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Research Article

Identification and Treatment of Collapse and Mud Inrush Caused by Deep Karst Trough in Tunnels

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To predict and prevent the collapse and mud inrush caused by the deep karst trough in tunnels, an engineering case is studied. Firstly, a comprehensive identification method for the hazard-causing structure of the deep karst trough in tunnels is proposed and successfully applied. Secondly, the morphological characteristics and developmental mechanism of the deep karst trough are studied. The hazard-causing structure is mainly developed at the entrance section of the karst tunnel, which is funnel-shaped, mostly filled with clay and a small amount of gravel. The development scale is affected by the geological structure, tectonic movement, formation lithology and inclination, sunshine and precipitation, and surface soil. Thirdly, four hazard-causing modes of the collapse and mud inrush are proposed, i.e., rock mass failure of tunnel face, direct exposure of tunnel face, direct exposure of tunnel roof, and rock mass failure of tunnel roof. Finally, a treatment technology for collapse and mud inrush is put forward. The treatment technology is to "remove the mud, fill the karst cave, conduct advance grouting, strengthen the support, waterproof the collapse area, backfill the collapse pit." The collapse and mud inrush of Qiyueshan Tunnel was successfully treated by using the above technology.

1. Introduction

Karst formations are widely distributed around the world [1–5]. With the rapid development of infrastructure construction such as transportation, water conservancy, and hydropower in recent years, more and more tunnels and underground projects will be built in soluble rock stratum [6–8]. The characteristics of karst development and its influence on engineering safety have gradually become a research hotspot in the field of tunnel and underground engineering [9–11].

There are various types of karst development with different structural characteristics and hazard-causing features [12]. Lu et al. [13] put forward five kinds of karst water-soil invasion into tunnels, i.e., closed karst water–mud burst into tunnel, rich water karst passages burst to tunnel, water–mud–stone of top underground river burst into tunnel, karst water and karst passage water burst into tunnel, and fault water burst into tunnel. Li et al. [14] divided karst bodies with abundant water and mud into three types, i.e., deep karst caves filled with water, fracture-induced karstified zones, and filled karst caves. Li et al. [15] divided the karst hazard-causing structures of water and mud inrush into three types from the perspective of developmental form and disaster scale, i.e., the corrosion fissure type, the karst cave type, and the pipe and underground river type. Based on the above research, Xue et al. [16] divided karst hazard-causing structures into four types, i.e., karst fissure, karst conduit, karst cave, and underground river. In addition, He et al. [17] proposed that the deep and large karst trough filled with clay is also a typical hazard-causing structure of mud inrush.

During tunnel construction, large safety accidents such as water and mud inrush, collapse, and ground collapse are very likely to occur once the karst structures are exposed, causing severe construction delays and even major economic loss and casualties [18–23]. The corrosion fissures are widely distributed in the soluble rock stratum, and its related disasters are characterized by continuous drainage type of water inrush with a relatively low severity of disaster and a long duration. For example, the Qiyueshan Tunnel of Lichuan-Wanzhou Expressway passes through the stratum where karst corrosion fissures are well developed. The construction was forced to stop nearly 10 times due to the tunnel flooding induced by surface rainfall. The maximum water inflow was 87,000 m^3/d, and serious cracking and water inrush occurred after the secondary lining construction [24]. The hazard-causing structure of karst caves is mainly characterized by instantaneous drainage-type of water and mud inrush with strong suddenness, large scale, and great severity of disaster [25, 26]. For example, a large, filled karst cave was exposed at the working face of the Chaoyang Tunnel and its continuous water inflow in the 40 minutes was about 57,000 m^3, causing 3 deaths [27, 28]. Karst pipes possess good underground connectivity. The related disasters are mainly characterized by climatic instantaneous discharge of water and mud inrush, with great suddenness, high frequency, and great severity [29]. The scale of water inrush caused by underground rivers is large, and the disaster is catastrophic because underground rivers are rich in water sources and greatly affected by rainfall [30]. Li et al. [31] studied the major water and mud inrush disasters in Lingjiao Tunnel and concluded that the water-bearing and mud-filled structure was the fracture-induced karstified zone rather than the main fault area. The researches on the structural characteristics and hazard-causing features of different types of karst structures mentioned above can provide good examples for water and mud inrush disaster prevention. The deep filled karst trough is a typical type of karst hazard-causing structure that is likely to cause collapse and mud inrush in the entrance and exit sections of karst tunnels. At present, only few studies have been conducted on the identification methods, structural characteristics, and hazard-causing mechanisms of the deep filled karst trough in tunnels.

The entrance of the Qiyueshan Tunnel on Moudao Connecting Line of the Lichuan-Wanzhou Expressway is located in the karst development area. The clay-filled karst trough connected to the surface was revealed at the chainage of GK0+411 and resulted in the collapse and mud inrush in the tunnel, which caused great difficulties to the tunnel construction and posed a great threat to the surrounding environment. Based on the collapse and mud inrush hazard in Qiyueshan Tunnel, the identification method, morphological characteristics, developmental mechanism, hazard-causing mode, and disaster treatment of collapse and mud inrush caused by deep karst trough in the karst tunnel are studied. The research results have been successfully applied to the treatment of collapse and mud inrush in Qiyueshan Tunnel. The results have certain reference and guiding significance for the prevention and treatment of collapse and mud inrush caused by the deep karst trough in other karst tunnels.

2. Project Overview

The Moudao Connecting Line of Lichuan-Wanzhou Expressway is located in Lichuan City, Hubei Province. It starts from the Shanghetaoshu in Ganyan Village, Nanping Township, Lichuan City, and ends at Dianziping Reservoir, Nanpu Village, Moudao Town, Lichuan City. The total length of the project is 6.389 km. It was built as a fast track to improve the traffic conditions of the G318 National Road from Nanping Township to Moudao Town. This project was managed to avoid crossing the high-altitude winding mountain road in Qiyueshan Mountain. It can greatly shorten the distance from Moudao to Nanping and ensure the safety of vehicle traffic in winters, especially during the rainy, snowy and icy weather conditions. Besides, it can greatly promote the development of provincial ecotourism demonstration area—Sumadang.

Qiyueshan Tunnel is a control project on the Moudao Connecting Line of Lichuan-Wanzhou Expressway. It is located between Nanping Township and Moudao Town, Lichuan City, Hubei Province, designed to cross Qiyueshan Mountain, as shown in Figure 1(a). The starting and ending chainages of the tunnel are GK0+350~GK3+310, with a total length of 2960 m and a maximum buried depth of 347 m. The tunnel is located between Qiyueshan Tunnel of Yichang-Wanzhou Railway (No. 1 Qiyueshan Tunnel) and Qiyueshan Tunnel of Lichuan-Wanzhou Expressway (No. 2 Qiyueshan Tunnel). The left side is about 6.5 km away from No. 1 Qiyueshan Tunnel, and the right side is about 3.5 km away from No. 2 Qiyueshan Tunnel. The above-mentioned three Qiyueshan Tunnels are located in the same geological unit with complex geological structures, extremely developed karst of changeable shapes, entailing a great risk of disasters such as water inrush, mud inrush, and collapse. Among them, the construction of No. 1 Qiyueshan Tunnel has encountered 10 faults, 3 underground rivers, 187 karst pipes and caves, and 8 serious mud and water inrush accidents. And 61 karst caves were revealed, and water inrush disaster occurred for 14 times during the construction of No. 2 Qiyueshan Tunnel.

