Application of comprehensive prediction method of water inrush hazards induced by unfavourable geological body in high risk karst tunnel: a case study

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ABSTRACT
While tunnelling in karst terrains, karst fissure water may endanger the safety of tunnel engineering and cause geological disasters such as water inrush. To ensure the safety of tunnel construction, in investigation stage, engineering geological and hydrogeological conditions of Jigongling Tunnel was analysed firstly. In design stage, a reasonable prediction method combining with optimization principle was selected to calculate the water inflow according to the geological and hydrogeological conditions analysed in the investigation stage. Then the advanced geological prediction was divided into different classes based on the water inflow. To make an accurate prediction, tunnel seismic prediction method, transient electromagnetic method, induced polarization method and advanced geological drilling were comprehensively applied in construction stage. This method combined with geology analysis, water inflow calculation and classification of advanced geological prediction is successfully applied in the Jigongling Tunnel of Fanba Expressway, and has provided a reference for the similar engineering constructions.

KEYWORDS
Karst fissure water; geological analysis; water inflow calculation; comprehensive geological prediction; engineering application

1. Introduction
In recent years, the construction of tunnels in China is developing rapidly, which is the largest number and widest scale in the world. Due to the complex hydrogeological conditions in the tunnel area, there are a variety of geological hazards, especially water inrush and mud gushing caused by large water-bearing structures and unfavourable geologic bodies (Wang 2004; Li et al. 2007; Li et al. 2010; Li et al. 2016; Chen et al. 2011; Shi et al. 2011; Shi et al. 2013). For example, some water inrush accidents occurred in Huayingshan Tunnel, the maximum inflow reached up to 14,400 m$^3$/d and the amount of sand discharge was over 1 million m$^3$; at K30+900 of Wuzhishan Tunnel, the maximum inflow was about 4.3 × 104 m$^3$/d and the spurt distance of water column was over 10 m (Liu et al. 2006; Li et al. 2008; Li et al. 2009). In the Malujing tunnel of Yichang-Wanzhou Railway, water inrush occurred in the ‘DK255 + 978’ karst tunnels on 21 January 2006, with the value of water inrush of approximately 7.2 × 10$^5$m$^3$. The water inrush flooded the 3152 m parallel heading and 2508 m main tunnel in the vicinity of exit, and resulted in damage to a large number of equipment and machinery. The economic losses had exceeded RMB ¥ 10 million (US$ 1.2 million). In the Yesanguan tunnel of Yichang-Wanzhou Railway,
water inrush were observed in 'DK124 + 602' karst tunnels on 5 August 2007, and the peak flow rate reached $1.5 \times 10^5$ m$^3$/h, causing the equipment and machinery in the tunnel to be seriously deformed and/or damaged, flooded about 500 m away from their positions. The economic losses were huge and subsequent treatments took two years. The damage caused by water inrush with high pressure and large capacity is obvious, therefore accurate prediction and effective governance of water-bearing structures are important problems to be solved (Zhao et al. 2013; Shi et al. 2014). With the increasing tunnel engineering build in geological complex karst zone, the accurate and timely forecast of the fissure water is the key to study and solve problems in tunnel engineering design and construction. Based on a large number of engineering experiences, this paper presents a prediction method of fissure water inrush in high-risk karst region, verified by engineering application.

2. Method

2.1. Three-stage prediction method

Three-stage prediction method for complex karst area tunnel fissure water inrush is proposed (see Figure 1) based on the engineering experiences of Shanghai-Chengdu Highway, Yichang-Wanzhou Railway, Fanba Highway and Yichang-Badong Highway Projects.

Figure 1. Prediction method of fissure water inrush in high-risk karst area.
In investigation stage, the geological analysis method from the aspects of lithology, geological structure and groundwater recharge factors is employed for the analysis of water occurrence situation and fissure development areas in the tunnel site. Thus, the fissure water and fissure developed area can be confirmed in macroscopic range. In tunnel design stage, a reasonable prediction combining with optimization principle was selected to calculate the water inflow, which take account of the rain infiltration method, equalization method, groundwater dynamics method and groundwater runoff. The comprehensive advanced geological prediction was divided into four classes according to the result of water inflow calculation. In order to ensure the detection accuracy and not take too much construction time and manpower, prediction plans of different classes were worked out. In the tunnel construct stage, according to the four-class advanced geological prediction method mentioned above, relevant method was selected for comprehensive advanced geological prediction. Furthermore, treatment measures can be taken based on the results obtained from the prediction method.

