Research progress in foundation pit engineering in karst area

Xiaogang Zhang, Chao Zheng, Shuxiang Song

Guangzhou Environmental Services Co., LTD., Guangzhou 510000, China

Abstract. Based on the stability problem of foundation pit engineering in karst area, this paper will introduce the stability of foundation pit engineering in karst area from theoretical research, model testing, and numerical analysis. On the basis of summarizing previous work and combining with the latest research results, this paper explores the impact of support forms on the stability analysis of foundation pit engineering in karst area, and summarizes the main influencing factors of foundation pit engineering stability in karst area, including the uncertainty of karst cave, unevenness of rock foundation, and underground water flow in underground river.

Keywords: Karst; Foundation pit engineering; Theoretical research; Model testing; Numerical analysis; influence factor.

1. Introduction

Karst is a geological process in which water primarily causes chemical dissolution of soluble rocks, supplemented by mechanical actions such as erosion, subsurface erosion, and collapse by flowing water, and the phenomena resulting from these actions. The landform caused by karstification is called karst landform. China is one of the countries with the widest karst distribution area in the world, with a distribution area of approximately 3.65×107 km2, exceeding one-third of China's national territory. China has many mountain ranges and highly developed mountain systems, corresponding to a wide range of limestone and a large area, often resulting in geological situations such as karst cave. Therefore, there are many area with karst cave. In addition to the two major karst plateaus with Shanxi in the north and Guizhou in the southwest as the center, the karst in South China and Southwest China is also widely distributed in 23 provinces and regions in China, with Guangxi, Sichuan, Yunnan and Guizhou being the most common [1,2]. Figure 1 shows the distribution of karst in certain regions of China.

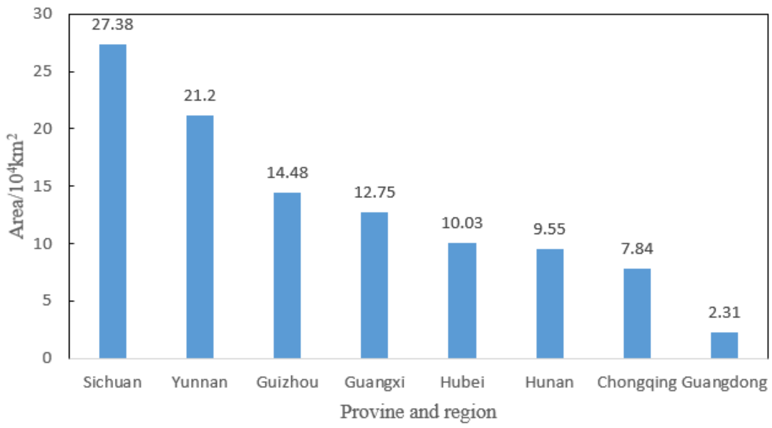


Fig. 1 Statistical Map of karst distribution in some provinces of China

In the past, due to the small scale of buildings, the depth of foundation pit engineering was generally within 5m. For the current high-rise large buildings, such excavation depth is not enough. Especially in karst area, it is often necessary to excavate deeper foundation pits, and discuss the support and support stability. Deep foundation pits will produce corresponding geological disasters due to karst problems, mainly in the form of foundation pit water gushing, settlement and collapse, tunnel water gushing, foundation pit support instability, slope instability, support pile cracking and groundwater erosion in some projects in karst area. Therefore, the problem of karst stability has become a prominent problem in the construction of foundation pit engineering. In order to carry out the engineering construction smoothly, we must solve the influence of karst on foundation pit engineering.

Due to the complexity of geological condition in karst area, it brings greater challenges to the selection of support forms and stability analysis of foundation pits. The different support forms cause great differences in the research results of foundation pit stability, and the theory and technology needed to be used are also getting higher and higher [4]. In view of this, scholars at home and abroad have carried out a lot of research on the stability analysis of foundation pit under Karst conditions, mainly focusing on different supporting structures, theoretical research, model test and numerical analysis.

