Mechanism of water inrush in tunnel construction in karst area

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ABSTRACT
With the rapid developing trend of long, large and deep construction characteristics for underground engineering in the world, China has the largest number of karst tunnels with the wide scales and great difficulties. As the hydrogeological conditions are becoming unprecedentedly complex, water inrush disaster becomes the bottleneck problem for the further development of traffic tunnels. Based on the statistical analysis of a large number of cases of water inrush in karst tunnels, influence factors of water inrush have been put forward from the view of karst hydrogeological factors and engineering disturbance of human factors. Karst hydrogeological factors include geological defect, strata dip, formation lithology, landform and underground level. Human factors of engineering disturbance include excavation and reinforcement geological prediction, monitoring and measurement of surrounding rock. It also introduces some geological disasters caused by the water inrush in tunnel excavation. In terms of the formation of water inrush channel, water inrush types are divided into geological defects inrush, non-geological defects inrush and the combination. Conclusions will be beneficial to further research on hazards control of underground construction.

KEYWORDS
Mechanism of water inrush; tunnel construction; geological disaster; karst area

1. Introduction

In China, karst areas cover about one-third of the total land area of the country, especially in southwestern China, such as Yunnan, Guizhou, Guangxi, Sichuan, Hubei and Hunan. With the rapid development of west regions, tunnel, hydropower station or inter-basin water transfer have been widely constructed in karst areas. However, the geological hazards, especially the water inrush, rock burst, collapse, and mud gushing may be encountered during the construction of underground engineering. The most serious geological hazard is water inrush.

In the statistics of major tunnel disasters, the casualties and property damage caused by large-scale water inrush are the top three in the world. And it brings great security risks and economic losses (Li, Li, & Cui 2008; Li, Xue, et al. 2008; Qian & Rong 2008; Zhang et al. 2011), as shown in table 1.
1.1. Traffic tunnels engineering

Up to the end of 2008, the number of highway tunnels in China had reached 5246, with a total length of more than 3000 km. And the 9000-km-length tunnel will be built in China. At the end of 2010, the number of railway tunnels in operation was about 9800 with a total length of 7000 km, and the number of tunnels in construction is about 4000 with a total length of 750 km. Furthermore, the number of tunnels is about 1500 with total length of 1100 km in planning. Based on the statistics data (Shi 2014), the water inrush is a common hazard during tunnel construction and operation in karst tunnels, and nearly half of the tunnels in construction and operation have encountered large-scale water inrush in karst areas (figure 1).

1.2. Water resources and hydropower engineering

In China, the construction scales and difficulties for karst tunnels are the no. 1 of the world. In the field of water resources and hydropower engineering, the cascade development of hydropower and the construction of hydropower infrastructural facilities at major river basins is the main objective of the 12th five-year plan. A considerable portion of large-scale hydraulic tunnels are located in western China, which have the features of deeply buried, long tunnel and complex geological conditions. During the hydropower development in south-west China — Jinsha River, Lancang River, Yalong River and other rivers, world-class engineering problems caused by the complex geological conditions were encountered.

The depth of Jinping II hydropower station diversion tunnels is more than 2000 m. Sudden water inrush of high pressure and large flow (water pressure is over 10 MPa, the maximum instantaneous water gushing reached $2.5 \times 10^4$ m³/h) encountered in this tunnel construction is quite rare at home and abroad. Local water inrush accidents happened many times which seriously delayed the construction progress (Yu et al. 2005; Chen et al. 2008; Xue et al. 2008; Zhang et al. 2009; Li 2011) (figure 2).

