Karst cave treatment technology for a subsea shield tunnel

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Abstract. The existence of karst caves brings great potential safety hazard to tunnel construction. When building a tunnel through underwater karst area, engineers will face greater challenges. This paper introduces the treatment technology of submarine karst caves, based on a large diameter subsea tunnel project in Dalian, China. This paper starts with the geological conditions of the tunnel, then introduces the treatment scope of karst, the treatment process, grouting technology and precautions, and finally the quality inspection after treatment and treatment effect are discussed.

1. Introduction

In tunnel construction, karst brings great threat to the safety of tunnel construction (Li et al., 2020; Xue et al., 2017). Because of the complexity of karst geology, there are many potential risk factors in karst distribution area, especially water and mud inrush (Gao et al., 2021; Li et al., 2021). And karst caves make the construction of tunnel more difficult and cost more (Ke, 2014). Therefore, karst caves are regarded as one of the most important geological key concerns in tunnel geological survey stage (Zhang et al., 2019), design stage and construction stage (Guo et al., 2019; Lei and Yang, 2007; Nie et al., 2019). Many scholars have studied the mechanism and evolution of karst and obtained many achievements (Kaufmann and Romanov, 2020; Petric et al., 2020). At the same time, the mechanism of karst collapse is also concerned by researchers (Huang et al., 2017; Yang et al., 2017).

When tunnel engineering projects meet karst caves, engineers and researchers always need to seek solutions. Yang studied on construction and Treatment Technology of Tunnel in Karst Water-Rich Stratum (Yang, 2018). Zhou, L. researched on the treatment materials of urban rail transit water-containing karst caves, some types of filling materials were compared and analysed (Zhou et al., 2020). And the long-term monitoring and evaluation of cement-based grouting used to govern the water seepage of karst caves also were studied (Fang et al., 2020). With the increase of engineering cases of tunnel excavation encountering karst caves, karst grouting treatment technology is gradually developing.

However, the construction experience of shield tunnel karst caves treatment grouting may not provide reliable references for underwater shield tunnel construction in karst caves area, especially for underwater shield tunnels in water conservation districts (Yang et al., 2020). In this paper, the treatment process, grouting technology and precautions, and finally the quality inspection after treatment were introduced based on a subsea tunnel project in Dalian, China.
2. Project overview

Dalian Metro Line 5 runs through the north and south of the city. On this subway line, a large shield with a diameter of 11.8m passes through the Suoyuwan Bay. The total length of large diameter shield is 2870m, including 2310m located under the seabed and 560m located on both sides of the Strait. The section, from the middle of the tunnel to the north launching shaft, is located in karst developed area, about half of the total length. The length of karst area within the tunnel length is about 1538m, including 180m in the land section and 1358m in the sea section (Figure 1).

![Tunnel plan of the shield tunnel and karst area.](image1)

Figure 1. Tunnel plan of the shield tunnel and karst area.

Figure 2 shows the geological profile of the tunnel. The geomorphic units of the bay where the tunnel is located are beaches and underwater slopes. The coast areas on both sides are about 2.5m~5.8m above sea level. The seabed terrain is generally gentle. The seabed elevation is -12.18m~ -4.43m, and the maximum height difference is about 7.75m. The depth of seabed gradually deepens from both banks to the middle, generally 6m- 14m. From top to bottom, the stratum is composed of clay, completely weathered or strongly weathered rock, and moderately weathered rock. The buried depth of the tunnel is about 11.9m~ 23.5m, mainly located in moderately weathered rock. According to the detailed survey data, 172 karst caves were found, with an average height of 2.35m. There are 133 full-filled karst caves, accounting for 77.3%, with an average height of 2.5m. There are 12 semi-filled karst caves, accounting for 7%, with an average height of 2.2m. There are 27 karst caves without filling, accounting for 15.7%, with an average height of 1.8m.

![Geological profile of the tunnel.](image2)

Figure 2. Geological profile of the tunnel.
3. Treatment technology

3.1. Scope of treatment

The influence on the tunnel caused by the karst caves’ locations and sizes were analysed by the Design Institute, based on the numerical calculation. When a karst cave is far away from the tunnel or the size of the cave is small, the adverse effect caused by the cave on the tunnel is also small. According to the convergence deformations of tunnel diameter caused by karst caves, the area of karst caves that need grouting was determined: ① The main influence area: The outer profile of shield tunnel is extended by 3m above and side and 5m below; ② The secondary influence area: The outer profile of shield tunnel is extended by 3m ~ 6m above and side and 5m~10m below (Figure 3). In the main influence area, all karst caves need grouting. In the secondary influence area, the karst caves with diameter (long side or equivalent long axis) ≥ 3m need grouting.

![Figure 3. The karst caves treatment range (unit: m).](image)

![Figure 4. Karst caves treatment process.](image)

3.2. Treatment process

Figure 4 shows the process of karst caves treatment: (1) Taking the survey drilling holes revealed to the karst cave as the reference point, a row of geological holes shall be applied at 2m intervals along the direction perpendicular to the line; (2) The geological holes are used to look for the boundary of the caves, and the holes drilling shall be stopped when caves’ boundary is found; (3) Other grouting boreholes are drilled according to the boundary of the karst caves. The layout is arranged as 2m × 2m quincunx. And the geological holes can also be used for grouting; (4) If the karst caves are full filled with mud or clay, pressure grouting can be carried out directly. If the karst caves are not filled or semi-filled, they should be filled with sand and stone particles first, and then grouted under pressure; (5) Finally, the quality inspection of grouting treatment should be conducted.