### 2.2. Optimal selection of karst tunnel water inflow prediction methods

At present, the water inflow prediction methods of karst tunnel is summarized in Table 1 (Han et al. 2010; Lin et al. 2008; Wang et al. 2012). In order to ensure the accuracy of water inflow calculation, the optimal method needs to consider the karst hydrogeological analysis and verification of advanced geological prediction.

#### Table 1. Methods for estimation of tunnel water inflow.

| Method                                | Method description                                                                 | Applicable range and examples                                                                 |
|---------------------------------------|-----------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------|
| Hydrogeology analogy method           | Compared with the area with similar hydrogeology condition to estimate the tunnel water inflow | (1) Hydrogeological condition of the tunnel similar to match location                             |
|                                       |                                                                                   | (2) The hydrogeological conditions of tunnel site changed little and the aquifer is relatively uniform |
|                                       |                                                                                   | (3) With homogeneous rock fracture                                                                |
|                                       |                                                                                   | Example: Similar hydrogeological condition with the completed project                             |
| Groundwater dynamics method           | According to the principle of groundwater dynamics method, by using of mathematic analysis for a given boundary conditions and initial conditions of groundwater movement to estimate the tunnel water inflow | (1) The tunnel pass through water-bearing structures in phreatic water zone                      |
|                                       |                                                                                   | (2) With homogeneous lithology                                                                    |
|                                       |                                                                                   | (3) With known radius of influence and permeability coefficient                                    |
|                                       |                                                                                   | Example:                                                                                         |
|                                       |                                                                                   | (1) Unsaturated zone                                                                             |
|                                       |                                                                                   | (2) Seasonal variation zone                                                                       |
|                                       |                                                                                   | (3) Fault or fracture zone                                                                       |
| Equalization method                   | According to the principle of water balance, find out the balance relationship between water supply and discharge during the construction of the tunnel to estimate the tunnel water inflow | (1) The calculation area located in Unified hydrogeological unit, water supply and discharge are easy to determine |
|                                       |                                                                                   | (2) The hydrogeological data of area have been long-term observed including rainfall and infiltration coefficient data |
|                                       |                                                                                   | Example:                                                                                         |
|                                       |                                                                                   | (1) Seasonal variation zone                                                                       |
|                                       |                                                                                   | (2) Shallow saturation zone                                                                      |
| Numerical calculation method          | Based on proper hydrogeological model, using the finite element method, finite difference method, boundary element method or other methods to predict tunnel water inflow | (1) Tunnel build in complex hydrogeologic areas                                                   |
|                                       |                                                                                   | (2) Cases difficult to solve for methods mentioned above                                          |
|                                       |                                                                                   | (3) water inflow can be dynamically corrected after excavation                                   |
|                                       |                                                                                   | Example:                                                                                         |
|                                       |                                                                                   | Weak karst development or weak permeable rock strata zone                                         |
2.3. **Classification of advanced geological forecast**

Classification of advanced geological prediction is a comprehensive analysis of the tunnel geological data, based on the hydrogeological analysis and the value of water inflow in the investigation stage, the result of classification is shown in Table 2. (Christian 2002; Li et al. 2009; Zhang et al. 2010; Chen et al. 2011)

2.4. **Introduction for advanced geological prediction methods**

2.4.1. **The tunnel seismic prediction method**

Tunnel seismic prediction (TSP) is an underground reflection seismic wave technology for advanced geological forecast before the tunnel face (Alimoradi et al. 2008; Gong et al. 2010). The seismic waves are excited by several (less than 24 generally) small-scale artificial blasting in specific blasting point, received by electronic sensor. When the seismic incident waves encounter formation interface and joint interface, especially unfavourable geology interface such as fault fracture zone, karst cave, underground river, etc., the reflected waves are generated and received by the receiver, and amplified, outputted and recorded by digital recorder (see Figure 2).

The calculation formula of longitudinal wave velocity \( V_p \) is:

\[
V_p = \frac{L_1}{T_1}
\]

where \( L_1 \) is the distance from the seismic source and sensor; and \( T_1 \) is the transmission time of the first wave arriving the sensor.