Obviously, due to the complexity of karst development and regularities of water-bearing structure occurrence, the main reason why the karst water inrush is difficult to avoid is the poor understanding of the water inrush mechanism. The influence factors of karst tunnel are varied under the specific engineering background. Influence factors are divided from the perspective of risk assessment (Li et al. 2011). A construction safety risk control system has been established and is used to guide construction. The application effect of the tunnel construction licensing mechanism operation effectively avoids the large- and medium-sized water geological disasters (Li 2011). The influence factors also were divided into groundwater level, unfavourable geology, formation lithology, topography, strata inclination, excavation, advanced geological prediction, and monitoring. And a software system for risk assessment of water inrush has been established with considering these risk factors (Li, Li, Chen, et al. 2011; Li, Li, Xu, et al. 2011). Although the predecessors put forward the risk influence factors of karst tunnel, their analysis for factors is not enough. The article will carry on the more accurate analysis and description to water inrush of karst tunnel. Therefore, based on the characteristics of karst water inrush, this paper mainly puts forward the influence factors of water inrush.

### Table 1. Typical case of water and mud inrush in the field of traffic tunnel engineering.

| Traffic tunnels engineering | Tunnel name          | The position | Water irruption quantity (m³) | Mud irruption quantity (m³) |
|-----------------------------|----------------------|--------------|------------------------------|----------------------------|
| Highway tunnel              | Huayingshan          | Left line    | $8.64 \times 10^5$           | 7000                       |
|                             |                      | Right line   | $2.40 \times 10^4$           | 1200                       |
|                             | Longtan              | ZK72+145~190 | -                            | 13,000                     |
|                             | Wuzhishan            | K30+900      | $1.03 \times 10^4$           | -                          |
| Railway tunnel              | Yuanlangshand        | DK354+879    | $1.70 \times 10^4$           | 4200                       |
|                             | Wulong               | 2# 3# underground river | $7.18 \times 10^5$ | -                           |
|                             | Yesaguan             | DK124+602    | $5.00 \times 10^4$           | -                          |
|                             | Maluqing             | PK255+978    | $5.46 \times 10^4$           | 10,000                     |

Note: The meaning of this symbol ZK72 for instance is the tunnel location coordinates and the landmark of highway in table 1.
from the view of karst hydrogeological factors, engineering disturbance of human factors, and the relationship between water inrush and underground level, landform, strata dip, formation lithology, geological defects, excavation and reinforcement, and geological prediction. And monitoring and measurement of surrounding rock have been discussed in detail. It also introduces some geological disasters caused by the water inrush in tunnel excavation. Based on the above discussion, types of water inrush have been given (Xue et al. 2008).

Figure 1. Water inrush and mud gushing in traffic tunnels. (a) Ma luqing tunnel. (b) Long Tan tunnel.
2. The environmental impact of water inrush

The balance of the original ecology is inevitably broken by the construction of tunnels in karst areas. The emissions of waste water and tunnel waste residue make certain impact to the surrounding environment. The excavation and blasting of tunnels will cause contamination of water supplies.

Figure 2. Water inrush in Jinping hydropower station. (a) Tunnel floor. (b) Tunnel vault.
around the tunnel and change the direction of flow of groundwater. Some scholars have carried out discussion and research on the influence of tunnel construction to the surrounding environment for many years.

Construction of mountain tunnel will cause pollution of the environment, such as dust emission, exhaust emissions from fuel vehicles and equipment, noise and solid pollution, soil erosion, etc. Most projects of mountain tunnel construction such as Zhongliangshan tunnel, Qiyueshan tunnel, Dabashan tunnel, Shangjiawan tunnel, etc. are so large that they cause exhaustion of water resources of the surface, water and soil erosion and ecological environment destruction as shown in table 2. Therefore, it is particularly important to do something regarding these problems of construction and to provide some effective control measures.

