Risk Analysis and Countermeasure Study of Shield Tunnelling in Karst Stratum of China

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ABSTRACT: In China, many cities have the experience of shield construction practice in Karst stratum, such as Guangzhou, Nanning, Changsha, Wuxi and Dalian. In the Karst area, there are many construction risks such as groundwater inflow, sand inflow, surface subsidence, cutter head damage and expulsion-retarded of slurry shield. Based on the analysis of the development mechanism of the Karst and the practice of the shield tunneling in the Karst stratum of Guangzhou and Nanning Metro, this paper analyses the main risks in the process of shield tunneling, and according to concrete construction risks, it proposes concrete controlling measures from the aspects of planning of the line shallow buried, the pretreatment of the Karst cave and shield selection and construction control, which provides significant guidelines for the shield tunneling under the similar Karst stratum condition.

KEYWORDS: Karst stratum, Shield tunneling, Risk analysis, Countermeasure study

1. INTRODUCTION

With the rapid development of China's urban rail transit industry and the advantages of shield tunneling in construction quality, safety and progress, shield tunneling method has been widely used in tunneling construction in Metro. At present, the number of shield machines in China has increased from 10 units in the early Twenty-first Century to 1500 units today. The geological adaptability of shield machine has been greatly improved through the engineering practice of shield tunneling in the past twenty years. However, The Universal Shield machine cannot be produced based on the current level of mechanical manufacturing, so we must clearly recognize the limitations of current shield machine for stratum adaptability. For example, shield construction in Karst stratum.

Construction practice shows that shield tunneling in Karst stratum has some construction risks, such as groundwater inflow, sand inflow, surface subsidence, cutter head damage and expulsion-retarded of slurry shield and so on. As the first shield tunnel in Karst Stratum of China, water inrush accident occurred during construction of Caonuan Park~Xiaobei section of Guangzhou Metro Line 5. At the same time, Guangzhou Metro Line 6, Line 2, Line 3, Line 8 and Line 9 all pass through a large area of karst stratum, of which the average karst cavity discovering rate of Line 9 reaches 43.4% and some contract sections reach 70%.At present, many cities in china such as Guangzhou, Nanning, Wuxi, Changsha and Dalian have encountered karst stratum during the construction of urban tunnels. According to the practice of shield tunneling in karst stratum in China, this paper summarizes the risk lessons of shield tunneling in karst developed areas of Guangzhou Metro, and puts forward corresponding risk control measures for reference.

2. THE CHARACTERISTICS OF KARST STURATUM AND ITS DIFFICULTIES IN INVESTIGATION

Karst is a general designation for various karst phenomena formed by long-term dissolution of water-soluble, which are mainly limestone, crystalline limestone, marble and dolomite. At present, most of the karst encountered by shield tunnels in China is developed in limestone stratum. From the formation mechanism of Karst, we can see that the three elements of Karst stratum are cave, water and rock, which are construction risk factors that cannot be ignored in shield construction. Therefore, it is necessary to ascertain the characteristics of the risk source as far as possible in order to formulate reasonable countermeasures.

2.1 Karst Cavity and Soil Cavity

The main forms of the soil dissolving cavities are unfilled, semi filled or fully filled. Fillers are mainly fluidity water, silty clay, round gravel, sand, etc. Karst and soil caves usually have a history of hundreds of millions of years, which geological model cannot be traced back. With the distance of exploration holes in the complex site required by the existing exploration code being 10-20m, there will be a large number of karst caves which cannot be detected. Figure 1 shows karst cave encountered during excavation of an underground project in Guangzhou Metro.

Figure 1 Karst cave encountered during excavation of an underground project in Guangzhou Metro

2.2 Fluidity Water

According to the development mechanism of karst caves, groundwater plays the role of "porter" and the cause of the formation of karst caves in Karst areas, and has the characteristics of large reserves, strong connectivity and quick recharge. Therefore, groundwater exploration in karst area should pay attention to groundwater distribution and connectivity. Figure 2 shows groundwater condition in limestone section of north extension section of Guangzhou Metro Line 8.

