Geological Disaster Survey and Treatment Strategies of Yingwanzhen Subway Station, Changsha

Chenguang Zhang1*, Daohan Zha2, Hongxia Zhou3, Xiangwei Tang1, Kuisong Liu1, Junfan Bao3, Yong Zhang3, Hai Peng Hu4 and Haidong Jiang5

1 College of Geographic Science, Henan Key Laboratory for Synergistic Prevention of Water and Soil Environmental Pollution, Xinyang Normal University, Xinyang, Henan, 464000, China
2 Hunan Key Laboratory of Land Resources Evaluation and Utilization, Changsha, Hunan, 410007, China
3 No.3 Institute of Geological & Mineral Resources Survey of Henan Geological Bureau, Xinyang, Henan, 464000, China
4 Hunan Geology Exploration Institute of China Chemical Geology and Mine Bureau, Changsha, 410004, China
5 Institute of Resources and Environmental Engineering, Guizhou University of Technology, Guiyang, Guizhou, 550003, China

*Corresponding author’s e-mail: paladin@xynu.edu.cn

Abstract. In order to solve such problems as ground subsidence, water and mud bursting and shield machine foundering in subway construction which are caused by water-rich karst geological conditions, complete technological process is establishe to detect and treat karst in urban areas. The occurrence of natural electric field frequency selection method and groundwater determine groundwater occurrence vector that karst and fault fracture zone, and make use of the grouting technology of karst fracture with the treatment. The construction of Yingwanzhen Station on Changsha Metro Line No. 4 proves the favorable effect of the detection technology and treatment measures, which provides experience and reference for the construction of Changsha subway and underground engineering in other cities with water-rich karst areas.

1. Introduction

The construction speed of China’s subways is staggering. By the end of 2019, more than 140 subways were constructed in 33 cities across the country, with a mileage of 4,600 kilometers. However, Wang Mengshu, an academician of Chinese Academy of Engineering, once pointed out that the cost of building subway in China (RMB500-800 million per kilometer) is much higher than that of foreign countries. Extensive construction and lack of refined management are among the main reasons. The detection and treatment of water-rich karst region and fault fracture zone has been an unavoidable problem that ran through the construction of Changsha subway[1][4]. Currently drilling and geophysical exploration are mainly adopted in detecting karst and fault fracture zone both home and abroad[5][7]. Nevertheless, drilling exploration has high cost and low speed, while geophysical exploration has low precision despite high efficiency, and it fails to accurately detect the footwall locations and scale.
parameters of karst caves\cite{8-12}. It’s particularly difficult to detect karst caves and fault fracture zones beneath architectural complex, which poses great risk to the treatment and construction\cite{13-16}. In conclusion, conducting research on key technology of new detection methods and comprehensive treatment in water-rich karst zones and fault fracture zones will provide theoretical basis and empirical data as well as complete set of technologies for subway design and construction. Moreover, it will offer guidance for the security and efficiency of subway construction, which has important theoretical and practical significance.

2. Geological Background

Based on the section from Yingwanzhen station to Fubuhelu station on Changsha subway No. 4 line, the underlying strata is devonian limestone stratigraphy, in which, the probability of encountering karst caves when drilling ranges from 11.3\% to 53.8\%, the line karst rate is 2.46\%~23.74\%>20\%, and the karst caves are semi-filled or fully filled (the filling substance is mainly gravels and cohesive soil, while some karst caves has no filling substance, and the karst is fairly developed). With the height ranging from 0.5m to 10.0m, the karst caves are mostly located within the scope of the subway structure and the scope influenced by the footwall or roof of subway tunnel (as is shown in Fig. 1). The section is affected by Erliban structural fracture, so the joint fissures of rock masses around the unconformity contact zone are quite developed, severely broken, with abundant groundwater, while karst, fissure water and river water intercommunicate with one another. There is soft-hard alternating and broken fault breccia in part of the section. The unfavorable geology may cause such construction accidents as ground collapse, tunnel collapse, water burst, mud burst, and shield machine foundering, which pose threat to the security of subway construction.