2.1. The impact to the surface water environment

Compared to bridge engineering and harbour engineering, tunnel engineering causes less damage to the natural environment though it also changes the original state of the environment. And the pollution is always difficult to restore. During the tunnel construction, it will be likely to encounter rock burst, water inrush, collapse and other geological disasters. It is also likely to encounter floor water inrush in coal mines (Li et al. 2014). Among these disasters, especially, water inrush is the most common and serious disaster. The tunnel water inrush often occurs with mud and sand. This will seriously affect the construction progress and cause property damage and even casualties. The governance of each accident is very difficult. There are two main types of water pollution in tunnel project (Li 2001). First, all kinds of sewage of the construction of tunnel, such as wastewater of tunnel grouting and flushing equipment, are released into the underground river and public waters. It makes the pH value and metal elements (Fe, Cu, Pb, Zn) of water increase and pours harmful chemical composition into rivers. Second, the water carries a lot of residue of spray anchor bracing and flows into the reservoir. Metal sulphides oxidize and hydrolyze into \( \text{SO}_4^{2-}, \text{Cu}^{2+}, \text{Fe}^{3+} \) and \( \text{Fe}^{2+} \). Steel arch and fabric are corroded. The tunnel water gushing not only seriously affects the quality and progress of projects, but also affects its ecological environment extensively and profoundly, such as the habitat environment of creature, water environment, soil environment (figure 3).

Geleshan mountain tunnel in the Chongqing railway is located in the suburb of ChongQing. Areas have several reservoirs with large capacity. And it also has the structure with high-pressure water. It must ensure that it would not cause water and soil erosion. Total length of the tunnel is 4000 m. It has landslide, karst, coal, gas, mined-out area, known as the ‘geological museum’ in the Huaiyu railway. The high-pressure water of the region is mainly the rich karst water. Water inrush occurred in the tunnel and the water inflow is more than 50,000 m³/d. The governance measure in

| The name of the tunnel | Casualty loss |
|------------------------|--------------|
| YuanLiangShan tunnel   | 71 times water inrush, 9 people died, the maximum water pressure 4.6 MPa, maximum water emission 72,000 m³/h |
| WuLong tunnel          | 10 times water inrush, maximum water emission 7.18 million m³/d, economic loss 20 million |
| BaiYun tunnel          | Instantaneous maximum mud emission 2,500 m³, 9 people died |
| MaLuJing tunnel        | 19 times water inrush, 15 people died, project schedule delay 2 years |
| YeSanGuan tunnel       | Maximum water emission 100,000 m³/h, maximum mud emission 53,000 m³, 10 people died, project schedule delay 0.5 years |
| DaZhiPing tunnel       | 14 times water inrush, maximum water emission 363,000 m³/d, mud emission 14,000 m³ |
| YunWuShan tunnel       | Water emission 46,000 m³/d, maximum water emission 172,000 m³/d |
| QiYueShan tunnel       | Large karst pipe and cave 187, 18 times water inrush |
| ZhongJiaShan tunnel    | The accident 14 times, the amount of water inrush 20,000 m³, the amount of mud inrush 27,900 m³ |
| TongYu tunnel          | 10 times water inrush, 5 people died |
| LongTan tunnel         | 2 times water inrush, mud inrush more than 9000 m³, project schedule delay 1 year |
the preliminary stage mainly is drainage. It made the water level of more than 10 reservoirs and 100 ponds reduce. After taking some appropriate measures, residents’ daily life resumed back to normal.

In addition, tunnel drainage will make the agricultural irrigation water pollute too, which will transfer the hazardous substances to crops. When these crops are eaten, it will cause harm to people’s health. So we need to monitor water indicators. According to the variety and characteristics of pollution sources, we should select the corresponding reference standard to monitor and evaluate, as shown in table 3.

**Table 3.** The basic standard limit of surface water environment (Li 2001) unit: mg/L.

| No. | Monitoring material          | Type I | Type II | Type III | Type IV | Type V |
|-----|-----------------------------|--------|---------|----------|---------|--------|
| 1   | PH                          | 6–9    |         |          |         |        |
| 2   | Chemical oxygen demand (cod) ≤ | 15     | 15      | 20       | 30      | 40     |
| 3   | Petroleum category ≤        | 1      | 3       | 5        | 15      |        |
| 4   | Hydrochloride[NH₄]          | <10    |         |          |         |        |
| 5   | SS suspended solids         | <20    | 20–30   | 30–50    | 50–70   | >100   |
| 6   | Dissolved oxygen (DO)       | >6.5   | 4.6–6.5 | 2.6–4.5  | <2.0    |        |
| 7   | NH₃-N                       | <0.5   | 0.5–0.99| 1.0–3.0  | >3.0    |        |
| 8   | Alkalinity                  | >5     |         |          |         |        |

