Karst Geology in Southwest Hubei and Mitigation of Geohazards During Mountain Tunnel Through a Large Karst Cave

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Abstract

The outcrop area of carbonate rocks accounts for 61.6% of the total area in Southwest Hubei. The action of tectonic application, erosion of surface and underground water system, topography, and carbonate geology leads to the formation of large karst caves, and their features are as following: considerably large, long and narrow, winding and in different forms. Limited by route directions, large karst caves would be encountered during tunneling through mountains, therefore causing hazards such as instability of the karst cave, water or stone ingress, damage to the tunnel, and long-term instability. A case study of mountain tunnel through a large karst cave is presented. The large karst cave is formed due to the erosion of limestone by two underground river systems. The length, width and volume of the cavity of the large karst cave are about 139 m, 91 m and $4.3 \times 10^5$ m$^3$. The large karst cave is overall stable without strong external factors. Engineering proposals and treatment of the large karst cave are introduced. The small pipe grouting method is used to treat the foundation. Two kinds of lining structure schemes are adopted, double lining open-cut tunnel structure, and traditional tunnel structure after backfill. The water outside the lining of the open-cut tunnel is introduced into the tunnel ditch and discharged through the tunnel drainage system. Monitoring and measurement during tunneling construction and operation process are introduced.

Introduction

With the rapid development of highway in China during the last three decades, large numbers of mountain tunnels have been constructed. Up to 2019 in China, there are 19067 highway tunnels of about 19 million meters, including 1175 extra-long tunnels of 521.75 million meters and 4784 long tunnels of 82.631 million meters. In recent years, the geology encountered in highway tunnel construction has become increasingly complex, such as hard rock, soft rock, and karst (Ju and Zhu 2007; Yang et al. 2007; Gui 2008; Li 2009; Cui 2015a, 2015b). Karst is widely distributed throughout China (Yuan 1976; Lu 2010). As the restrictions of funds, survey conditions, tunnel directions, judgment of engineers and other factors, it is arduous to fully expose the real geology, such as large karst caves. Geological hazards, such as cave collapse, water or stone ingress and tunnel structure damage can occur during engineering construction in karst regions. Although there are many reports on tunneling in karst region, mountain tunnel excavation in large karst cave has not been systematically discussed in existed studies (Li and Du 2004; Yilmaz 2007; Zhao et al. 2007; Qian et al. 2011; Luo 2012; Zhang et al. 2012; Zhao et al. 2012; Tóth et al. 2013). Therefore, it is essential to study karst geology and to take effective countermeasures to mitigate geohazards during mountain tunnel excavations through large karst caves.

Southwest Hubei of 2 cities and 8 counties, with an area of 29000 km$^2$, is located in the southwest of Hubei Province. There are plenty large mountains, which belong to the subtropical monsoon humid climate zone. Carbonate area accounts for 61.6 % of total area (Yang et al. 2003; Zhou and Liu 2009; Xu 2018). Water systems abound in the region, such as Qingjiang River, Yujiang River, Tangyan River, Youshui River and Loushui River. Annual average rainfall and annual average temperature are relatively high. Many large karst caves formed under the action of heavy rain, underground river systems and
crustal movement. Most of the large karst caves revealed have been transformed into tourist caves. For example, Tenglong Cave located in Lichuan City is one of the most famous caves with a length of 525000m, it is composed of water caves, dry caves, catfish caves, cold wind caves and other caves. Its main cave and branch caves are interconnected, and its water caves and dry caves are connected. Generally large caves should be avoided in engineering design process, and thus there are few cases and related studies of tunneling through large caves.