The transmission time of the reflected wave \( T_2 \) can be calculated as follows:

\[
T_2 = \frac{(L_2 + L_3)}{V_p} = \frac{(2L_2 + L_1)}{V_p}
\]

Table 2. Classification and the corresponding items of fissure water advanced geological prediction.

| Classification | Engineering geological characteristics | The value of water inflow | Advanced geological prediction |
|----------------|----------------------------------------|--------------------------|--------------------------------|
| A              | There are big geophysical anomalies likely to cause significant environmental geological disaster. Development of large-scale weak water-rich hydraulic conductivity fault, the fissures develop strongly and fissure water occurrence conditions are good. | More than 10,000 m³/h | ① TSP (≤100 m) ② Advanced geological drilling (30~60 m, 3~5 holes) ③ TEM (30~60 m) and GPR (20~30 m) ④ IP (15~30 m) ⑤ Radially advanced blast hole (5 m, 5 holes) |
| B              | There are big geophysical anomalies likely to cause great environmental geological disaster. Development of large-scale weak water-rich hydraulic conductivity fault, the fissures develop strongly and fissure water occurrence conditions are good. | More than 1000 m³/h | ① TSP (about 100 m) ② Advanced geological drilling (30~60 m, 1~3 holes) ③ TEM (30~60 m) or GPR (20~30 m) ④ IP (15~30 m) ⑤ Radially advanced blast hole (5 m, 5 holes) |
| C              | There are geophysical anomalies, the fissures are strongly and the fissure water occurrence conditions are good. | 100 m³/h ~ 1000 m³/h | ① TSP (100~150 m) ② Advanced geological drilling (10~30 m, 1~3 holes) ③ Radially advanced blast hole (5 m, 5 holes) ④ TEM (30~60 m) or GPR (20~30 m) for geophysical anomaly areas |
| D              | The fissures and fissure water develop weakly. | Less than 100 m³/h | ① TSP (150 m) ② GPR (30 m) when necessary |

Note: In parentheses is prediction depth, TSP is tunnel seism prediction, TEM is transient electromagnetic method, GPR is ground penetrating radar and IP is induced polarization method.
where $L_2$ is the distance from the blasting hole to the reflector; and $L_3$ is the distance from sensor to the reflector.

The sensor can receive the reflected wave information, and present the characters and occurrence related to the interface by different dates. The Poison’s ratio (Equation (3)), Young modulus (Equation (4)), etc. of the tunnel can be obtained by the following formula so as to make the prediction of the unfavourable geology before the tunnel face.

\[
v = \frac{V_p^2 - 2V_s^2}{2(V_p^2 - V_s^2)}
\]

(3)

\[
E = \rho V_s^2 \left( \frac{3V_p^2 - 2V_s^2}{2V_p^2 - V_s^2} \right)
\]

(4)

where $V_s$ is shear wave velocity, $V_p$ is longitudinal wave velocity, and $\rho$ is the rock density (Shi et al. 2014).

2.4.2. The transient electromagnetic method

Transient electromagnetic method (TEM) is an electromagnetic-induced method, and its application fields include mineral exploration (Xue et al. 2012), groundwater detection (Mitsuhata et al. 2006) and geological survey (Hatch et al. 2010). TEM has a sensitive response to low resistivity geological bodies, which can help to detect low-resistive geological formations with water (see Figure 3). So, it has widely been used in tunnel prediction and water bearing structure detection in mines after years of development (Li et al. 2015).
When homogeneous isotropic surface of the earth, where electrical conductivity is $\sigma$ and magnetic permeability is $\mu$, is laid by rectangular transmitter loop of which area is $S$ and being supplied with the step pulse current in the return wire,

$$I(t) = \begin{cases} I & t < 0 \\ 0 & t \geq 0 \end{cases}$$

(5)

Before the current is disconnected ($t < 0$), transmitting current establishes a stable magnetic field in the earth and space around the loops, as shown in Figure 4.

Disconnect the current suddenly when $t = 0$, and the magnetic field generated by the current also disappears immediately. This dramatic change of a magnetic field spreads to the earth around the loops through the air and underground conductive medium, and stimulates induced current in the earth to sustain existing magnetic field before the transmitting current is disconnected and make the magnetic field space not disappear immediately (Sun et al. 2011).