The main unfavorable geological structures in the tunnel site area are Qiyueshan anticline and Zhongcao reverse fault (F1). The two wings of the Qiyueshan anticline are asymmetrical, and the lithology is mainly limestone, interbedded with shale and coal seams. The southeast flank occurrence of the tunnel crossing area is $115^\circ \angle 70^\circ$, and the northwest flank is about $32^\circ \angle 60^\circ$. The exposed stratum at the core of the anticline is the medium-thick limestone of the Changxing Formation, and the two wings are in contact with faults at the core of the anticline, where the karst is highly developed. The F1 fault is a compressive fault, which is oblique to the tunnel at a large angle near the chainage of GK1+680, with a width of about 40 m. The karst is developed in the fault zone. The tunnel area belongs to the tectonic dissolution-denudation Zhongshan landform, the surface elevation is 1260~1660 m, and the terrain is undulating as a whole. Karst microtopography such as ravines, troughs, funnels, and sinkholes is well developed. The surface of the tunnel site area is partially covered with Quaternary residual slope silty

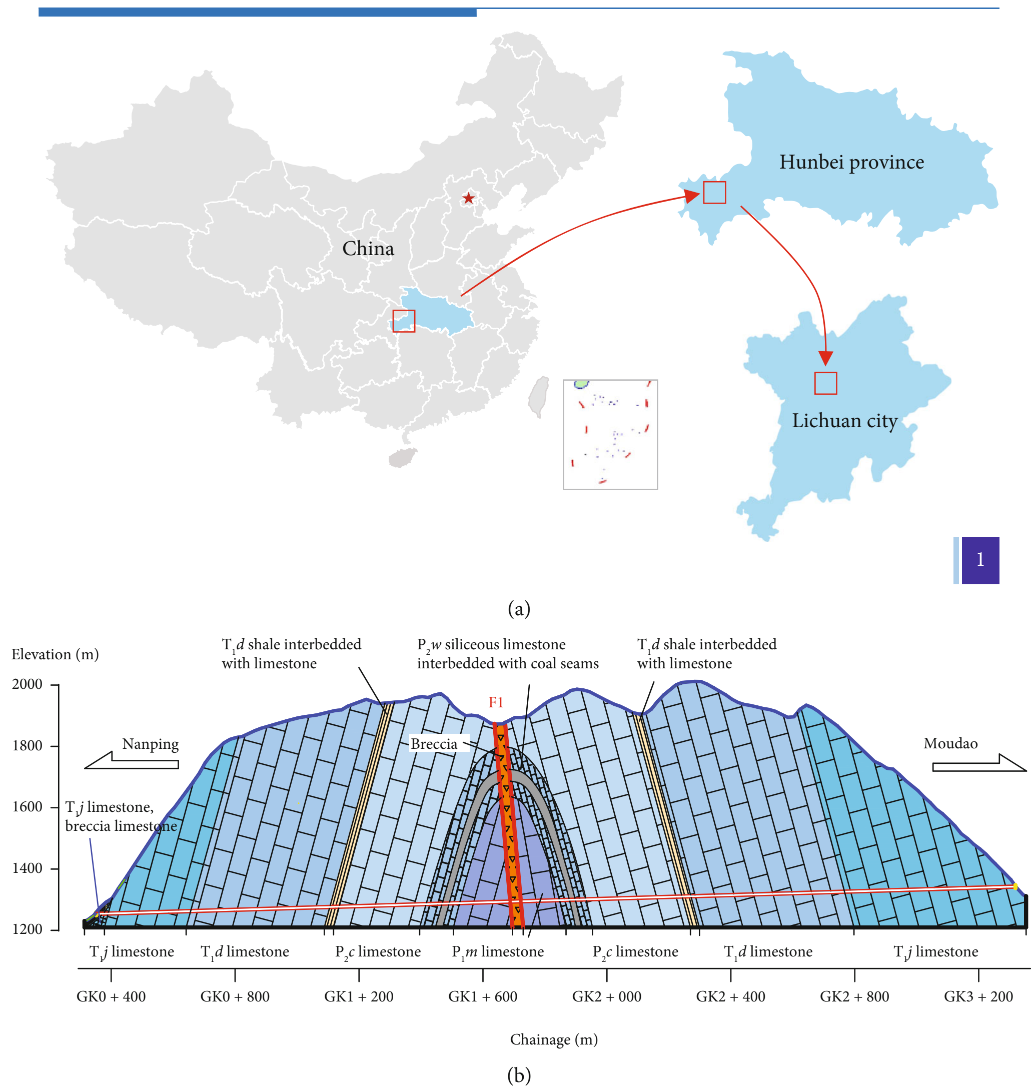

Figure 1: Location and geology maps of the study area. (a) Location of the study area; (b) longitudinal geological profiles of the Qiyueshan Tunnel [32].

clay. The lithology of the strata in the tunnel area are mainly limestone, shale interbedded with limestone, siliceous limestone interbedded with coal seams, and fault fracture zone, as shown in Figure 1(b), accounting for 89.70%, 2.20%, 6.75%, and 1.35%, respectively, as shown in Figure 2(a). The surrounding rock levels are level III, level IV, and level V, accounting for 73.48%, 16.39%, and 10.13%, respectively, as shown in Figure 2(b).

3. Identification Method for the Hazard-Causing Structure of Deep Karst Trough

The clay-filled deep karst trough is a common hazard-causing structure of collapse and mud inrush in karst tunnels. It is often developed at the entrance and exit sections of karst tunnels. Once treated improperly, it will pose a great safety threat to tunnel construction and operation. Therefore, it is very important to identify the hazard-causing structure of deep karst trough in advance. In the entrance section of Qiyueshan Tunnel, the method of "geological analysis, surface geological radar detection, and tunnel face geological radar detection" was adopted to identify the deep karst trough.

3.1. Geological Analysis. From the perspective of hydrogeology, there is no perennial flowing water near the tunnel. The underground water mainly receives atmospheric rainfall. The rainfall enters the karst aquifer through surface karst depressions, funnels, sinkholes, etc.; runs off through dissolution fissures and karst pipes; and discharges in the form of karst springs and underground rivers. The entrance section of the tunnel is generally located at the source of the Dayuquan karst water system. The design elevation of the tunnel is higher than the groundwater level and is much higher than that of the Deshengchang trough and the Deshengchang underground river. Therefore, the tunnel entrance section is in the karst vertical infiltration zone, and the developed karst is mainly vertical.

From the perspective of stratum lithology, the tunnel entrance section is located in the extremely developed karst

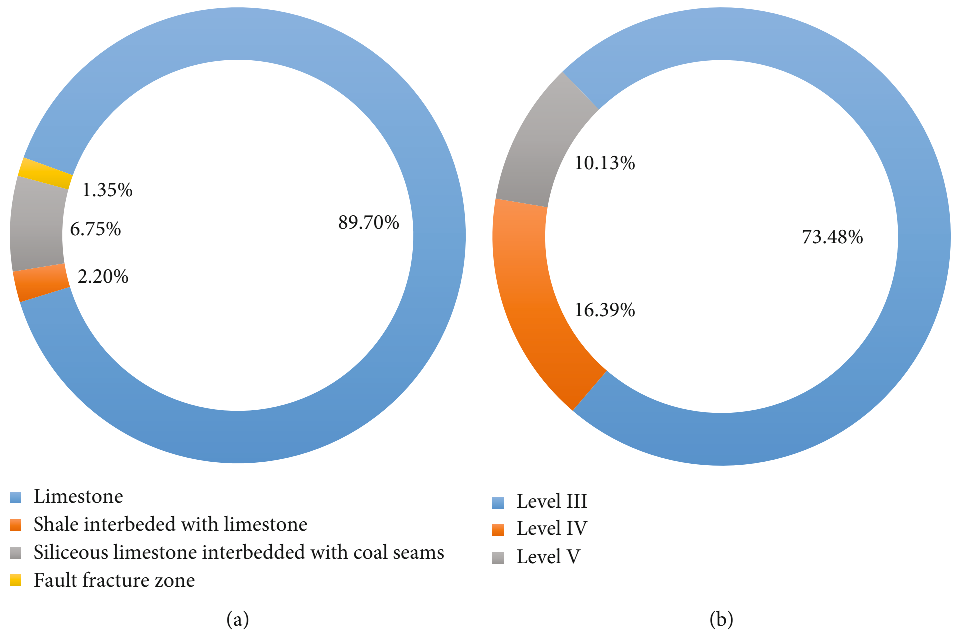

Figure 2: Lithology and surrounding rock level proportion: (a) lithology proportion; (b) surrounding rock level proportion.