2. Analysis and research method of foundation pit stability under Karst condition

Due to the uncertainty of karst cave, the unevenness of rock foundation, underground rivers and other underground instability factors in karst area, the stability of foundation pit engineering in karst area often appears different problems [5, 6]. In depth study of the influence of karst cave on the stability of foundation pit in karst area will help to get a better design scheme from the design stage and promote the development of construction technology in karst area. Scholars at home and abroad have done a lot of research on the influence of karst cave on the stability of foundation pit in karst area, including theoretical research, model test and numerical simulation.

2.1 Theoretical research

So far, the stability research of foundation pit engineering in karst area has been relatively mature [7-11]. In 1996, George Sowers [12] wrote “Building on Sinkholes: Design and Construction of Foundation in Karst Terrain”, which introduced the design and construction of foundation in karst area in a relatively complete way. In 2004, Tony Waltham et al. [13] wrote “SINKHOLES and SUBSIDEENCE: Karst and Cavernous Rocks in Engineering and Construction”, which comprehensively introduced the Karst Treatment in karst area. In 2005, He et al, [14] coauthored the first treatise on karst collapse in northern China, karst collapse in northern China, which collected a large number of practical engineering cases in karst area north of the Huaihe River, and analyzed the formation process of karst collapse. In 2006, Liu [15] compiled the book "influence of karst cave and soil cave on building foundation in karst area", which systematically summarized the construction treatment methods of karst cave in various construction cases when encountering karst at that time, and put forward a series of quantitative calculation methods and formulas for foundation stability and pile foundation safety.

Liu et al. [16] combined with Terzaghi's loose soil pressure theory and BOTDR technology to carry out the scheme design for the monitoring of soil cave in karst area, which can analyze the stability of soil cave and predict the development trend of soil cave, and provide reference for engineering design. Cao et al. [17] used a new measurement method to evaluate the safety of the underlying karst cave roof based on the information gap theory. This method is less affected by uncertain parameters and is suitable for projects lacking sufficient sample quantity and information. Jiang et al. [18] considered the suddenness of karst cave roof fracture phenomenon, introduced the initial fuzzy membership function on the basis of catastrophe theory, and established a structural model for roof stability evaluation considering catastrophe in rock. Zhao et al. [19] used the upper bound finite element method to calculate the upper bound solution of the pile end bearing capacity of rock socketed piles, and then transformed the parameters such as roof thickness, span, internal friction angle and analyzed their influence laws.

At present, when encountering karst cave, karst ditch and other karst bodies, it is only necessary to avoid or take certain structural measures to ensure the stability of the foundation, but there is no quantitative design and calculation method. Most of the existing research results are aimed at the stability of vertical bearing piles in karst area, and the stability of foundation pit supporting piles in karst area and the effect of karst cave treatment on supporting piles have not been studied in depth.

2.2 model test

The underground conditions in karst area are complex and have different shapes. The existing theoretical research is mainly based on a series of strength failure criteria, which have certain assumptions. The conclusions based on the idealized model are difficult to be accurately applied in practical engineering. In contrast, the model test can indirectly reflect the stability change process and law of foundation pit engineering in karst area. Model test refers to the corresponding test conducted on a scaled down or proportional model.

Li [20] based on the foundation pit slope engineering of a building in karst area, studied the deformation and stability behavior of the building slope with karst cave through model test, taking two kinds of slope sections with karst cave as the prototype. Nie et al. [21] used cement, sand and water to simulate bedrock, and built a 1.25m×1.25m×0.625m scale semi symmetrical model box, the 3D karst cave under the pile foundation is simplified as a rectangle, and the results show that the failure mode of the roof is punching failure. Zhang et al. [22] took the Fangchenggang steel raw material plant construction project as the test site, and conducted three groups of DX rock socketed piles with a total of 18 piles and model tests of straight hole rock socketed piles. The model test data were compared with the field static load test, and further analyzed the load transfer characteristics and bearing mechanism of the two kinds of rock socketed piles. The results showed that the performance of DX rock socketed piles was better than that of straight hole rock socketed piles. Based on the similarity theory, Wu et al. [23] designed three groups of large-scale indoor model tests on the failure forms of karst cave roof under the condition of different thickness, analyzed the failure forms of karst cave roof under various thickness, and established the calculation formula of the minimum safe thickness of karst cave roof based on this combined with the theoretical calculation method. Lei et al. [24] classified the roof with underlying karst cave as a punching body, respectively assuming that the punching body is a cone and a rotating body to obtain the ultimate bearing capacity of the karst cave roof, and designed a small indoor model for comparison and verification. The results show that when the roof thickness is 1D-3D, the rotating body punching failure occurs; At 4D, it is tearing + punching composite failure; At 5D, it is plastic failure. At 5D, the bearing capacity of the roof is basically equal to that of the solid bedrock.

