karst area of steep slope passes through many strata. This paper mainly analyzes the influence of the change of the different size of pile karst cave on the vertical bearing characteristics of pile foundation.

In the calculation of the model, horizontal constraints are applied to the x and y directions, vertical constraints are applied to the z direction at the bottom, and free surface is unconstrained at the top.

After referring to the relevant literature and the field geological prospecting report, the numerical simulation tests are carried out by selecting typical influencing factors: cave span. The test scheme is shown in Table 2.

| Karst cave position (°) | Analyzing factors | Influencing factors |
|-------------------------|------------------|--------------------|
| Pile diameter (m) | Pile length (m) | Karst cave size (m) | Karst cave span |
| pile body | 45 | 2 | 24 | No karst cave, 2×2×4, 4×4×4, 6×6×4, 9×9×4, 12×12×4 |

4. Results and analysis

Based on the single variable method, the influence of various factors on the bearing characteristics of pile foundation is discussed by using Marc numerical simulation software, and the P-s curve and pile side resistance are obtained.

4.1. Sensitivity analysis of karst cave in pile body

4.1.1. Analysis of influence of karst cave on bearing characteristics of pile foundation

When the span of karst cave changes from 0m to 12m, the P-s curve of karst pile foundation is shown in Fig.4.

From the figure above, we can see that the law of P-s curve is basically similar. Under the conditions of different karst cave span, the ultimate bearing capacity of the pile foundation is 22.60MN, 22.02MN, 21.52MN, 20.78MN, 20.23MN and 19.80MN respectively, and the reduction of the ultimate bearing capacity is 2.61%, 4.99%, 8.76%, 11.67% and 14.12% respectively (based on the absence of karst caves), as shown in Fig. 5.
The fundamental reason for this phenomenon is that with the increase of the span of the karst cave, the lack of rock and soil on the side of the pile will lead to the settlement deformation of the roof rock mass and reduce the bearing capacity of the pile foundation.

Compared with the change of karst cave span, the bearing capacity of pile foundation is more sensitive to the change of karst cave height.

4.1.2. Analysis of the influence of karst caves on pile lateral friction resistance

Take the slope of 45° and the loading of 30MN on the top of the pile as an example. With the gradual increase of the karst cave span from 0m to 12m, the variation curve of the lateral friction resistance under the condition of different karst cave span is shown in Fig.6. The specific analysis is as follows:

Under the condition of different span of karst caves, the pile lateral friction resistance increases slowly in the range of cover layer and presents a certain depth effect. After entering the bearing layer, the lateral friction resistance starts to increase. As the pile foundation passes through the karst cave, the lateral friction resistance drops sharply and then slowly increases. When the pile reaches the bearing layer, the lateral friction resistance rises sharply.

The reason for this phenomenon is that the strength of the overburden soil layer is weak, and the lateral friction resistance is mainly provided by the bearing layer. When the span of the karst cave is less than 2m, the existence of the pile karst cave has little influence on the lateral friction resistance. When the span of the karst cave is more than 9m, the lack of rock and soil on the pile side is obvious, and the obvious settlement deformation of the roof rock mass leads to the significant reduction of the lateral friction resistance of the pile karst cave. Therefore, the emergence of large-span karst on the pile body should be paid special attention in the construction process.

5. Conclusions and recommendations

According to the field exploration data, the reasonable constitutive model and related parameters are determined, and the representative design schemes of 6 kinds of span are selected. The effects of the
size of karst cave and the slop of steep slope on the bearing characteristics of pile foundation are studied systematically. Draw the following conclusions and recommendations:

(1) When other conditions are certain, with the increase of the size of karst caves, the variation law of P-s curve is basically similar, and the bearing capacity shows a decreasing trend. The larger the size of the karst cave, the larger the range of pile lateral friction resistance reduction, the smaller the pile lateral friction resistance provided by the soil around the pile, and shows a certain depth effect. When there is a karst cave in the pile, the proportion of tip resistance increases sharply. with the increase of the size of the karst cave, the proportion of tip resistance also increases.

(2) In engineering design, when there is a karst cave in the pile body, the influence of failure pile length on the bearing characteristics of the pile foundation should be considered. In particular, when the span of the cave is larger than 9m, it has a significant effect on the bearing characteristics of the pile foundation. Therefore, it can be considered to add steel casing to the pile foundation or carry out grouting on the karst cave of the pile body to improve the bearing capacity of the pile foundation.

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