*Figure 3. The loss of the surface water.*
2.2. The impact to the groundwater environment

In karst areas, there are many water storage structures. The disturbance to karst caves and underground rivers caused by excavation of the tunnel will be inevitable. And it also caused a large number of consumption of storage capacity in the form of landing funnel. The negative impact on the groundwater environment has gradually aroused people’s concern in the recent years. In order to prevent lining under high hydraulic pressure, tunnels often have some drainage measures of tunnel construction. But if the drainage is too much, it will cause groundwater erosion. For mountain tunnel, in dealing with the problem of water, it always uses the principle of ‘the combination of drainage and interception.’ The tunnel drainage can effectively reduce water pressure of the structure, but the destruction of groundwater environment and loss of groundwater resources cannot be ignored.

Tunnel construction and groundwater can influence each other (Wang 2013). On the one hand, the risk of water inrush and mud inrush occurring is high. It will threaten the security of tunnel construction when excavating tunnel in the rich water formation. On the other hand, the tunnel construction in the water-bearing strata will destroy the groundwater balance and make groundwater level decline and cause ecological and living environment deterioration. Tunnel construction and the protection of groundwater are sometimes contradictory. The contradiction between them will influence the tunnel construction safety, economic investment, social effects, environmental impact, etc.

(1) In the construction of mountain tunnel, the in situ stress will redistribute and relaxation zone of rock mass will form when the free face formed after the excavation. The excavation disturbance and blasting vibration will affect the integrity of rock mass. It usually makes natural water insulation fault transform into transmissibility fault and make rock mass permeability coefficient increase. After changing the natural seepage field, the tunnel will encounter water seepage or water inrush. Large amount of groundwater seepage is likely to cause adverse effects to the progress and safety of tunnel construction. After tunnel excavation, groundwater will continuously flow into the tunnel. In the perturbation range, the permeability of rock mass, groundwater seepage flow direction and surface water will change to some extent. And it will form a precipitation funnel of groundwater. The precipitation funnel of groundwater will develop until the tunnel sewage is completely supplied by the plenty underground water. So the tunnel excavation breaks the original hydrogeological groundwater balance system.

(2) After the occurrence of water inrush, it could lead to groundwater levels decline and soil moisture decrease even to affect vegetation survival (Jiang et al. 2010). When the underground water leakage caused by tunnel excavation, underground water level falls. Total vegetation coverage and groundwater depth have certain correlation. In general, the vegetation coverage is high in the area of small embedded depth of groundwater table. The requirements of water level for different plants are different. Soil moisture is a restrictive factor which decides a plant’s growth and distribution. Soil moisture also can influence the plant’s growth and species. Each plant has the appropriate underground water level for its growth. For example, the growth of reed needs more water, compared with poplar. Low plant coverage will increase water and soil erosion. If groundwater erosion is excessive, it will also affect the growth of crops.

2.3. Inducing geological disasters of ground

During the construction of tunnel, deep disturbance often spreads to ground for the reason of the surface of rock mass and deep karst area having certain connectivity. Due to the pumping of groundwater in some projects, such as unreasonable pumping of groundwater, the construction of
tunnel and deep foundation pit, the underground water level reduces rapidly. It will induce geological disasters, such as forming the ground floor empty and slope sliding, causing the upper soil settlement and ground collapse (figure 4). The karst caves or holes in the karst areas may cause collapse and subsidence of rock and soil layer due to natural factors or human factors. Cause analysis of tunnel collapse and information management can provide a beneficial reference for avoiding tunnel collapse (Li et al. 2014). Surface collapse and subsidence is the most direct geological environmental effect caused by water inrush of karst tunnel. It is about 27% of the railway tunnel surface collapse related to the tunnel water inrush in the 1990s. The exit of Qiyueshan tunnel always causes water inrush during the rainy season. The potential water inrush channel provides conditions for heavy rainfall infiltration of surface water, a serious threat to the safety of tunnel construction and operation after the completion of tunnel. Geological disasters caused by water inrush have the characteristics of sudden and continuous strong destructive power. So tunnel water inrush can cause the effective stress mutation and dynamic water pressure fluctuations of the overburden and loose soil in a short period of time (Li 2011).