Figure 2 Groundwater condition in limestone section of north extension section of Guangzhou Metro Line 8

2.3 Dissoluble Rock

Soluble rocks in China are mainly divided into three types: carbonate rocks, sulphate rocks and halogen rocks. A large number of Limestones in Guangzhou area belong to carbonate rocks, which are easy to be eroded by water. The karst limestone rock mass has channelling or fluid bowl and so on, the rock-soil interface shape is irregular, which result in the excavation surface also to be uneven. It is impossible to identify the interface between rock and soil by the current exploration method. The distortion rate of exploration results is very high only with one view, one line view or one side view. Figure 3 shows shield excavation face in limestone area of Guangzhou Metro Line 9.

Figure 3 Shield excavation face in limestone area of Guangzhou Metro Line 9

3. RISK OF SHIELD TUNNELLING IN KARST STRAUM

3.1 Geological Risk

3.1.1 Groundwater

The fluidity of groundwater is the main factor for the formation of karst caves in Karst stratum. A large amount of groundwater is often accumulated in the caves. The probability of groundwater interconnection between the caves is very large. When shield passes through the karst cave with groundwater accumulation, not only the groundwater gathered in the karst cave flows to the excavation surface, but also the groundwater far away from the construction affected area flows to the excavation surface through the water connection between the karst caves, which causes the water gushing from the excavation surface and affects the construction progress as shown in Figure 4.

Figure 4 Water gushing from shield excavation face in Karst stratum

3.1.2 Collapse of karst cave and overlying soil

The loss of groundwater causes the karst cave or soil cave break the original stress balance, which causes the collapse of karst cave and overlying soil in karst stratum. Therefore, the pre-treatment grouting construction of karst cave and shield tunneling in karst stratum may break the original stress balance of karst cave and soil cave, which causes cave collapse, and then result in ground or structure subsidence and collapse. In addition, the overlying soil of the limestone stratum in Guangzhou area is usually sandy stratum, which is more sensitive to the vibration caused by shield tunneling, which is more likely to cause sand loss and then lead to stratum collapse as shown in Figure 5.

Figure 5 Road subsidence caused by shield construction in Karst Development Area

3.2 Mechanical Risk

3.2.1 Damage of shield cutter head

There are two notable characteristics in the excavation face of karst stratum. 1) Uneven stratum, which the hardness of the limestone is large, and the strength of the filler is relatively small. For example, the strength of clay and sand is small. The rotary cutter head of shield is damaged by hard impact from soft to hard. 2) The uneven surface of limestone causes unevenly stressing on rock breaking by hob, especially double-edged hob, which cannot achieve the desired construction effect, but the damage degree of cutter head increases as shown in Figure 6.

Figure 6 Abscission and eccentric wear of double edged disc in Karst stratum

3.2.2 Damage of internal components of slurry shield

Due to poor rock breaking effect and limestone's characteristics, secondary rock blocks are easy to be produced during shield tunneling in karat stratum. If slurry shield tunneling is used, massive rocks accumulate at the bottom of the slurry warehouse and displacement occurs with the rotation of the cutter head. It is easy to cause damage to the mixing rods and grilles in the warehouse. Figure 7 shows grille deformation of shield.

Figure 7 Grille deformation of shield

3.3 Construction Risk

3.3.1 Felling of shield cutterhead

During the shield machine passing through the karst and soil caves, the destruction of caves caused by shield tunneling will lead to the loss of filling materials (mostly groundwater, soft soil, etc.) in the caves, and since the gravity centre of the shield nears the front will lead to the phenomenon of shield head felling, which is not conducive to the shield posture control. When the volume of karst and soil cave is large, even the accident of shield machine falling into cave will happen.

3.3.2 Shield parameters are uncontrollable

When shield machine crosses karst cave frontally, the filling material in the bin may also flow into karst cave, resulting in the loss of pressure of the shield, especially the balance medium of slurry shield lost quickly, which has the risk of instantaneous loss of pressure in the slurry warehouse. In the process of shield tunneling in uneven limestone karst stratum, the parameters of shield tunneling often change abruptly. For example, when shield meets rock surface protrusion, the torque of shield tunneling will increase instantly. In addition, for the underlying limestone and overlying soft soil, that is, the soft and hard uneven stratum, shield tunneling is easy to shift to the direction of soft soil, which is not conducive to the shield posture control. Figure 8 shows shield construction face limestone protruding.