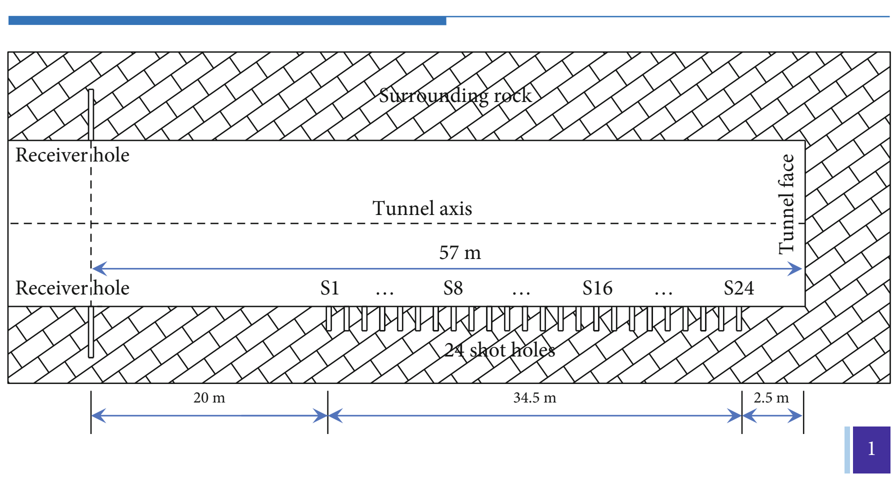

Figure 3: Acquisition layout of TSP advance geological prediction.

horizon of the Jialingjiang Formation. The karst is mainly in the form of vertical karst pipes. According to the previous geological survey, the vertical corrosion fissures are well developed, and most of them are filled with clay. The surface is covered with Quaternary residual silty clay and vegetation, which is conducive to the development of karst to the deep layer; hence, it is not very visible on the surface. Consequently, during the construction at the entrance section of the Qiyueshan Tunnel, it is likely to encounter wide corrosion fissures, karst pipes or karst caves, and even the deep karst trough and weathered troughs connected to the surface.

3.2. Geophysical Identification. In order to further find out the geological conditions in front of the tunnel face at the entrance section and avoid the disaster of collapse and mud inrush, advance geological exploration is required during the tunnel construction. TSP is one of the main methods for long-distance geological detection of tunnels. It can effectively identify faults, karst caves, and other unfavorable geology in karst tunnels [33–35]. TSP detection needs to arrange a sensor receiver hole and 24 shot holes on the side wall of the excavated tunnel. The interval between shot holes is 1.5 m. The distance between the first shot hole and the tunnel face is 2.5 m, and the distance between the last shot hole and the receiver hole is 15~20 m, as shown in Figure 3. Therefore, a long working space is required to carry out TSP detection. In general, the space required for TSP advance geological prediction is not realistic in the tunnel entrance section. Therefore, the geological radar is primarily used for the deep karst trough advance detection at the entrance of the karst tunnel.

It is of great guiding importance for the construction of the tunnel entrance section to conduct the geological radar detection on the surface once the detection conditions are

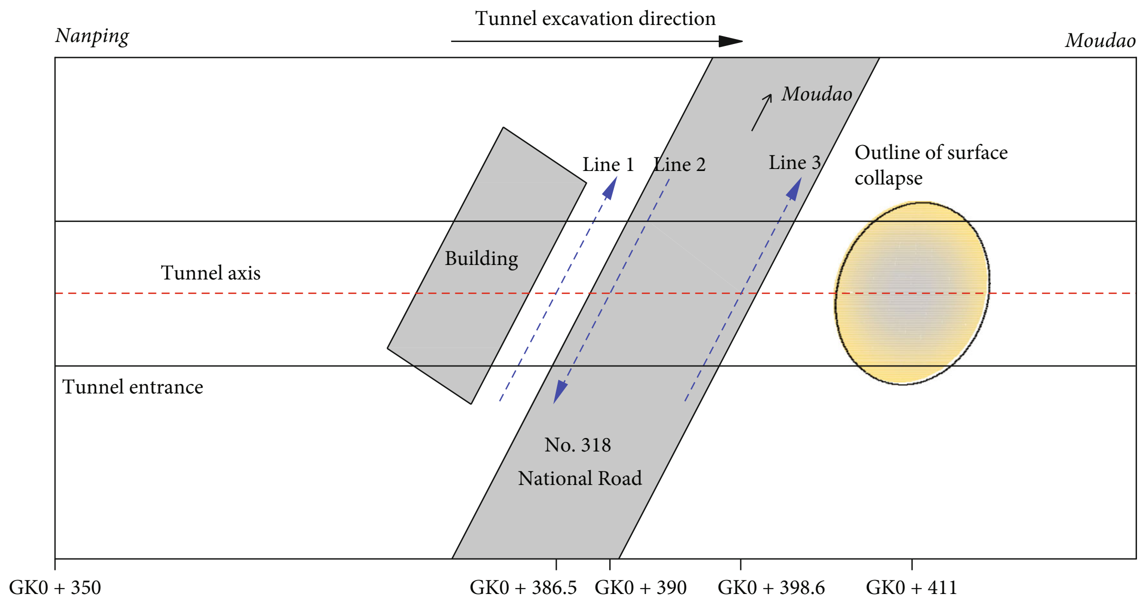

Figure 4: Survey line layout on the ground surface.

met. The entrance section of Qiyueshan Tunnel has a large surface slope which is covered with plants and overgrown with vegetation, thus making it impossible to carry out the surface geological radar detection. However, the G318 National Road crosses from above the tunnel and it is 45 m away from the tunnel entrance. It provides favorable conditions for the tunnel surface geological radar detection. Therefore, geological radar was used for advance geological detection both on the ground surface and in the tunnel.

3.2.1. Surface Geological Radar Detection. Geological radar was used to detect the tunnel surface. Three survey lines were arranged, and the tunnel axis was taken as the center line. The detection went along the direction of the G318 National Road. The layout of survey lines on the ground surface is shown in Figure 4, and the detection results are shown in Figure 5 and Table 1.

It can be seen from Table 1 that within 20 m below the surface at the chainage of the GK0+386-GK0+398.6, the surrounding rock is relatively broken and contains weak interlayers. Considering the lithological characteristics of the stratum that the tunnel passes through, it can be concluded that this section of the tunnel is in a karst development zone where karst fissures or small karst caves are relatively developed, and some fissures or small karst caves are filled with mud.

The surrounding rock conditions revealed during the actual construction of the Qiyueshan Tunnel are shown in Figure 6 and Table 2. Wide corrosion fissures and small karst caves were developed in the range of GK0+398~GK0+405. The corrosion fissures and karst caves were wet inside the cavity and filled with mud or without any filling. There was no fissure water.

During tunnel construction, the frequent occurrence of corrosion fissures, small karst caves, and other geological phenomena is usually regarded as one of the geological precursor information of serious water and mud inrush. At the entrance and exit of the tunnel, the frequent occurrence of corrosion fissures, small karst caves, and other geological phenomena can be regarded as the geological precursor information for the occurrence of collapse and mud inrush caused by the deep karst trough. Based on this, it can be preliminarily concluded that there is a greater risk of collapse and mud inrush within a certain range in front of the tunnel face.