Slurry grouting is often adopted for the treatment of small karst caves (Ju and Zhu 2007; Gui 2008; Cui 2015a, 2015b). For large karst caves, comprehensive judgment is required to take treatment measures. Large-scale karst mainly provokes two problems. One is treatment of water in the cave and the surrounding rock, and the other is the treatment of karst cavity (Shi 2017; Shi 2018; Zhao et al. 2021). The principle of the treatment of large karst cave is to build a tunnel that meets the needs of construction and operation with acceptable cost. The treatment measures should focus on the stability of tunnel foundation, the durability and safety of tunnel structure, the overall stability of karst cave and the diversion of karst water (Fan et al. 2018). The karst water can be treated by plugging and drainage, without undermining the original flow system. As the spatial relation between karst caves and tunnels, large karst caves are often treated by bridges, piles, backfill concrete and grouting (Fan et al. 2018). In order to obtain accurate stress and deformation of the cave and tunnel, monitoring and measurement should be emphasized during the construction and operation of the tunnel.

Comprehensive considerations of geology, safety, economic and technical feasibility should be taken to treat large karst cave. At present, a stable treatment system has not been proposed yet. In this study, a mountain tunnel through a large karst cave in Southwest Hubei is presented as a case to introduce mitigation of geohazards during mountain tunnel through large karst cave. The objectives of this paper are as follows: (1) to investigate geology and distribution of large karst caves in Southwest Hubei; (2) to discuss potential geo-hazards by tunneling through large karst caves; (3) to introduce a case of mountain tunnel through a large karst cave; and (4) to introduce formation process of the large karst cave and the engineering measures and treatment technique.

Geology In Southwest Hubei

Southwest Hubei belongs to subtropical monsoon mountainous moist climate zone, which borders Chongqing on the west and Hunan on the south (Yang et al. 2003; Zhou and Liu 2009; Xu 2018). The karst in Southwest Hubie belongs to Yun-Gui plateau and south basin karst area, where extensive karst landforms are found, including soluble depressions, peak forest valleys, isolated peak plains, and subsurface streams. (Lu 2010). Figure 1 shows main rivers in Southwest Hubei. The branch water system, which composed of Qingjiang River, Yujiang River, Tangyan River, Zhongjian River, Youshui River and Loushui River, is strongly influenced by the rising crust of geotectonic movement (SKQRB 1996). From Qingjiang River Valley, taken as the center, to mountain tops on both north and south sides of Southwest Hubei, the annual average temperature decreases from 16°C to 8°C, while the annual average rainfall increases from 1100mm to 1800mm. There are two heavy rainfall centers, Lvcong slope (1825
mm) and Hefeng (1701 mm). The erosion of the river is extremely strong due to its sudden surges and falls, and therefore leads to a 'V' shape canyon on the cross section of the river valley.

Figure 2 shows the geology of the Southwest Hubei. Except for upper Silurian, lower Devonian and upper Carboniferous, strata in Southwest Hubei are exposed from Mesoproterozoic to Quaternary (Yang et al. 2003; Zhou and Liu 2009). The carbonate rock area is $2.1 \times 10^4$ km$^2$, which mainly consists of Cambrian, Ordovician Middle-Lower Carboniferous, Permian and Middle-Lower Triassic. Structurally, the area is located in the Bamianshan platform fold belt on the Yangtze paraplatform, north of Hubei fold fault zone, west of Sichuan platform depression, and east extension under the Jianghan fault depression. The fracture in the area is dominated by folds, and secondary by faults. Geology in Southwest Hubei is an extension part of the northeast direction of the Yunnan-Guizhou Plateau (Yang et al. 2003; Zhou and Liu 2009). The geomorphological morphology is dominated by middle mountains and a few low mountains. The external force in the process of landform formation is dominated by corrosion and secondary by erosion. Influenced by the tectonic line, the western mountains are mostly NE-trending, while the eastern mountains are mostly EW-trending. The elevation of the mountain top is generally more than 1000 m, and the peaks of more than 2000m are mostly distributed in the Qingjiang River, Yujiang River, Tangyan River, Youshui River, Loushui River, and the watershed area with the Yangtze River, which generally decline to the valley. Affected by the outcrop and distribution of carbonate rocks and uneven tectonic uplift, the karst landform of slope canyons is mainly formed by erosion in the east. The karst landform of valley between plateaus is mainly formed by dissolution in the west. Karst development is characterized by layer, depth, heterogeneity and vertical zoning.