Figure 8 Shield construction face limestone protruding

3.3.3 Mud cake, hindered mucking and spewing risk

1) The shield cutter head is easy to form mud cake when the filling material in the karst and soil cave is clay soil;
2) The secondary rock blocks produced by the shield tunneling accumulate at the bottom of the slurry warehouse in limestone karst stratum, which causes the blockage and hindered mucking of the slurry shield pipeline;
3) In addition, hindered mucking often means that the sediment improvement effect is poor, and the separation of muck from water. If the earth pressure shield is used, it will be accompanied by spewing.

4. COUNTERMEASURE OF SHIELD TUNNELLING IN KARST STRAUM

4.1 Risk control before construction

Guangzhou Metro builders summarized the shield construction experience of several metro lines crossing karst stratum for a long distance and concluded that the direct tunnelling through karst stratum by shield cost greatly and the risk is uncontrollable. It is the best way to avoid the risk before the excavation by route planning, pre-treatment and shield selection.

4.1.1 Strengthening geological exploration

The premise of geological risk control is to identify the characteristics of geological risk sources. Engineering practice shows that the exploration hole spacing required by the current Code for Geotechnical Investigation of Urban Rail Transit (GB 50307-2012) cannot meet the requirements of exploration in karst developed areas. Therefore, geological exploration must be strengthened. In the practice of engineering geological exploration of karst strata in Guangzhou Metro, geophysical prospecting and drilling combination are adopted. The recommended value of drilling hole as follows: interval survey hole spacing is less than 5m, station is less than 3m, and the drilling depth is 2m below the design floor of the first complete rock formation.

4.1.2 Reasonable metro route planning

In order to avoid the risk of shield tunneling in karst stratum by route planning, the principle of tunnel shallow buried without entering rock stratum and reducing tunnel section in "half soil and half rock" should be taken into account. If necessary, the design of energy-saving slope of route cannot be considered. Figure 9 shows shallow buried route planning in karst development area of Guangzhou Metro Line 9.

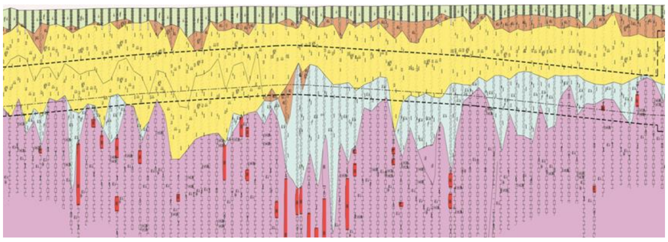

Figure 9 Shallow buried route planning in karst development area of Guangzhou Metro Line 9

4.1.3 Karst pre-treatment

The karst pre-treatment usually adopts grouting filling method, which can be combined with "filling treatment", "grouting on rock surface" and "reserved grouting pipe on ballast". It should be emphasized that the karst pre-treatment should not only consider the filling of karst caves, but also consider the sliding of the rock-soil interface. At the same time, the influence of repeated vibration caused by train operation on the surrounding karst caves should also be considered.

The treatment scope of karst caves should be judged comprehensively according to the properties of the overlying soil, the filling of karst caves and the characteristics of rock mass, so the treatment scope of karst caves in different projects is different. At the same time, the treatment scope should be enlarged according to the actual situation in the shield tunneling process, such as enlarging the treatment of karst cave after large leakage occurs in the tunneling process.

4.1.4 Strengthening equipment selection and configuration

The EPB shield and the slurry shield have been used in the karst area of Guangzhou. The construction results show that the two types of shield have their own limitations, such as, the subsidence control effect of EPB shield is poor, it is easy to be spewing, and the slurry shield is easy to blockage. In order to improve the adaptability of the shield machine to the stratum as far as possible, it is suggested that the slurry shield should be first selected in the upper watered sandy layer and the lower limestone area. It is suggested to adopt auxiliary construction measures such as adding the stirring bar on the outside of the cutterhead, and enlarging grille size and so on. If the EPB shield machine is adopted, the twin screw conveyor is recommended. In addition, the slurry & EPB dual-mode shield can be selected. Guangzhou Metro Line 9 tried to cross the river under the karst development zone with dual-mode shield machine, and the construction effect was satisfactory.