3.2.2. Tunnel Face Geological Radar Detection. In order to further check the surrounding rocks in front of the tunnel face, the geological radar detection on the surface at the chainage of GK0+405 was conducted with a detection depth of 20 m. The layout of the survey lines is shown in Figure 7(a). Line 1 ran from left to right, and line 2 ran from right to left. The detection results of line 1 are shown in Figure 7(b).

According to the radar detection results, it is inferred that corrosion fissures or small karst caves filled with mud are relatively developed ahead the tunnel face in the below sections, i.e., the left side at the chainage of GK0+406~+418, the central left side of GK0+406~GK0+422, and the right side of GK0+407~GK0+425.

According to the geological radar detection results on the ground surface of the tunnel and inside the tunnel, as well as the frequent revealed corrosion fissures or small karst caves and other geological phenomena during the tunnel construction, it can be inferred that 20 m ahead of the tunnel face at the chainage of GK0+405 is located in the karst development area, and the tunnel construction is extremely likely to expose deep karst troughs or small karst caves filled with mud. So, there is a relatively high risk of collapse and mud inrush in the tunnel.

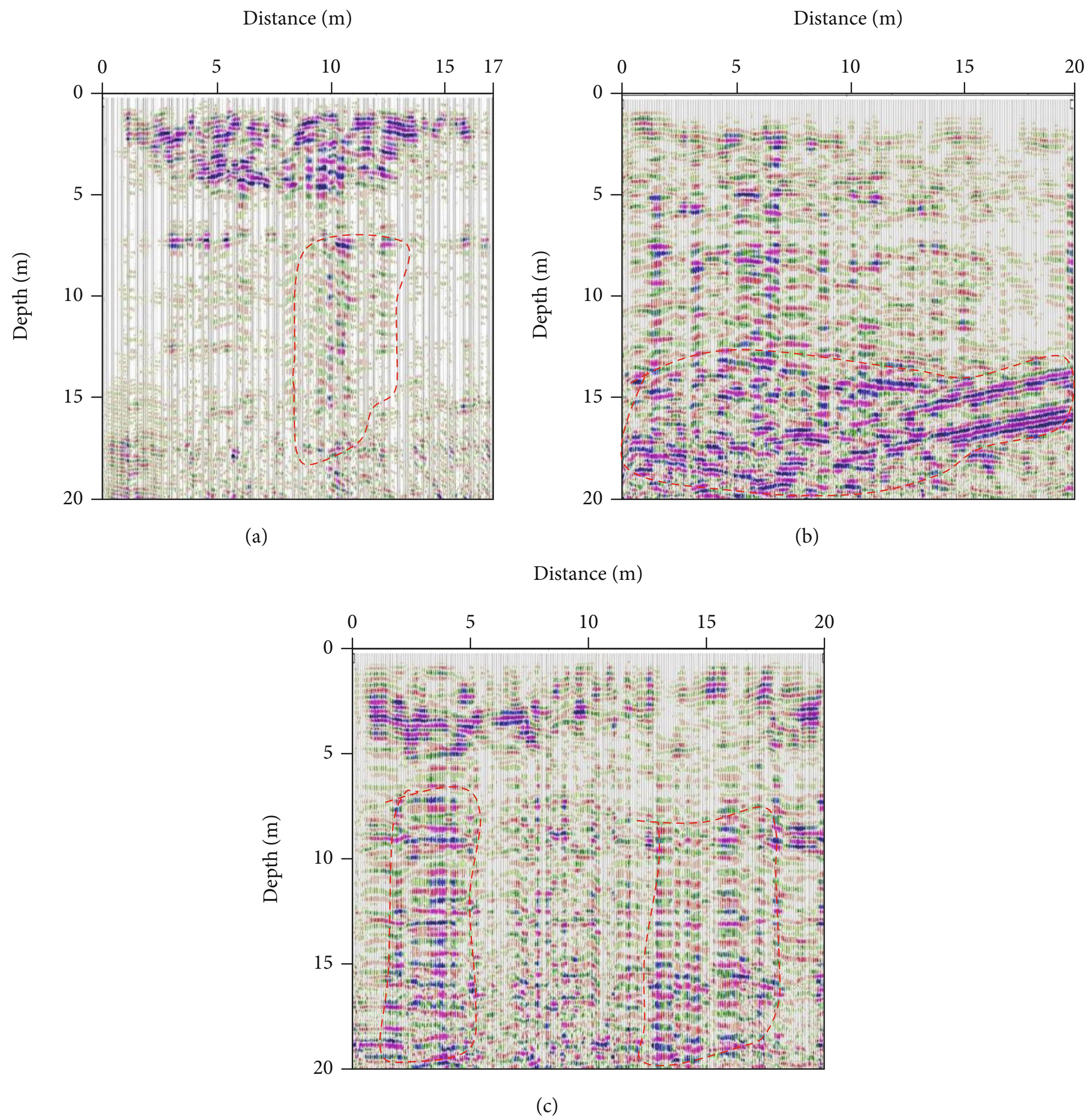

Figure 5: GPR profiles of ground surface detection: (a) line 1; (b) line 2; (c) line 3.

4. Hazard-Causing Structure and Mode of Collapse and Mud Inrush in Deep Karst Trough

A collapse and mud inrush disaster happened at the chainage of GK0+411 of Qiyueshan Tunnel, because the construction revealed a common hazard-causing structure for collapse and mud inrush at the tunnel entrance in karst areas, that is, the deep karst trough filled with clay. The investigation on its developmental characteristics, filling status, and hazard-causing mechanism can provide guidance for the prevention and treatment of collapse and mud inrush disasters at the entrance of karst tunnels. It can also be used as a reference for similar projects.

4.1. Disaster Description. At 14:00 on December 13, 2014, three karst caves were revealed during the construction of the tunnel face at the entrance of GK0+411. The left karst cave was about 3.5 m long, 2 m wide, and 9 m high. A karst cave on the right was about 3.5 m long, 2.2 m wide, and 8 m high. The other karst cave was about 3.5 m long, 2 m wide, and 12 m high. A large amount of mud and stone fell off in the three karst caves, and the total volume had reached about 60 m^3 by 8:00 on December 16, showing a stable trend. At 17:00 in the afternoon, the mud and rock in the middle karst cave suddenly collapsed, and the collapsed mud and rock were about 800 m^3, as shown in Figure 8(a). The collapse caused the surface subsidence, with an area of about 10 m × 12 m, as shown in Figure 8(b). Thanks to the advance identification of the possibility of collapse and mud inrush and the precautionary measures, the disaster did not cause casualties and mechanical damage. The collapse and mud inrush point was located 60 m away from the tunnel entrance. The G318 National Road was 10 m away from the surface where the collapse and mud inrush occurred along the entrance direction and its left side was a civilian house. Surface subsidence and mud inrush seriously threatened the driving safety on the G318 National

Table 1: Surface detection result of GPR.

Survey line	Location	Depth to tunnel vault/m	Detection results
1	GK0 +386.5	14.353	Within the depth of 0~5 m, there may be accumulative layer or Quaternary clay layer, with serious weathering and large pores. Corrosion fissures are developed at the depth of 8~16 m, and small karst caves may exist at about 20 m below.
2	GK0 +390	13.968	Corrosion fissures and pores are relatively developed at the depth of 2~12 m, and the rock mass is relatively broken. The corrosion fissures within the depth of 15~22 m are abnormally developed, and there may be small cavities.
3	GK0 +398.6	13.981	Within the depth of 8~20 m, corrosion fissures and pores are relatively developed, and the rock mass is relatively broken.

(a) (b)

Figure 6: Pictures of the revealed karst caves: (a) GK0+400; (b) GK0+405.

Road. It also had a certain impact on the safety of the civilian house. The disaster situation of tunnel collapse and mud inrush is shown in Figure 8(c).