![Figure 1. The geological profile of the Yingwanzhen station on Changsha subway No.4 line](image)

3. Karst Exploration

3.1. Drilling Prospecting

Drilling prospecting is the fundamental means in exploring the geological disasters in karst areas, so hole-drilling distributing method is adopted to further investigate the karst zone around the subway stations.
The enclosure structure, advanced borehole of single-pile foundation, and probe-holes of foundation pit and basement are shown in Fig. 2a-2f. Based on detailed prospecting, drilling sites are arranged closely. For example, within the range of 3 meters around the boreholes in the exposed karst caves, supplementary boreholes should be arranged in quincunxes with the distance no more than 2
meters. When karst caves are exposed by supplementary boreholes, more boreholes should be supplemented in the void area overlapped by foundation pit within the range of 2 meters around the exposed boreholes. The subsequent hole-drilling should be arranged cyclically in this way. When advanced drilling reaches 5 meters deep in medium/slightly-weathered rock masses under the foundation pit, the drill has to penetrate karst caves if it meets them; if the basement doesn’t reach the bedrock, the drill should reach 10 meters deep under the basement; when there are special geological conditions like dissolution grooves and fracture zones, then end-hole standard is that drill should be taken 1 meter deeper within the treatment area based on the buried depth and groundwater properties. As for those special conditions like large-diameter karst caves, channelings, fluid bowls, fracture zones (including collapsed karst sections), etc., corresponding exploration ought to be carried out according to the practical conditions.

3.2. Exploration via Natural Electric Field Frequency-selection Method

Common geophysical exploration methods are unable to obtain such information as footwall locations and scale parameters of karst caves, and karst caves and fault fracture zone serve as the main carrier and flow path of stored groundwater. Consequently, direct karst cave exploration is replaced with natural-electric-field-frequency-selection method to detect the aquifer information (i.e. the stratigraphic horizon, water content, distribution, strike, etc.), so as to indirectly grasp the spatial distribution and scale of karst caves and fault fracture zone. With the subject as the unfavorable geological bodies (i.e. karst, fault fracture zone) and groundwater in the section from Yingwanzhen station to Fubuhelu station on Changsha subway No. 4 line, this research conducts numerical analysis, model test, on-site detection, and on-site experiment to probe into the detection and treatment of karst and fault fracture zone as well as groundwater. Moreover, this research also establishes a comprehensive evaluation system of their influence on the construction of subway tunnels and stations. In this way, it is expected to develop the technologies of detecting and comprehensively treating karst and fault fracture zone as well as groundwater.

4. Research on Technologies of Karst Disaster Evaluation and Treatment

The construction site in this subway station has very complicated geological conditions, e.g., karst development is quite intense; several bottom plates are located in karst caves; karst is exposed in part of the station area (occurrence rate is 70.59%); karst water has direct hydraulic connection to the upper phreatic water and the water of Xiangjiang river. Besides, if the foundation pit is dug excessively deep, soil flow may happen in foundation pit, and groundwater may gush out from corrosion fissures. All these result in great construction difficulties and high risks. Therefore, in order to stabilize the basement when digging foundation pit, some measures are taken as treatment, i.e., filling and sealing the holes and fissures, pressure grouting, etc.

Prior to the construction of enclosure structure, advanced geological drilling is conducted to explore the covered karst in the enclosure structure. The results will sent to be analyzed by those units of design, geology, supervision, construction and owner, then proper treatment should be done if necessary. When groundwater in the site has favorable connection to Xiangjiang river, and bottom plate of the station is located in soft and thin soil stratum, bottom plate uplift and inrush may occur in case of high water head of Xiangjiang river. Correspondingly, such methods as pressure grouting, or rotary jet grouting, cement mixing are adopted to treat the loose stratum.

Karst area is explored to obtain its distribution locations, and in-door tests are conducted to simulate the reinforcement effect of karst area, which will be applied in on-site construction.

4.1. Grouting Hole Arrangement

Engineering quantity should be considered when grouting is carried out in karst cave test area. Grouting holes are arranged in square form, with average distance as 2.0 meters, effective grouting radius as 1.2 meter, grouting holes approximately 21 meters deep, and the amount of grouting holes are about 4 per cave. In each area, grouting is carried out in accordance with I, II, III, IV, in which hole
II and III can detect the grouting diffusion radius of I. The borehole in the center is the inspection hole (as is shown in Fig.3).

4.2. Grouting Hole Depth
As to fully-filled karst caves, grouting is carried out in one time, i.e., choking plug is set in medium-weathered marlomite in the roof of caves, grouting depth is set at 15m~20m of the boreholes. For semi-filled karst caves, first step is to adopt grout with slow fluidity and low water-cement ratio (or paste-slurry, which is chosen according to the test) to conduct backfill grouting, in which the key is to control the diffusion range. Grouting in this stage should be focused on those key areas. After the intensity reaches the design standard, hole should be drilled 21 meters deep, then grouting goes on, with grouting depth being 13~21m.