Using suitable materials to simulate bedrock and karst cave for model test is a relatively low cost and can be simulated to the failure stage. It is a relatively economic research method. However, in the stage of selecting simulation materials, it is necessary to select materials with similar mechanical properties to rocks to obtain more similar results with the engineering site.

2.3 Numerical analysis

With the development of numerical calculation technology, numerical simulation software has been widely used in foundation pit engineering in karst area. The operation principle of the software mainly includes finite element method, finite difference method, discrete element method, finite volume method, finite quadrature element method, simplex method, meshless method, etc. the commonly used numerical analysis software includes Midas GTS, FLAC3D, ADINA, PLAXIS, etc. With the help of these numerical simulation software, scholars at home and abroad have achieved a lot of meaningful results in the field of foundation pit engineering in karst area.

Wang et al. [25] used Roclab Software to establish a three-dimensional numerical model to conduct sensitivity analysis and Research on the span, height and thickness of overlying soil layer of karst cave. The results showed that the sensitivity of rock mass strength, roof thickness, upper soil thickness, karst cave span and karst cave height to the settlement of pile foundation was from strong to weak. Huang et al. [26] studied the influence of beaded karst cave distribution on the bearing capacity of pile foundation by using the technical means of PLAXIS 2D and ABAQUS. The results showed that under the influence of pile lateral friction, the failure mode of roof was mainly punching shear failure when the ratio of roof thickness and karst cave span was small, and punching shear failure when the ratio was large. Feng et al. [27] used Marc finite element software to build a three-dimensional numerical simulation of a highway in a karst area for parameter analysis. The results showed that with the increase of karst cave span, the ultimate bearing capacity of pile foundation decreased significantly, while the pile side friction also decreased significantly in the karst cave area, the proportion of end resistance increased, and showed a certain depth effect. Xiao et al. [28] based on the modified Hoek Brown criterion and the upper and lower limit theorem of limit analysis, used Matlab to compile the corresponding numerical model to analyze the double pile foundation of bridge in karst cave area. The results showed that with the increase of the load of the overlying soil layer and the rock socketed depth, the ultimate bearing capacity of the double pile foundation increased; The increase of GSI can also make the ultimate bearing capacity increase nonlinearly; The rock gravity can improve the ultimate bearing capacity within a certain range, but when the double piles are close to the karst cave, the influence of gravity is not significant. Taking the pile foundation construction of transmission tower in a karst area in Guangdong as the engineering background, Hua et al. [29] established a numerical model using FLAC3D to study the deformation law of pile foundation and underlying karst cave; The results show that the surrounding rock stress around the karst cave is sensitive to the upper load, which is prone to stress concentration and failure; Different rock socketed depths affect the overall shape of the cave to a certain extent, and the influence law is positive. Based on a bridge project, Wang et al. [30] conducted modular treatment of karst cave in karst area, carried out numerical analysis of the influence of karst cave on the strength of super long-span pile foundation, and deeply studied the influence of roof span, depth and thickness on the horizontal and vertical bearing capacity of pile foundation.