4.2. Morphological Characteristics of the Deep Karst Trough. The clay-filled deep karst trough exposed by excavation is located at the junction zone of the medium-thick strongly weathered breccia limestone and the medium-weathered thick limestone near the entrance of the tunnel. The surface slope angle is 25°, and the slope aspect is 270°. The occurrence of the rock formation is 140°∠72°, which is formed at a high and steep angle. The combination relationship between slope aspect and rock formation dip is reverse. The surface is covered by Quaternary sediments and vegetation. The deep karst trough is not easy to be found on the surface. The deep karst trough is elliptical on the surface and funnel-shaped on the section. It was developed along the rock stratum. The maximum depth of the deep corrosion trough is more than 20 m. The trough is filled with clay and a small amount of gravel, and the bottom is complete limestone. The vertical fissures of the rock mass are extremely developed and are mostly filled with clay.

4.3. Developmental Mechanism of the Deep Karst Trough. The formation of the deep filled karst trough is related to the tectonic movement, geological structure, formation lithology and stratum inclination, climate conditions, surface soil, and other factors in the Qiyueshan Tunnel site area.

4.3.1. Tectonic Movement. In general, the formation of the deep karst trough is due to the strong uplift of the ground or the continuous development in depth of the ground surface karst trough during the uplift period [17]. In this process, the surface water carries soils such as the Quaternary residual silty clay and weathered eroded residual soil to fill the karst trough. The Qiyueshan Tunnel site is controlled by tectonic movement, and the crust rises intermittently in a large area, forming a five-level layered geomorphic landscape of E'xi Age, Taiyuan Age, Shanyuan Age, Shanpen Age, and Sanxia Age. Especially since the Late Triassic, the crust has been uplifted continuously. The elevation of the deep filled karst trough is about 1,300 m.

4.3.2. Geological Structure. The deep filled karst trough is located at the entrance section of the tunnel, which is mainly affected by the development of joints and fissures and less affected by fault structure. There are two groups of joints developed at the entrance of the tunnel. (1) Group I joints have the strike of 300°~325°. The joints are nearly vertical. The surfaces of the joints are open for 1~5 cm. The spacing of the joints is about 1 m. The extension length is generally greater than 10 m. (2) Group II joints have the occurrences of 310°~320°∠20°~30°. The extension length is generally several meters. Vertical fractures provide good basic conditions for rainfall infiltration and favorable conditions for karst development.

4.3.3. Formation Lithology and Stratum Inclination. The deep karst trough is located at the junction zone of the

Table 2: Revealed karst caves before mud inrush and collapse.

Serial no.	Chainage	Location	Size of the karst caves	Filling status
1	GK0 +398	Left side of tunnel face	The karst fissure developed along the longitudinal direction of the tunnel at 15°, with a width of about 2 m, a height of 17 m, and a length of 16 m.	Wet inside the cavity, without fissure water, filled with mud
2	GK0 +400	Right side of tunnel face	The karst cave is 3.6 m long and 4 m wide upward along the tunnel, and the vertical height above the vault is 7.5 m.	Wet inside the cavity, without fissure water, filled with mud
3	GK0 +405	The right sidewall	The karst cave extends downward, with a diameter of 3.5 m and a visible depth of about 6.5 m.	No filling

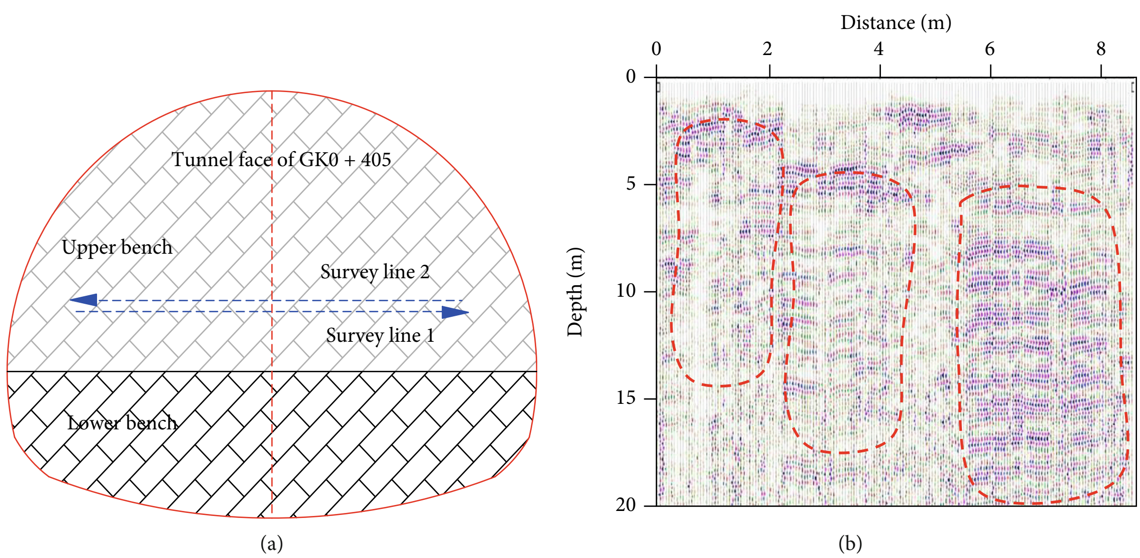

Figure 7: Tunnel face geological radar detection: (a) layout of survey lines in the tunnel; (b) detection result.

medium-thick strongly weathered breccia limestone and the medium-weathered thick limestone of Jialingjiang Formation. The surrounding rock is highly soluble. The rock transits from strong weathering to medium weathering, and the surrounding rock is relatively broken. In addition, the rock stratum is formed at a high angle, which is conducive to the infiltration of groundwater along the rock stratum. Therefore, the formation lithology and dip angle are very conducive to the development of karst.

4.3.4. Sunshine and Precipitation. The tunnel site has a subtropical monsoon climate. The climate is mild with sufficient sunshine, and annual average temperature is 15.5°C. There is no perennial surface water passing through. The groundwater is mainly supplied by rainfall. With long rainy season and abundant rainfall, the annual average rainfall reaches 1400 mm, which enhances the dynamic dissolution. In addition, high temperature and rainy weather contribute to the increase of CO_2 content in soil. It is beneficial to karst development.

4.3.5. Surface Soil. Generally speaking, the development depth of the karst will be greater if there is a thin layer of soil covering the surface. The surface of the collapse and mud inrush area is covered with the Quaternary residual deposits, which are brown, slightly wet, and plastic, containing a small amount of gravel. The maximum exposed thickness by the borehole is 1.7 m. As the surface is covered with soil and vegetation, it has a certain water retention capacity, which strengthens the infiltration of surface rainfall and increases the volume and time of rainfall infiltration. Therefore, it is favorable for karst development. However, when there is no relative water-resisting layer or weak karstification layer, the precipitation infiltration firstly forms the surface karst water and then turns runoff downward to supply the deep karst water system. In this condition, the filled karst trough generally has less water content, and the disasters mostly occur in the form of collapse and mud inrush. From the perspective of influencing factors of karst development, the mechanical destruction of the roots of surface covered vegetation, the decomposed plant residues, and humus can produce a large amount of free CO_2 and organic acids. A large number of microorganisms in the soil can also produce a large amount of CO_2. The produced CO_2 can provide favorable circumstances for groundwater to dissolve soluble rocks and hence promote the underground karst continuous development to the deep.