According to the practice of shield tunneling in karst stratum of Guangzhou Metro, it is suggested to adopt single-edged disc for shield tunneling in upper soft and lower hard section of karst stratum. In addition, the scraper should be retrofitted.

4.2 Risk control in construction process

4.2.1 Strengthening the improvement and management of muck

Before entering the cave section, carefully check the foam injection and mud adding system to ensure the normal operation of the system. The amount of foam agent is determined according to the stratum characteristics. Due to the poor self-stability of stratum in karst cave section, it is necessary to strictly control the balance between the amount of muck and tunneling speed to ensure the stability of excavation face. We should strengthen the observation of the composition and water content of muck, and stop the machine in time when abnormalities occur.

4.2.2 Reasonable selection of tunneling mode and strict control of tunneling parameters

In order to protect the cutterhead and cutter, it is advisable to adopt low penetration into rock when tunneling with EPB shield. Strictly monitor the pressure, torque and other parameters, when the pressure of the soil chamber change suddenly, immediately stop the machine, analyse the reasons, and then resume tunneling after the completion of the treatment. Strengthen the analysis of muck samples, provide feedback for adjustment of tunneling parameters. Strictly control the thrust and the rotational speed of the shield, according to the force distribution of the cutter head that can be displayed in the main control room, determine the location of rock block distribution on the excavation face to prevent cutter wear and cutter ring cracking.

4.2.3 Strengthening management and rational allocation of cutter head

According to the engineering geological investigation report, work out the mileage of opening chamber and changing cutter tools in advance.

4.2.4 Shield posture control

Shield tunneling always pays attention to the trend of shield attitude, and adheres to the principles of "diligence correction", "less correction" and "moderation".

4.2.5 Ensure waterproof effect of hinged seal and shield tail seal

Before the shield machine enters the karst area, it is necessary to check the hinged seal and shield tail seal, and at the same time to strengthen the sealing grease injection of the shield tail seal to ensure the anti-seepage effect of the seal.

4.2.6 Grouting behind segment

The back grouting of shield segment should be combined with synchronous grouting and secondary supplementary grouting. The grouting pressure and grouting quantity of synchronous grouting should be adjusted reasonably according to the engineering geological conditions. In order to prevent the segment from forming a longitudinal waterway channel, the necessary secondary grouting should be carried out in time according to the construction monitoring.

4.3 Emergency rescue

4.3.1 Mud preparation

Aiming at the risk of sudden pressure loss of shield caused by slurry loss in karst area during construction of slurry shield tunneling, the slurry reserve can be increased by increasing the storage volume of slurry pool to prevent the risk of no slurry replenishment when slurry loss occurs.

4.3.2 Emergency rescue

Shield tunneling in karst strata is very difficult to avoid sudden ground collapse, so the timeliness of emergency rescue becomes particularly important. In order to reduce the ground traffic pressure, Guangzhou Metro has developed a comprehensive engineering vehicle to deal with ground collapse caused by shield tunneling in Karst strata.

5. CONCLUSION

The main characteristics of shield construction risk in karst stratum are karst and soil cave latency, groundwater interconnection, uneven rigidity of excavation section and poor adaptability of shield machine. According to the shield construction experience in karst stratum of Guangzhou Metro, the risk control of shield construction in karst stratum should be avoided or reduced as early as possible. At the same time, it is suggested to strengthen the engineering geological investigation to grasp the distribution of karst cave, soil cave and groundwater as far as possible, and to pre-treatment the karst and soil cave in advance within the influence of shield construction, and to ensure the effect of pre-treatment. Strengthen the configuration of shield equipment and improve the adaptability of shield machine to stratum as much as possible. The fine management of shield construction includes tool replacement management, parameter control, and synchronous grouting and seal management of shield tail.

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