Numerical simulation software is used to study and analyze the influence of the spatial location, size, height, bedrock strength, rock quality, different embedded depth and other factors on the roof bearing capacity. The main factors affecting the sensitivity are: cave size, roof thickness, cave span, rock and soil strength, etc. At present, most of the research is to use the two-dimensional numerical model to simulate the stability of karst cave and supporting piles for analysis and research, but the two-dimensional numerical simulation can't accurately consider the spatial effect of karst cave, and at the same time, there is a lack of in-depth research in the current measured analysis.

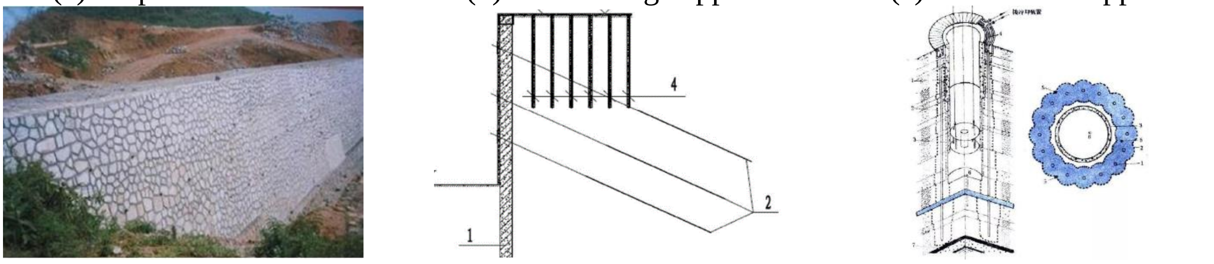
3. Supporting structure of foundation pit engineering under Karst condition

3.1 The common supporting structures of foundation pit engineering

The supporting form of foundation pit has very important significance in the construction of foundation pit engineering. Especially for the support of deep foundation pit in karst area, the best support scheme for deep foundation pit in karst area can be selected through selection and comparison. China has a vast territory, different geological conditions exist in different area, and the difference is also large. After decades of development of foundation pit engineering in China, a variety of different, distinctive foundation pit support structure forms have been formed, which has its applicability in different area. The form of supporting structure is often selected according to different working conditions on site, combined with actual construction conditions, site conditions, soil layer conditions, excavation depth, economy and environment.

Supporting forms are divided into sloping excavation, soil nailing support, cantilever support, cement-soil gravity support, anchor bolt support and artificial freezing method according to different supporting principles and different supporting systems. As shown in Figure 2.

(a) Slope excavation (b) Soil nailing support (c) Cantilever support



(d) Cement-soil gravity support (e) Anchor bolt support (f) Artificial freezing method

Fig. 2 Schematic diagram of common support structure

3.2 The common supporting structures of foundation pit engineering under karst condition

The characteristics of foundation pit engineering in karst area: (1) The geological conditions of foundation pit are relatively complex, mostly the upper covering soil layer, and the lower part is the soluble rock layer; (2) The foundation pit is prone to destabilization. In addition to the sliding failure of the rock-soil interface and the failure of the upper soil body, the destabilization of the rock mass will also cause the sliding failure of the rock layer (or the whole), the block failure, etc., which increases many unpredictable factors for the stability of the foundation pit; (3) Due to the uniqueness and complexity of karst, it is difficult to find out the distribution law of karst water, which increases the difficulty of foundation pit dewatering. In the later period, if the karst water level rises or the excavation depth continues to increase, the karst water will have different degrees of impact on the stability of the foundation pit; (4) The selection of foundation pit support is very difficult to determine, and the cost of foundation pit support is relatively high. The instability mechanism of foundation pit engineering in karst area is complex and the failure forms are various. Therefore, it is often difficult to select the supporting structure of foundation pit.

Foundation pit engineering support in karst area is mostly combined support. Combined support refers to two or more different foundation pit support forms in karst area. Combined support can be divided into two types, one is different depth, select different types of upper and lower combined support system, that is, longitudinal combined support; The other type is the combined support with different types at different positions in the same plane, i.e. the combined support in the horizontal direction. The common foundation pit supporting structures in karst areas include row pile (supporting pile) + internal support and pile + anchor support, as shown in Figure 3.