In addition, external weathering cannot be ignored. Weathering agent penetrates into the rock mass along structural fissures and corrosion fissures, making the rock mass

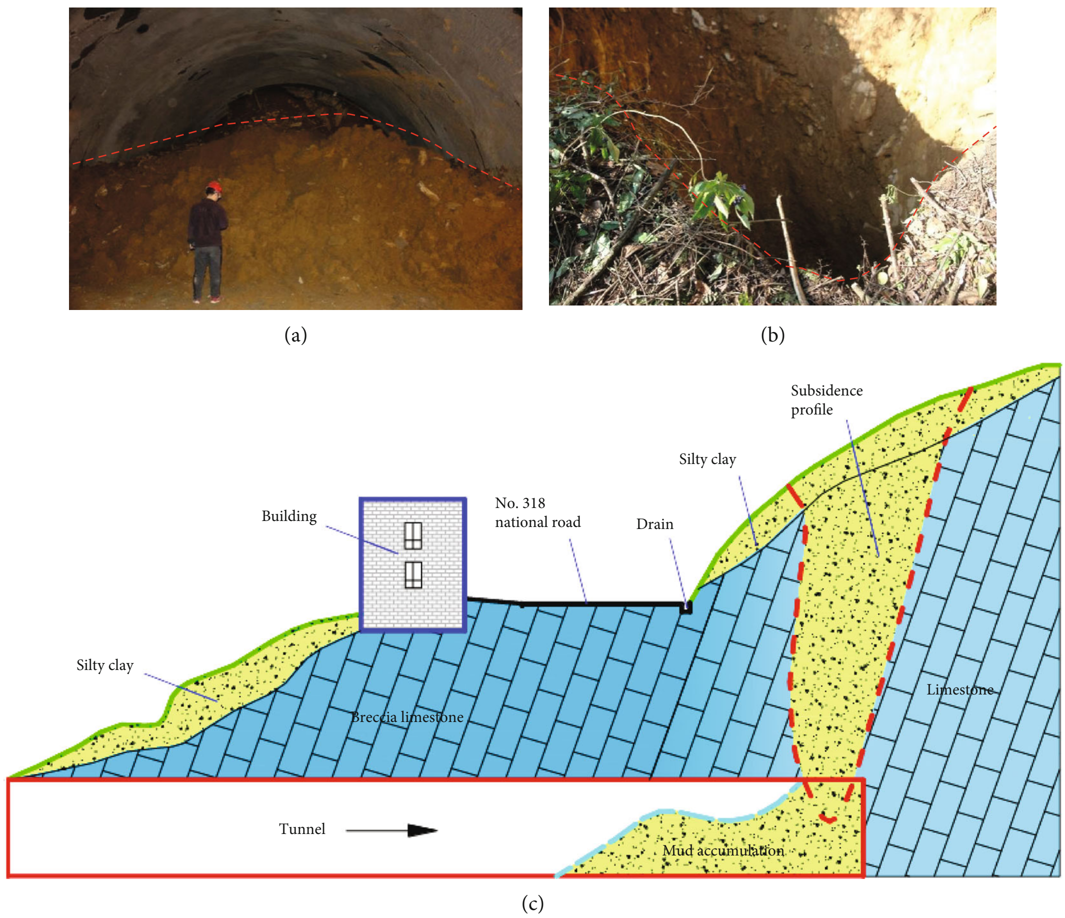

Figure 8: Mud inrush and collapse situation: (a) picture of mud inrush in tunnel; (b) picture of surface subsidence; (c) sketch of mud inrush and collapse.

on both sides of the fissure into fragments and loose state. Coupled with the infiltration of surface water, the fracture surface is eroded and expanded continuously. The weathering agent goes down with the trend, and the rock mass is further weathered downward.

4.4. Hazard-Causing Mechanism. The deep karst trough is funnel-shaped as a whole, and the filling medium is mainly clay with a small amount of gravel. The filling medium is continuously compacted under the action of self-weight, with poor water permeability. In the process of tunnel construction, the impact of karst water is relatively small, and the disasters are very likely to occur in the form of collapse and mud inrush. After the surface rainfall enters the deep karst trough, it will increase the water content and the self-weight of the filled clay. The water can reduce the friction of the clay and the friction between the clay and the surrounding rock mass. Besides, it will increase the fluidity of the clay, and hence, the stress acting on the surrounding rock mass increases. The risk of collapse and mud inrush ultimately increases. According to the spatial relationship between the tunnel and the filled karst trough, the hazard-causing modes of the filled karst trough can be divided into the following four categories, as shown in Figure 9.

4.4.1. Rock Mass Failure of Tunnel Face. The tunnel route is proposed to pass through the middle of the filled karst trough. Before the trough is exposed, the thickness of the inrush-resistance rock mass between the tunnel face and the trough gradually decreases with the continuous excavation. When the thickness of the inrush-resistance rock mass is not enough to bear the lateral earth pressure in the trough, the inrush-resistance rock mass will break and lose stability, and the filled clay will flow into the tunnel, causing collapse, and mud inrush. Large-scale mud inrush may cause surface subsidence. The insufficient thickness of the inrush-resistance rock mass is the main reason for this kind of hazard-causing mode.

4.4.2. Direct Exposure of Tunnel Face. The tunnel route is proposed to pass through the middle of the filled karst trough. With the continuous excavation of the tunnel face, all of the rock mass between the tunnel and the filled karst trough was removed ultimately. Under the condition of no inrush-resistance rock mass, the filled clay in the trough is continuously pressed down under the action of self-weight and ultimately gushes out from the tunnel face, causing collapse and mud inrush. Similarly, large-scale mud inrush may cause surface subsidence. As to this hazard-causing mode,