**Large Karst Caves In Southwest Hubei**

From Sinian to Middle Triassic, thick marine carbonate deposits in Southwest Hubei (Xu 2013). The exposed area of carbonate rocks accounted for 61.6%. Figure 1 also shows a plan view of the distribution of karst caves in Southwest Hubei. The karst caves in this area are considerably large, long and narrow, winding and in different forms. The karst forms include small stone teeth, stone pillars, ditches, troughs, micro-karst gaps, holes, caves, pipes, large rock houses, shallow caves, depressions, funnels, shallow underground rivers, surface karst springs, and etc. Miniature and small karst caves are widely distributed from tops to slopes and valleys. Large karst mainly develops and distributes in areas with strong dissolution and underground river system development. 73 large karst caves have been found, mainly for tourism purposes.

Karst caves are usually formed by the interaction of rock, water and cave. Large karst caves are mainly distributed in the range of 1800m ~ 2500m near the main stream and tributaries (Xu 2013). The main reason is that the nearshore areas of Qingjiang River, Youshui River, Loushui River and Tangya River are mostly deep canyons, and the erosion datum of groundwater is low, which increases the hydraulic gradient of groundwater and strengthens the water cycle movement. Coupled with the continuous accumulation of surface water and groundwater in the vicinity, the dissolution and erosion of water to
carbonate rocks in the formation become stronger, which makes the karst caves in the coastal zone develop more and in greater sizes.

In Southwest Hubei, affected by the intermittent activities of neotectonic movement, mountains are formed by uplift (Shen et al. 1996). Local fault depressions and depositions formed multi-level leveling surfaces and intermountain valley fault basins. The development and formation of karst caves are also affected by the intermittent activities of neotectonic movement. In each stratigraphic uplift period, the riverbeds of the main rivers, such as Qingjiang River, Youshui River and Loushui River, are continuously cut down. Base level of groundwater discharge decreases which accelerates the development of karst cave. At each relatively stable uplift interval, a horizontal karst cave consistent with the discharge datum will form. Since the Cenozoic, affected by five intermittent tectonic uplift movements with different scales, four types of karst caves have been formed, including medium-low altitude karst caves, medium-high altitude karst caves, and high altitude karst caves. There is a one to one These four types of caves almost correspond one-to-one with the 500-700m, 800-900m, 1000-1200m and 1300-1500m planation surfaces (Shen et al. 1996).

Hazards Of Tunneling In Large Karst Regions

As there are massive mountains in China, it is inevitable for expressway tunnels to go through mountains. Due to its wide existence and difficulty to find during engineering survey, large karst caves are likely to be encountered during the tunneling process in karst developed areas, such as Southwest Hubei. The following hazards may be encountered during tunneling in large karst caves: (1) instability of the large karst cave, (2) water or stone ingress, (3) damage to the tunnel, and (4) long-term instability (Day 2004; Knez 2008; Alija et al. 2013).

Since large karst caves are naturally formed, their states are relatively stable without disturbance. However, boulder falling, side wall and top collapse, and foundation instability would occur due to the disturbance by tunneling. Before construction, the existence of karst caves might not be predicted in advance by detailed geological survey due to lack of engineering founding, deep buried tunnel, and inaccurate experience. Figure 3 shows that a boulder hit the digger during the Taiping Tunnel construction. The location was 25m away from the edge of the large karst cave. The rocks in the dome are distributed in layers with different thicknesses, and the medium-thick layers dominate. The dip angle of rock stratum is relatively blunt. Most of the thin–medium-thick layered limestone in the dome is not supported. Boulder would fall when acted by an external force, which can be mechanical operation of the tunnel, construction outside the mountain, blasting construction, and etc. Due to rains, especially the heavy ones, the rock at the dome of the karst cave was eroded, and the frequency of boulder falling significantly increased.

Because the formation of large karst caves is related to the surrounding groundwater system, water ingress may occur during tunnel construction. The water pressure around the tunnel lining structure may be high, even if the drainage channel is set in the tunnel. Once water blocking is untimely, large stones
often accompany the water ingress. Relevant experts have established unknown water and soil inrush models based on actual engineering data to obtain index weights of impact factors for more effective control the risk of water inrush and mud outfall to ensure the safety of the tunnel (Li et al. 2013; Li et al. 2017).