(a) Row pile (supporting pile) + internal support (b) Pile + anchor support

Fig. 3 Schematic diagram of combined support structure in karst area

4. Conclusion and prospect

The influence of karst environment on foundation pit engineering is very complex. This paper introduces the research method of stability of foundation pit engineering in karst area, and summarizes the supporting structure of foundation pit engineering in karst area. The conclusions are as follows:

(1) The stability research methods of foundation pit in karst area include theoretical research, laboratory test and numerical analysis. The design and construction of foundation pit in karst area are summarized through theoretical study; The stability process and law of foundation pit engineering in karst area under different supporting conditions and different karst environment are obtained through model test; Through numerical analysis, the influence of spatial location, size, height, bedrock strength, rock quality and different embedded depth of karst cave on roof bearing capacity is analyzed.

(2) Common supporting forms of foundation pit engineering include sloping excavation, soil nailing support, cantilever support, cement-soil gravity support, anchor bolt support and artificial freezing method; The foundation pit engineering support in karst area is mostly combined support, and the common combined support forms include row pile (supporting pile) + internal support and pile anchor support.

(3) The main factors affecting the stability of foundation pit in karst area include: uncertainty of karst cave, irregularity of rock foundation, underground river and underground flow of groundwater.

Through the research, the following points are found and proposed: (1) The stability analysis theory of foundation pit engineering in karst area has been deeply and systematically studied on the basis of the previous efforts, but the stability of foundation pit supporting piles in karst areas and the influence of karst cave treatment effect on supporting piles have not been deeply studied, and there is no quantitative design calculation method, there is still huge research space on the influence of supporting piles in karst areas; (2) Some scholars adopt model test for research, which is a relatively economical research means, so what kind of material should be selected to make it more similar to the rock material, so as to obtain the results more similar to the project site; (3) At present, most of the researches are based on 2D numerical model to simulate the stability of karst cave and supporting pile. However, 2D numerical model cannot accurately consider the space effect of karst cave, and there is no in-depth problem in the current measurement analysis.

In a word, it is hoped that this study can provide some theoretical basis and guidance for the future foundation pit engineering in karst areas.

References

[1] Yuan Daoxian, Zhu Dehao, Weng Taojin, et al. Karst of China[M]. Beijing: Geology Press, 1994, 18 -36.

[2] Cao Huqi. Study on Karst Detection、Disaster Prevention and Treatment technology in Tunnel[D]. Chang’an University, 2021.

[3] Li Yuze. Brief discussion on the key points and development trend of modern high-rise building design[J]. House, 2018(33): 11.

[4] Yang Chunbo. Research on Optimization Design and Application of Deep Foundation Pit Support Scheme[D]. North China University of Water Resources and Electric Power，2018.

[5] Shen Bin. Research on Stability of the Pile Foundation in Karst Areas[D]. Guangxi University, 2006.

[6] Yi Jianhui. Research on Stability of the Pile Foundation at Overburden-karstic Free Face[D], Guangxi University, 2007.

[7] Lin Zongyuam. Geotechnical engineering governance Manual[M]. Beijing: China Architecture & Building Press, 2005.

[8] Ministry of Construction of the People's Republic of China. GB 50021-2009 Code for geotechnical investigation [S]. Beijing: China Construction Press, 2009.

[9] Fang Qiuyan，Han Jiayong，Chen Feiyu. The Stability Analysis of Overburden-karstic Free Face[J]. Journal of Guangxi University (Natural Science Edition) [M], 2004(04): 342-345.

[10] Li Bin, Fan Qiuyan, Qin Fengrong. Analysis on Roof Stability of Karst Cave in Karst Areas. Chinese Journal of Rock Mechanics and Engineering, 2002(04): 532-536.

[11] Chen SX, Xu XC, Dai ZJ, Xu HB. Numerical Study on the Stress of Pile Foundation Influenced by the Beaded Karst[C]. Proceedings of the 6th International Conference on Information Engineering for Mechanics and Material, 2016, 97: 475-479.

[12] Sowers G F. Building terrain[M]. ASCE Publications, on sinkholes: design and construction of foundations in karst, 1996.