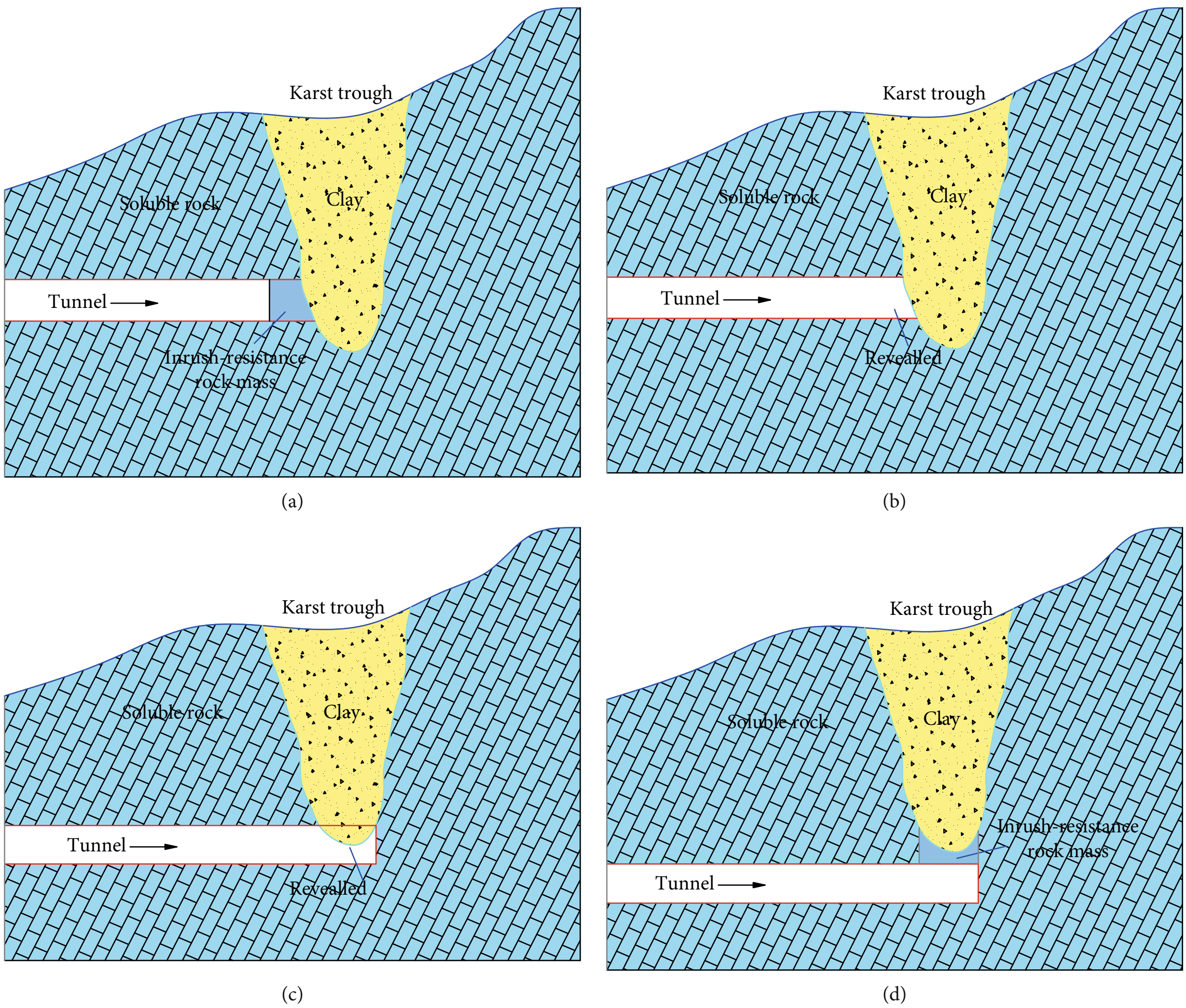

Figure 9: Collapse and mud inrush mode of the filled karst trough: (a) rock mass failure of tunnel face; (b) direct exposure of tunnel face; (c) direct exposure of tunnel roof; (d) rock mass failure of tunnel roof.

the scale of the hazard is closely related to the height and content of the filling medium in the trough.

4.4.3. Direct Exposure of Tunnel Roof. When the tunnel passes through the lower part of the filled karst trough, the tunnel excavation will directly expose the bottom of the trough. At the initial stage of exposure, the loose soil at the bottom of the trough takes the lead in collapse, and the upper soil remains temporarily stable under the clamping action of the surrounding rock mass. Subsequently, the upper soil mass continuously deforms under the action of self-weight and gradually loses its stability, resulting in a larger-scale collapse and mud inrush and even surface subsidence. The collapse and mud inrush disaster of the Qiyueshan Tunnel belongs to this category of hazard-causing mode.

4.4.4. Rock Mass Failure of Tunnel Roof. When the tunnel passes through the bottom of the filled karst trough, if the inrush-resistance rock mass between the tunnel roof and the bottom of the trough can bear the weight of the upper filling clay, there will be no collapse and mud inrush. Otherwise, if the thickness of the inrush-resistance rock mass is insufficient, the inrush-resistance rock mass will be broken and unstable, and the filling clay will flow into the tunnel, causing mud inrush and possibly surface subsidence. As to this hazard-causing mode, insufficient thickness of the inrush-resistance rock mass above the vault is the main reason for hazard occurring. Notably, this hazard-causing mode has the characteristic of certain concealment. That is because the inrush-resistance rock mass may remain stable at first. However, after the tunnel passes this section, the rock mass would break due to the persistently blasting excavation and construction disturbance or the increase of the soil mass weight in the trough due to rainfall and other factors. It will result in lagging collapse and mud inrush. What is worse, the tunnel may be closed by the clay and the workers are trapped at the tunnel face. Therefore, it has a high degree of catastrophability in this circumstance.

Therefore, when the tunnel passes through the soluble rock stratum, the following measures shall be taken in order to ensure the safe construction against collapse and mud inrush. First, conduct the karst development characteristics

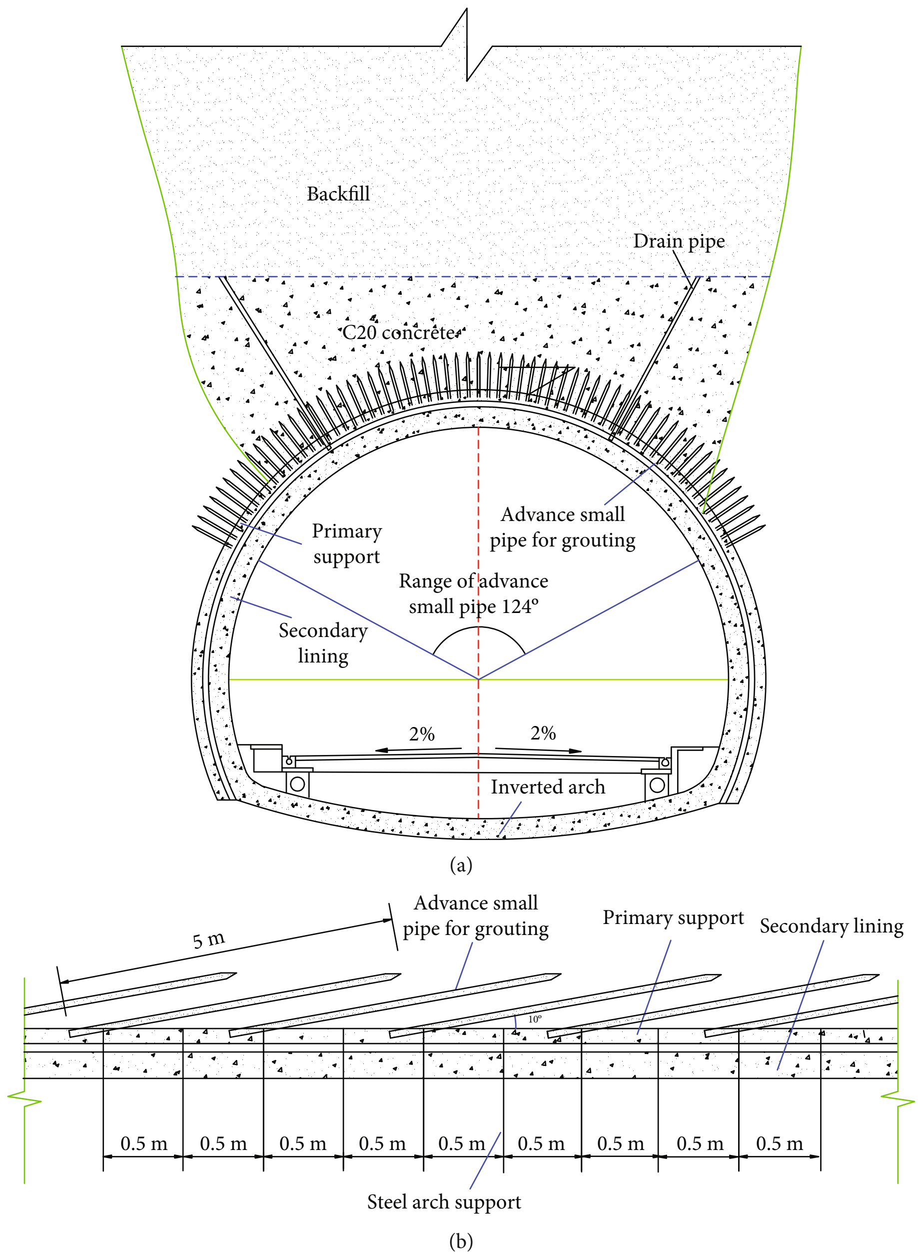

Figure 10: Diagram of collapse and mud inrush treatment: (a) cross-section diagram of disaster treatment; (b) longitudinal section diagram of advance small pipe grouting.

analysis and hydrogeological investigations at the tunnel entrance section. Second, carry out the geological analysis, surface detection, and inside tunnel detection. Third, observe the geological precursors of collapse and mud inrush inside the tunnel. Fourth, identify the hazard-causing structure of the deep karst trough in advance, and determine its spatial relationship with the tunnel. Finally, reduce the construction disturbance, and make appropriate prevention and control plan.

5. Treatment Technology for Collapse and Mud Inrush in Deep Karst Trough

According to the structural characteristics, the situations of collapse and mud inrush, and its hazard-causing mechanism of the deep filled karst trough in the entrance section of the Qiyueshan Tunnel, the following measures were adopted for treatment and construction.