A tunnel built in a large karst cave may be destroyed by the surrounding geology and water system. Tunnel structures may not be able to bear the load of boulder falling. The tunnel lining structure may be subjected to tremendous water pressure and need to increase its thickness. The ground at the bottom of the karst cave may be a virtual filler or a harder rock, which is difficult to ascertain. The foundation needs to be treated by replacement method or slurry grouting to ensure the bearing capacity and stability. Blasting construction, backfill treatment, cave reinforcement and other schemes will inevitably destroy the original stability of surrounding rock, which may impact on the whole mountain. All of the above factors will result in schedule delay, engineering cost increase, soil disturbance, or tunnel collapse.

Long-term deformation of geotechnical structure, groundwater erosion, post-construction settlement induced by tunneling disturbance, cyclic loading of the cars, geological tectonic movement, and etc. would also cause long-term instability in a karst cave region in the tunnel project. Affected by external conditions, new karst caves may be formed within the mountain, bringing new hazards. Therefore, in the construction process and subsequent operation process, it is necessary to intensify the observation of the tunnel and the whole karst cave, and to apply timely treatment measures. The treatment measures adopted should help to maintain the long-term stability of the tunnel.

Description Of Construction Site

Figure 4(a) shows the plan view of the Taiping Tunnel which is part of the Yidu to Laifeng Expressway of Hubei Province. The Taiping tunnel is a separated tunnel, which is constructed by drilling and blasting method. The length of the left tunnel is 626m with a maximum buried depth of 118m. The length of the right line is 634m with a maximum buried depth of 145m. A large karst cave (LKC) was found during tunneling. Five geological boreholes were drilled to find out the geology and space of the LKC, as shown in Fig. 4(a). The lengths of the LKC along the right and left tunnel are 127m and 148m. The maximum width of the LKC is about 91m and the height of the karst cave is 20 ~ 66m. Figure 4 (b) and Fig. 4(c) show the longitudinal sectional view (b), and cross sectional view of the tunnel, according to the comprehensive inference of drilling and field investigation. The length, width and volume of the cavity of the LKC are about 139 m, 91 m and $4.3 \times 10^5$ m$^3$. The LKC consisted of a large number of boulders and blocks, the largest diameter of which is about 3m, and a small amount of clay filling. The rock surrounding the tunnel is limestone of the second member of Jialingjiang Formation in the lower Triassic. The limestone is medium weathered or breezy with developed joint fissure development. The color of limestone is steel-gray or dark gray. The limestone is of brittleness, strong resistance to weathering and karst-developed properties. Table. 1 lists the geotechnical properties of the limestone. The compressive strength is about 9 ~ 57 MPa. Figure 5 shows the cavity, deposits, internal environment of the LKC.
Formation Of The Lkc

Figure 6 shows a plan view of the underground river systems near the tunnel. As shown in Fig. 5, there are two underground river systems on both sides of the tunnel. One is Taiping-Hefeng underground river system and the other is Leijiaping-Hefeng underground river system. Figure 7 shows the sectional view of Taiping-Hefeng and Leijiaping-Hefeng underground river systems. Both these two underground river systems flow from the top to the deep of the mountain in an angle of 18° to horizontal. Figure 8 shows the formation process of the LKC. These two underground river systems and the LKC originally belong to the same erosion datum and there may be karst fissures, dissolved pipes, small cavities in the mountain (Yi et al., 2015). As shown in Fig. 8, the mountain where the Taiping Tunnel lies is uplifted due to crustal movement. The gradual loss of the limestone in the mountains, which are eroded down by these two underground river systems, eventually formed a large karst cave. Mountain tectonic movement and erosion of the underground river system should be the main factors for the formation of the LKC.