Figure 4. Surface collapse.
3. Types and criterions of water inrush

3.1. Geological mode of water inrush

In essence, water inrush and mud inrush include disaster sources, sudden surge channel and prevention layer. It is shown in figure 1. The process is caused by losing its balance of aqueous medium system, hydrodynamic system and surrounding rock mechanics equilibrium. Dramatic changes of balanced state which are due to the tunnel excavation make the water energy storage in underground instantly release. It is a dynamic failure phenomenon with mud, sand and gas transport into the free surface in high speed in the form of fluid (figure 5).

First, disaster sources are source power. It is a three-phase hybrid which is composed of water, deposit and gas within a certain space, such as filling karst cave.

Second, sudden water inflow channel is a dominant migrating pathway of disaster sources. It is hybrid coupling evolution via place of three-phase (solid–liquid–gas migration). The solid–liquid–gas coupling migration patterns and the flow pattern evolution rule are very complex after disaster sources defending into channel.

Third, prevention layer is the last barrier of disaster sources defending into channel. This is the final fracture location. The sudden water inflow is the dynamic failure process caused by the front dynamic impact of disaster sources and construction disturbance in the back of tunnel face.

3.2. The failure modes of water inrush channel

Based on the analysis results of large-scale disasters of water inrush (Li et al. 2009; Ge et al. 2010; Li et al. 2010), water inrush can be divided into three types induced by geological defects or not. There are as follows: geological defects inrush, non-geological defects and combinations of the above two forms. These are shown in table 4.

Table 4. Type classification of water inrush for failure mode (Li 2011).

| Water burst type       | The water inrush prevention structure                                | Water inrush channel                                                                 |
|------------------------|------------------------------------------------------------------------|-------------------------------------------------------------------------------------|
| Geological defects inrush | Integral surrounding rock (prevention layer)                           | In the preliminary stage, it is fracture network and in final period, it is rupture of water-resisting layer Fracture, fault, cavity and karst pipes etc. The different combination of the above two kinds of water inrush channel |
| Non-geological defects | Filling medium                                                         |                                                                                     |
| Combination type       | Integral surrounding rock + filling medium                             |                                                                                     |
3.2.1. Geological defects inrush
Most of the water inrush channels are rock faults, fracture zones and karst pipelines, whose initiation, growth and formation are under the action of outside interference such as large seepage pressure, ground stress and construction disturbance, leading the seepage instability of filling medium or slip of filling blocking in the water inrush channel. Water inrush occurs (figure 6).

3.2.2. Non-geological defects
For relatively complete fractured rock mass, under the disturbance of artificial construction, karst water and water pressure, fractured rock mass where behaviour of crack initiation, expansion and transfixion happen gradually change the seepage and storage conditions of the fractured water, resulting in the formation of water channel. Water inrush occurs (figure 7).
3.2.3. Combination type

Water channels are mostly composed of geological defects and fracture of inrush control layers, and their formation contains the disaster evolution processes of water inrush types of both the geological defects and non-geological defects (figure 8).

4. Conclusions

Based on the statistical analysis of a large number of cases of water inrush in karst tunnels, the influence factors tunnels’ water inrush are elaborated from two aspects. The two aspects are as follows: karst hydrogeological factors and engineering disturbance of human factors. For karst hydrogeological factors, the relationship between water inrush and underground level, landform, strata dip, formation lithology and geological defects has been discussed in detail. For engineering disturbance of human factors, the relationship between water inrush and geological prediction, excavation and reinforcement, and monitoring and measurement of surrounding rock has been discussed in detail. Constructing tunnel in karst areas should take some measures to prevent the occurrence of geological disasters. In terms of the failure modes of water inrush channel, water inrush has been divided into three patterns, the three patterns are geological defects inrush, non-geological defects and combinations of the above two forms.

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