3.3. Grouting technology

In order to complete the grouting, the following steps are required (Figure 5): (1) After drilling the hole, put the mixed casing material (water: cement: bentonite = 2.3:1:1, viscosity = 28), lower the grouting pipe to the bottom of the hole, and start to pump the casing material to replace the slurry in the hole until the casing material flows out of the hole. (2) Install sleeve valve grouting pipe to the depth of 0.5m under the karst cave. (3) Install the double plug grouting core pipe, then layered pressure grouting makes the filling material in karst caves compacted, permeable and consolidated. (4)
Pump in clean water to clean the sleeve valve tube, if the grouting fails to meet the design requirements, the grouting can be carried out again.

3.4. Grouting precautions

The grouting process may encounter some abnormal conditions, some precautions and corresponding countermeasures are provided here for reference.

(1) Grouting must be carried out continuously. If it is interrupted for some reason, it can be treated according to the following principles: 1) After interrupted, Grouting should be resumed as soon as possible. Otherwise, the sleeve valve pipe shall be flushed by the pump using clean water immediately, and then grouting shall be resumed. 2) If the flushing cannot be done or is ineffective, the hole shall be cleaned by other tools, and then the grouting shall be resumed. 3) When the grouting is resumed, the grouting shall be conducted with the thin cement slurry at beginning. If the injection rate is similar to that before the interruption, the cement slurry with the same grade before the interruption can be used to continue pumping; If the injection rate is much less than that before the interruption, the slurry should be thickened step by step to continue perfusion. 4) After the grouting is resumed, remedial measures should be taken if the injection rate is much less than that before the interruption and the slurry suction is stopped in a short time.

(2) When the grouting section has a large amount of injection and it is difficult to finish the grouting, the following measures can be selected: 1) Low pressure, thick slurry, limited current, limited quantity and intermittent grouting; 2) The slurry is mixed with accelerating agent, or double liquid grouting is adopted.

(3) In the process of grouting, if the return slurry becomes thicker, the new slurry with the same water cement ratio should be used for grouting. If the effect is not obvious, the grouting can be stopped after 30 minutes.

(4) In the process of grouting, if any slurry leakage is found, the methods of caulking, surface sealing, low pressure, concentrated slurry, current limiting, limited limit and intermittent grouting shall be adopted according to the specific conditions.

3.5. Quality inspection

In order to check the quality of karst reinforcement, some measures need to be taken. The strength test of karst cave grouting body generally needs drilling out core and uniaxial compression test. The water injection test can be used to test the permeability of grouting solid in karst cave. In situ
standard penetration test can be used to test the bearing capacity of grouting solid foundation in situ, and it is also one of the key methods used in this project. The quality inspection requirements are as follows:

(1) Detection principle and quantity: spots check according to 1% holes number, and no less than 3 points, each cave larger than 2m in the treatment scope is required to be detected once; Random drilling and coring are adopted for compression test, and the unconfined compressive strength is required to be no less than 1MPa. The water injection inspection should be carried out more than 7 days after the grouting of the unit project.

(2) In shield launching section, the permeability coefficient of grouting solid should not be greater than $1 \times 10^{-4}$ cm/s.

(3) The random in-situ SPT test can be used, and the standard penetration should be not less than 15 strokes.

According to drilling holes on site and getting the grouting massive solid cores, it can be inferred that the grouting body has almost full filled the karst cave. The integrity of the cores from grouting body is good, which is composed of cement slurry and original filling material of karst cave (Figure 6).

![Grouting body core](image)

**Figure 6.** Grouting core taking from karst caves after treatment

### 4. Conclusions

This paper introduces the treatment technology of submarine karst caves, based on a large diameter subsea tunnel project in Dalian, China. According to the geological conditions of the tunnel, the treatment scope of karst, the treatment process, grouting technology and precautions are introduced, and finally the quality inspection after treatment is discussed. With the feedback from the engineers at the tunnel construction site, the following conclusions can be drawn.

(1) Based on the feedback from the shield drivers, the shield posture parameters are controllable when the tunnel passed through the karst area. It can be inferred that the karst treatment scope and grouting technology proposed in this paper are suitable for the large shield tunnel with diameter of 11.8m.

(2) For the semi-filled or unfilled karst caves, the method of filling sand aggregate first and then grouting is adopted, which greatly saves time and cost compared with the method of direct grouting filling. But the direct grouting method is effective for full filling karst caves. It can be seen that it is necessary to adopt different treatment processes for karst caves with different filling conditions.

(3) The advantage of karst treatment technology of subsea shield tunnel is to ensure the safety of tunnel construction, but the treatment of subsea karst caves is more difficult than that of land karst caves. Due to the sea waves’ fluctuation, the stability of the drilling platform is difficult to guarantee, and the positioning of offshore drilling points is also very difficult. More efforts may be needed to solve these problems in future research.
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