When floods occur during crustal uplift or cave formation, sediment and gravel carried by underground rivers enter the LKC through karst fissures or karst conduits (Fig. 7 and Fig. 8). Sediment and gravel are trapped in the LKC after floods. Since part of the gravel in the karst cave are already calcified and consolidated, it is speculated that the current LKC experienced multiple flood levels a long time ago. Inferring from the evolution process of the tunnel and underground river systems (Fig. 7 and Fig. 8), the current flood level is probably lower than the historical ones. No horizontal karst conduits are found around the karst cave walls.

According to the observation in a hydrological year (August 2017 ~ August 2018), rainwater infiltrates into the tunnel along the karst fissure, and there is no sign of bulky water entering the tunnel. The rock at the bottom of the karst is dissolved by underground river, while the jointed rock at the top of the karst cave collapses under the erosion of karst water or surface water (Fig. 8). According to the formation and development process, the properties of the filling and the surrounding geological analysis, the LKC is self-balanced and would not collapse.

Engineering Proposals And Treatment Of The Lkc

The treatment scheme of the LKC needs to consider (1) the stability of tunnel foundation, (2) the stability of cave dome, (3) the safety during construction and operation period.

Stability evaluation of the LKC

The large quantity of year-round boulder falling at the bottom of the LKC are of different sizes. The depth of accumulation is between 18~28m. Fig. 9 shows the falling boulders in the LKC. Plane projection area of dome is about 8000m$^2$. The color of the middle LKC is grey, while the rock surface is fresh, and dripping sound can be heard, which indicates that there are cracks in the middle part. The weathering time of rock surface here is not long, and the rock is basically stable. The dome and side wall of the south entrance section of the tunnel into the cave are dark yellow and seriously weathered, and some of the
rocks have been completely argillized, which suggests that this area may be the trigger point of dome instability. The lowest part of the LKC cavity is in the north. The boulder is dry on the surface and loosely piled up. Height of accumulation in south is higher than that in north, because more collapses occurred here. Linearly distributed stalactites are developed in the dome along the joint fracture surface, ranging from 2cm to 20cm in length, which are approximately perpendicular to the direction of the tunnel, and are more concentrated in the south than north. On the south side of the LKC dome, karst fissure water drops like raindrops, and in some parts, there are karst troughs with linear continuous karst fissure water flowing down. The northern dome of the LKC is relatively dry.

The south side of the accumulation in the cave is about 20 m higher than the north side. The moderate weathered boulders of 8.2~15.2m can be exposed below the bottom of the left tunnel, which maintains a good stability. The right tunnel exposes at least 8m moderately weathered rock, and the 48m of which bottom rock has good stability. The terrain of 79 m on the north side is a groove, and the elevation is significantly lower than that of the left tunnel. Due to the loss of large amount of the accumulation, it is speculated that there is a karst channel (karst funnel or karst gap) at the bottom leading to the erosion datum plane.

The top of the LKC is dome-shaped, which benefits to self-stability. Vertical karst develops in the surrounding rock, and seepage, dripping or small strand flow occurs in the dome during flood periods. The dome is basically stable, and there are a few partial collapses or falling blocks. The stability evaluation shows that the LKC is overall stable without strong external factors (He et al. 2014). Conventional mechanical construction and manual operation would not cause overall instability, severe collapse and boulder falling.

Consideration of dome stability

Considering the stability of the dome during operation, it is necessary to prevent the falling of small stones and boulder along the occurrence, fracture and weathering zone under the action of gravity. Fig. 10 shows the schematic diagram of the treatment of the dome. Two dome reinforcement schemes were initially proposed. (1) Reinforce the dome by steel strand anchor cable through drilling holes from the mountain surface. However, the construction of this scheme is difficult, and the prestressed anchor cable may destroy the stability of the existing LCK. Both the construction cost and the construction risk are high. (2) Reinforce the dome by 7m long Φ32 cartridge anchor. The scheme takes full advantages of the suspension effect of the anchor rod and sprays concrete onto the hanging net to prevent rock weathering and enhance the overall stability of the dome. However, the dome height too high for the mechanical equipment to go up, and the supporting effect is difficult to evaluate, moreover the stability of the LKC would be significantly affected by the construction disturbance. Considering that the dome is currently in a self-stable state, the safety of the tunnel structure can be enhanced by strengthening the buffer layer at the top of the tunnel without disturbing the dome. Finally, it was decided not to take any engineering measures in the dome to maintain its original state. The backfilling of concrete, lightweight foam
concrete and old tires above the tunnel lining can alleviate the impact of boulder falling from the dome onto the tunnel.