[13] Waltham T, Bell F, Culshaw M. Sinkholes and Subsidence: Karst and Cavernous Rocks in Engineering and Construction[J]. Engineering Geoscience, 2005,11(2):180.

[14] He Keqiang, Wang Bin, Du Rulin, Karst collapse in north China [M]. Beijing: Geology Press, 2005.

[15] Liu Zhikui, Liang Quancheng. The Influence of karst cave and soil cave on building foundation in karst area [M]. Beijing: Geology Press, 2006.

[16] Liu Yongli, Guan Zhende, Xiao Henglin. Monitoring and analysis of deep buried karst soil caves based on BOTDＲ technology [J]. Carsologica Sinica, 2018, 37(03): 427-432.

[17] Cao Wengui, Li Yuan, Zhai Yongcheng. Active Analysis Method for Stability of Karst Roof Under Foundation Pile Based on Info-Gap Theory[J]. Chinese Journal of Rock Mechanics and Engineering, 2013,32(02): 393-400.

[18] Jiang Chong, Zhao Minghua, Cao Wengui, Liu Xiaoping. Research on Stability Evaluation Method for Cave Roof under Pile Tip in Karst Region Based on Fuzzy Theory and Catastrophe Theory [J]. Journal of Highway and Transportation Research and Development, 2008(12): 49-53.

[19] Zhao Minghua, Lu Xiaoming, Zhang Yue. Upper bound finite element method for ultimate bearing capacity and failure mechanism of subgrade above void[J]. Rock and Soil Mechanics, 2017, 38(01): 229-236.

[20] Li Dajian. Study on the deformation and stability characteristics of slope containing vugs[D]. Hunan University of Technology, 2016.

[21] QINGKE N, XILAI L, WEI Y, et al. Calculation Method for the Critical Thickness of a Karst Cave Roof at the Bottom of a Socketed Pile[J]. Advances in materials science and engineering, 2021,2021: 1-11.

[22] Zhang Dehua, Guo Peng. Model Tests Study of Bearing Mechanism of Rock-Socketed DX Pile[J]. Journal of Disaster Prevention and Mitigation, 2018, 38(4): 684-692.

[23] Wu Gaoqiao. The research of karst area rock socketed pile vertical bearing mechanism and test method [D]. Hunan University, 2018.

[24] Lei Yong, Yin Junfan, Chen Qiunan, Yang Wei. Experimental Study on Bearing Capacity of Ｒock-Socketed Pile over Karst Cave[J]. Mining and Metallurgical Engineering, 2017,37(03): 19-22.

[25] Wang Hualao, Zhang Peng, Li Ning. Research on Influence of Concealed Karst on Bearing Capacity of Top Plate of Highway Tunnel[J]. Journal of Highway and Transportation Research and Development, 2010, 27(02): 91-96.

[26] Huang Ming, Zhang Binqi, Chen Fuquan, Huang Zhijing, et al. Numerical Calculation on Load Transfer Progress of Pile Foundation in Beaded Karst Cave Stratum[J]. Journal of Engineering Geology, 2017, 25(06): 1574-1582.

[27] FENG Z, CHEN J, HE J, et al. Study on Vertical Bearing Characteristics of Bridge Pile Foundation in Karst Area Considering the Size[J]. IOP conference series. Materials Science and Engineering, 2020,780(2): 22003.

[28] Xiao Yao, Zhao Minghua, Zhang Yue, et al. Finite Element Limit Analysis of Bridge Double-Piles Foundation in Karst Areas[J]. Journal of Engineering Geology, 2019, 27(04): 923-932.

[29] Hua Shuai. Numerical simulation research on the stability of transmission towerpile foundations in a karst area of Guangdong Province [J]. Carsologica Sinica, 2014, 33(01): 44-50.

[30] WANG P, DING H, ZHANG P, et al. Influence of Karst Caves at Pile Side on the Bearing Capacity of Super-Long Pile Foundation[J]. Mathematical problems in engineering, 2020,2020: 1-13.