5.1. Remove the Mud. The mud and slag were removed from the collapse by benching method. Sandbags containing sand and gravel mixture were used to protect and retain the mud body so as to avoid the secondary collapse and mud inrush during the construction. The damaged steel arches and initial support at the chainage of GK0 + 410 were restored.

5.2. Fill the Karst Cave. The C20 concrete was used to fill the karst cave at the top of the tunnel. The pumping concrete range was beyond the outer edge of the initial support,

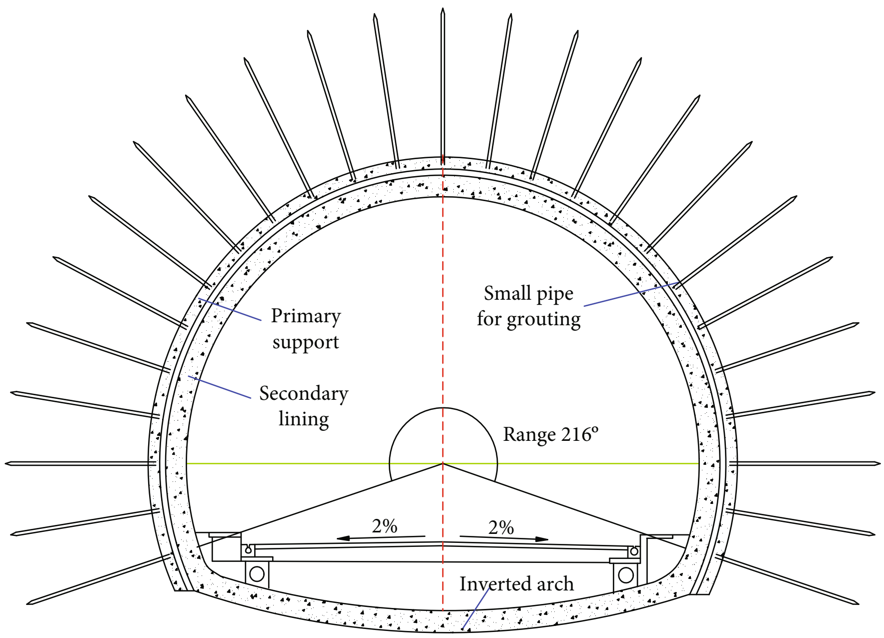

Figure 11: Diagram of tunnel support structure.

which was not less than 1.5 m. A reserved drain pipe was connected with the longitudinal drainage system of the tunnel, as shown in Figure 10(a).

5.3. Conduct Advance Grouting. Small advance grouting pipes were arranged at the chainage of GK0 + 413~GK0 + 420 of the tunnel. The layout is shown in Figure 10(b). The hot-rolled seamless steel pipes with diameter of 42 mm and wall thickness of 3.5 mm were adopted as the grouting pipes. Each pipe was 5 m long, and the extrapolation angle was 10°. The longitudinal spacing was 1 m. The circumferential spacing was about 0.2 m. In addition, the front end of the steel pipe was tapered. The tail of the steel pipe was welded onto the reinforced hoop with a diameter of 6 mm. The pipe wall was drilled with grouting holes with a diameter of 6 mm, and no grouting hole was set within 1 m at the pipe tail. The tail of the advance small pipes was welded with the steel arch into a whole. Single cement slurry was used for grouting. The water cement ratio was 1 : 1, and the grouting pressure was 0.5~1 MPa. After the advance small pipe grouting was completed, the subsequent treatment should be carried out only after the surrounding rock was stable.

5.4. Strengthen the Support. In the section of GK0+405~GK0+420, the reinforced V-class composite lining support was adopted. The types and specific parameters of tunnel support from outside to inside were as follows: (1) a single-layer steel mesh has a diameter of 8 mm and a spacing of 25 cm × 25 cm; (2) I_{18}-steel was used to assemble the steel arch. The longitudinal spacing between of the steel arches was adjusted from 0.75 m to 0.5 m; (3) the C20 wet-mix shotcrete with a thickness of 24 cm was adopted for initial support; (4) the circumferential systematic bolts were adjusted from the ϕ 25 hollow bolts to the ϕ 42 small grouting pipes. The small grouting pipes were 3.5 m long. The longitudinal spacing was adjusted from 0.75 m to 0.5 m, and the circumferential spacing was 1 m. The grouting small pipes were arranged in a plum blossom shape; (5) nonwoven geotextile and EVA waterproof plate were adopted as the waterproof layer between the initial support and the secondary lining; (6) the C25 model-building waterproof reinforced concrete was used for secondary lining, with a thickness of 45 cm. The C25 model-building reinforced concrete was used for the inverted arch, with a thickness of 45 cm. If the karst cave continued to develop forward, the support needed to pass through the front of the collapse body by no less than 5 m. The reinforced support structure is shown in Figure 11.

5.5. Waterproof the Collapse Area. Waterproof and drainage measures in the collapse area of the tunnel top were well arranged. Catchwater-drain was arranged around the subsidence area. Therefore, the surface water could be avoided flowing into the tunnel.

5.6. Backfill the Collapse Pit. After the construction in the tunnel was completed, the surface collapse pit should be backfilled.

After the treatment of collapse and mud inrush, the supporting structure system of Qiyueshan Tunnel was stable. The tunnel was successfully opened to traffic on January 13, 2017. So far, no secondary disasters such as collapse and mud inrush have occurred again, which proves that the treatment method is reasonable and can effectively ensure the safety of later construction and operation of the tunnel.

6. Conclusions

Deep karst trough is a kind of common collapse and mud inrush hazard-causing structure in a karst tunnel. The development and disaster characteristics of the hazard-causing structure have been preliminarily studied in the past, but how to identify the hazard-causing structure, how the disaster occurs, and how to deal with it are not involved. This paper proposes a comprehensive identification method, four hazard-causing modes, and a treatment technology which can be used for prevention and control of the collapse and mud inrush disaster. The main conclusions of this study are as follows.

(1) The deep filled karst trough is mostly developed in the soluble rock stratum at the tunnel portal section. It is funnel-shaped developed downward from the surface. The trough is mostly filled with clay with a small amount of gravel. The development scale is affected by the geological structure, tectonic movement, formation lithology, climate conditions, and other factors. The exposure of the hazard-causing structure during construction is very likely to cause collapse, mud inrush, and other disasters

(2) Frequent appearance of corrosion fissures and small karst caves can be adopted as the geological precursory information to identify the hazard-causing structure. The distance required to carry out TSP is usually not available at the tunnel portal section. Surface geological radar detection and tunnel face geological radar detection are effective means to identify the deep karst trough. Comprehensive usage of geological identification, surface geological radar detection, and tunnel face geological radar detection can identify the hazard-causing structure effectively

(3) The hazard-causing modes of the filled karst trough can be divided into four categories. (a) The tunnel passes through the middle of the trough, and the thickness of the inrush-resistance rock mass is insufficient, namely, rock mass failure of tunnel face. (b) The tunnel passes through the middle of the trough which is revealed directly, namely, direct exposure of tunnel face. (c) The tunnel passes through the lower part of the trough which is revealed directly, namely, direct exposure of tunnel roof. (d) The tunnel passes through the lower part of the trough and the inrush-resistance rock mass the trough is insufficient, namely, rock mass failure of tunnel roof

(4) The hazard-causing mode of collapse and mud inrush caused by a deep filled karst trough in Qiyueshan tunnel was direct exposure of tunnel roof type. A series of treatment measures including "remove the mud, fill the karst cave, conduct advance grouting, strengthen the support, waterproof the collapse area, and backfill the collapse pit" were used, and the disaster was successfully treated. The treatment technology was proven to be effective in use

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare no conflict of interest.

Acknowledgments

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