Ground treatment

The accumulation at the bottom of the LKC are mainly stone and clay, which are loose and partially calcified, as shown in Fig. 8. Among them some are moderately weathered rock, or grooves. Initially, replacement method is planned for foundation treatment for about 5m, and replacement materials are clay or gravel. However, considering that the replacement involves rolling and digging out the ground, and the 10 m elevation difference between the accumulation in the LKC, replacement method may affect the stability of the excavated tunnel. Eventually, it is decided to use the small pipe grouting method for foundation reinforcement. Fig. 10 shows the Schematic diagram of small pipe grouting method for treating the foundation. The bottom soil, stone and boulder are compacted by slurry to enhance the overall stability of foundation and improve the bearing capacity of foundation.

Tunnel lining structure

The lining structure should meet the needs of driving and resist the impact of falling stones on the top. Considering the height difference of accumulation and stability evaluation of the LKC, two kinds of lining structure schemes are adopted, (1) double lining open-cut tunnel structure, (2) traditional tunnel structure after backfill.

Fig. 11 shows the section of double lining open-cut tunnel structure. The lining is a double layer arch structure, which consists of 50cm inner reinforced concrete and 120cm outer reinforced concrete. There are 50cm cavity and 50cm waste tire between the inner and outer reinforced concrete. The exterior of the outer reinforced concrete is a buffer layer with 3m used tire. The outer lining and the buffer layer of waste tire is mainly used to resist the load of rockfall. The inner lining can still work even if the outer lining is broken. The foundations of inner and outer lining are completely separated by setting a 10 cm longitudinal joint to form through bottom plate.

Fig. 12 shows the cross sectional view and longitudinal sectional view of the backfill in the LKC. Backfill C15 plain concrete below tunnel arch waist to tunnel bottom. Backfill about 7m C20 plain concrete on C15 plain concrete. Backfill about 6m foam concrete on C20 plain concrete to resist rockfall load. Concrete and foam concrete backfill process is simple with no large machinery required. After backfilling, the New Austrian Method is adopted to excavate the tunnel.

Fig. 13 shows the section of traditional tunnel structure. The primary support combinates bolt, steel mesh shotcrete and steel arch, and the secondary lining is the 80cm reinforced concrete structure of C30. 20cm is reserved for the deformation between primary support and secondary lining, and to prevent primary support deformation caused by foundation settlement during construction.

Drainage system
In Taiping Tunnel geological survey, the water of surrounding underground river system infiltrates vertically with a flow of 142.4L/s at elevation of 896m and 1200L/s at elevation of 460m. The length of the underground river is about 12km and the hydraulic gradient is 36.3‰. Seepage, dripping, or small strands of water may occur above the tunnel in flood season. The maximum water flow through the tunnel under the flood period is 148L/s, and the maximum water flow above the tunnel is 17.97 L/s. There is no horizontal karst channel around the karst cave, and no sign of surface water flowing into the tunnel along the horizontal karst pipeline. According to the hydrogeological level, the tunnel karst cave is located in the recharge and runoff area of the underground river, but the catchment area is small. In general, the overall stability of the tunnel project will not be affected by the flood.

In the special investigation report of karst cave hydrogeology, it is difficult to fully discover the distribution of hydraulic channels. Therefore, the drainage channel at the bottom of the original cave should not be destroyed in construction. As shown in Fig. 11, for open-cut tunnel, a comprehensive drainage scheme is proposed by setting trapezoidal ditches in the middle of left and right lines and rectangular ditches outside the tunnel. A HDPE blind pipe with a diameter of 10 cm is laid every 10 meters along the route to drain water from the cave. Water flows outside the tunnel with a rectangular drain. For covered-excavation tunnel, set up two rectangular ditches in the tunnel for drainage.