![Figure 3. Diagram of grouting borehole arrangement in karst area](image)

4.3. Research on Parameters of Grouting Technology
As for grouting treatment of tunnel karst, grout should meet these requirements: proper fineness of particles so as to fill the tiny fissures of rock masses; certain stability and low syneresis rate so as to prevent solid particles from premature precipitation (which may affect the continuous grouting); favorable fluidity with proper viscosity so as to enable the diffusion of grout. Moreover, the stone resulted from filling grout into rock fissures must be dense and uniform with favorable anti-seepage, stability, durability, intensity, viscosity, and resistant to dissolution and destruction. The density, viscosity and fluidity of backfill grout should be investigated particularly, so that the grout may have necessary diffusion radius and certain intensity.

Cement-silicate grout (adding other admixture if necessary) has controllable gel time, and grouting materials could solidify rapidly to such a degree as to seal fissures. When grouting, grout formula should be adjusted on the basis of stratum in the test area, grout hole depth, grout sequence and locations of grout hole, so as to effectively control the diffusion distance of grout, and to prevent the grout from diffusing too far.

The cement-silicate grout in the test area mainly consists of ordinary portland cement (P.O.42.5) and 40°Bé silicate. When grouting, silicate need diluting to 35 °Bé, its modulus being 2.8. Parameters of cement-silicate grout: volume ratio of cement to silicate is 1:0.05~1:0.1, while volume ratio of cement to water-cement is 0.6:1~1:1.

As for backfill grouting, clay-cement grout is adopted, and proper amount of silicate (adding other admixture if necessary) is added in order to control setting time and diffusion distance. Clay-cement grout consists of ordinary portland cement (P.O.42.5) and clay (plasticity index >10), in which cement
accounts for 20%~30%, water-solid ratio is 0.8:1~2:1, while the ratio of silicate to cement is 0.03:1~0.1:1.

Referring to Technical Specification for Cement-Silicate Grouting in Building Engineering (JGJ/T 211-2010), calculation formula and parameter selection of grouting amount are as follows:

$$\sum Q = V \cdot n \cdot \alpha \cdot (1 + \beta)$$

In which: \(\sum Q\) denotes total grout amount (m³); \(V\) the volume of grouting reinforcement body (m³); \(n\) stratum porosity (fissures degree), usually 30%~50% in rock-soil mass; \(\alpha\) the filling rate of stratum pores or fissures, usually as 60%~80%, and \(\beta\) denotes the grout loss rate (generally 10%~30%). The volume of grouting reinforcement body in two karst caves is approximately 178 m³, stratum porosity is set as 20%, and filling rate as 80%. Then grouting amount is: \(\sum Q=178 \times 0.2 \times 0.8 \times (1+0.1) =31.3\) m³. Considering conical diffusion, the volume of partly-filled reinforcement body is approximately 108 m³.

In the process of grouting, grouting pressure must be strictly controlled. Grouting pressure is generally kept at 0.1~0.3MPa in backfill grouting, and at 0.6~0.8MPa in cement-silicate grouting. Grouting is conducted in one step in fully-filled karst caves, and two times in semi-filled caves (i.e., backfill grouting first, then cement-silicate grouting after the intensity reaches design standard). Grouting in each area is conducted in the sequence of I, II, III, IV (as shown in Fig.3), in which II and III could detect the grouting diffusion radius of borehole I, and the central borehole serves as inspection hole. In grouting, grout pipe is placed at 30cm~50cm from borehole bottom so as to start grouting. During grouting, grouts ratio should be adjusted in time (or adding/reducing additives) in case of excessive grouts absorption volume or slow rise in grouts pressure. In the beginning or course of grouting, if such problems occur as high pump pressure and low grout absorption, grouting must be stopped, and start again after cleaning the hole. Grouting in one borehole can be ended when meeting either of the two requirements: when the grouting pressure at the hole’s top reaches the designed pressure, and grouting ratio is less than 1L/min, continue the grouting for 10 minutes, then cease grouting; when grout volume in a single borehole is 1.5~2.0 times more than the average grout volume, and grout volume reduces remarkably, then cease grouting. If none of these requirements is met, then adjust grout volume promptly to supplement grouts.

5. Conclusion

Two types of techniques are generally adopted in exploring water-rich karst region and fault fracture zone, i.e., drilling and geophysical exploration (CT among holes). Both of them have advantages as well as disadvantages, so in practice, generally two or more methods are combined. This combination of methods shows favorable results in the construction of Yingwanzhen subway station in Changsha, Hunan Province.

There have been many successful examples of treating water-rich karst areas and fault fracture zones in the construction of roads and railway tunnels, which, however, differ greatly from subway tunnels in view of their spatial distribution. Consequently, different areas and geological conditions as well as properties should be taken into account, so as to promote systematic research, especially into the connection between the spatial distribution and treatment measures. Furthermore, specific and corresponding technologies and materials are likely to be researched systematically.

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