Monitoring and measurement during construction and operation period

It is necessary to strengthen the monitoring and measurement of surrounding rock during tunneling construction. A monitoring section should be laid in the longitudinal direction of 3-5 m, and a monitoring point should be set in the circumferential direction of 3-5m. Monitoring projects include dome subsidence, vertical and horizontal displacement of the karst cave, settlement and clearance convergence of the tunnel, side wall surface and deep displacement. Then the evolution law of cave surrounding rock deformation with the construction process can be grasped. Once abnormal deformation or other risks are found, timely measures should be applied. During the tunnel operation period, parameters such as surface settlement, dome displacement, and foundation settlement should be monitored. Set up an alarm system and make an emergency prevention plan. In order to ensure the long-term safe and stable operation of the tunnel during construction and operation, the corresponding monitoring, lighting and alarm systems should be monitored at the dome of the karst cave.

Conclusion

The following conclusions can be drawn.

1. Mountains and water systems are widely distributed in Southwest Hubei. Annual average rainfall and annual average temperature are relatively high. The outcrop area of carbonate rocks accounts for 61.6% of the total area and underground river system is developed. Tectonic application and erosion of water system leads to the formation of large karst caves.
2. Hazards will appear when tunnelling in large karst cave regions, such as (1) instability of the large karst cave, (2) water or stone ingress, (3) damage to the tunnel, and (4) long-term instability.

3. A case study of mountain tunnel through a large karst cave is introduced. The treatment scheme of the large karst cave needs to consider (1) the stability of tunnel foundation, (2) the stability of cave dome, (3) the safety during construction and operation period.

4. Considering that the dome of the large karst cave is already in a self-stable state, reinforcement by bolt or steel strand is not advised, and no engineering measures were adopted to treat the dome. Small pipe grouting method, rather than replacement method, is recommended to treat the foundation, for it helps to reduce the disturbance to the cave.

5. Two kinds of lining structure schemes are adopted, (1) double lining open-cut tunnel structure, (2) traditional tunnel structure after backfill. These two structures can both resist rockfall load. In order to avoid water accumulation, the water outside the lining of the open tunnel is introduced into the tunnel and discharged through the tunnel drainage system.

6. Monitoring and measurement should be emphasized during tunneling construction and operation.

**Declarations**

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Tables

Table 1. Geotechnical properties of the limestone

| Rock   | Unit weight (kN/m³) | Compressive strength (MPa) | Cohesion (kPa) | Softening coefficient |
|--------|---------------------|-----------------------------|----------------|----------------------|
| limestone | 27.2-27.9          | 9-57                        | 146-300        | 0.93-0.96            |

Figures
Figure 1

Distribution of karst caves and main rivers in Southwest Hubei (Created based on Xu, 2018)
Figure 2

Geology of the Southwest Hubei (Created based on Zhou and Liu, 2009)
Figure 3

A boulder hit the digger during the construction of Taiping Tunnel
Figure 4

(a) plan view, (b) longitudinal sectional view, and (c) cross sectional view of the project

Figure 5
Cavity, deposits and internal environment of the large karst cave

Figure 6

Plan view of the underground river systems near the tunnel
Figure 7

Sectional view of (a) Taiping-Hefeng underground river system and (b) Leijiaping-Hefeng underground river system
Figure 8

Formation process of the large karst cave
**Figure 9**

Falling stones in the large karst cave
Figure 10

Schematic diagram of the treatment to the dome and the foundation

- Anchors and shotcrete (not adopted)
- Contour line
- Tunnel
- Small pipe grouting

| Waste tyre (3m)  |
|------------------|
| Reinforced concrete(C30, 120cm) |
| Waste tyre (50cm)*cavity(50cm) |
| Reinforced concrete(C30, 50cm) |
Figure 11

Double lining open-cut tunnel structure

Figure 12

Cross sectional view (a) and longitudinal sectional view(b) of the backfill
Figure 13

Cross section of traditional tunnel structure