Due to the Ohmic loss of medium, the induced current will rapidly decrease, and the magnetic field generated by it will also rapidly decrease with it, and as well this rapidly decreasing magnetic field induces the new weaker vortex in the underground medium around it. This process continues, until the Ohmic loss of the earth consumes the magnetic energy completely. This is the transient electromagnetic process in the earth, and the existing electromagnetic fields accompanied with this process are the TEM of the earth. The principle of TEM is shown in Figure 3.

### 2.4.3. The induced polarization method

Induced polarization method (IP) is an important branch of electrical exploration method. The electrical difference reaction between surrounding rock and water body is the basis of induced polarization. Therefore, this method is particularly sensitive to water bodies (Nie et al. 2012; Li et al 2011). As shown in Figure 5, under the action of applied electric field, the current will propagate in the surrounding rock. When the electric current meets the water bodies in surrounding rock, the spatial electric field of surrounding rock will change, at the same time, the positive and negative ions in the water will separate to form secondary electric field, as the power supply continue over a period of time, the positive and negative particles will reach equilibrium and the potential differences will reach stability state as well. When the electric current is disconnected, the applied electric field disappear, instantaneous electric potential decline sharply, then decreased slowly, positive particles and negative particles being separated will gradually restore to its original position, and by testing the secondary electric field attenuation process, rich water area of three-dimensional (3D) space location can be achieved.
3. Engineering application

3.1. Geological analysis

Jigongling Tunnel in Fanba Highway is 4.5 km long with a maximum burial depth of 338.5 m, so the tunnel is classified for extra-long deep tunnel (Figure 6). Jigongling Tunnel is located in the typical karst geological disaster-prone areas of southern China. There is less large-scale fault structure in this area but with developmental joint fissure. The attitude of rocks is 130°~150°. The upper layer of the tunnel is mainly composed of strong karst carbonate, and lower shale layer is relatively impermeable. Karst develops strongly in the contact zone of soluble rock and non-soluble rock, and the groundwater level is 150~200 m higher than the tunnel floor. According to the geological investigation, there are karst dome-depressions, valleys and gully with high density located in the tunnel site. In conclusion, the formation lithology and geological structure of the tunnel are very complex, the fractures develop strongly and groundwater has a strong hydraulic connection with surface water. Therefore, the water inrush accident is easy to happen at the boundary of the limestone layer and shale layer during construction.

3.2. Prediction of water inflow

The middle part of Jigongling Tunnel (ZK19+240~ZK20+600) is located in shallow saturated zone. The water head is about 150 m high. Based on the optimization principle of water inflow calculation, the equalization method is selected. The calculation needs to consider the static reserves ($Q_s$), dynamic reserves of dry season ($Q_m$) and dynamic reserves of flood season ($Q_f$).
Prediction of static reserve $Q_s$

The drainage volume $V$ is calculated by:

$$V = \frac{LRH}{2}$$  \hspace{1cm} (6)

where $L$ is the length of tunnel in seasonal zone; $R$ is the supply belt width of karst water; and $H$ is the aquifer height from tunnel floor. According to the tunnel hydrogeological conditions, the supply belt width in the left and right sides of tunnel are $R_1 = 2000$ m and $R_2 = 900$ m, respectively. Aquifer height $H = 150$ m, as can be seen from Figure 6. The tunnel enters the dolomitic limestone (Shilongdong group) stratum, because the shale is the aquifuge. So the length of tunnel in seasonal zone $L = 120$ m. The drainage volume $V$ can be calculated by Equation (6):

$$V_{\text{left}} = 1.8 \times 10^7 \text{ m}^3 \quad V_{\text{right}} = 0.81 \times 10^7 \text{ m}^3$$

$$V = V_{\text{left}} + V_{\text{right}} = 2.61 \times 10^7 \text{ m}^3$$  \hspace{1cm} (7)

The static reserve $Q_s$ is calculated by:

$$Q_s = \frac{N \cdot \mu \cdot V}{T}$$  \hspace{1cm} (8)

where $N$ is the coefficient of water inrush and its value is 0.7 according to the karst structure; $\mu$ is rate of karstification, its value is 0.7 according to the Shilongdong group limestone date of similar tunnel; $T$ is drainage time, $T = 5$ d according to the local climate conditions over the years. So the static reserve $Q_s$ can be calculated by Equation (8):

$$Q_s = \frac{N \cdot \mu \cdot V}{T} = \frac{0.7 \times 0.0008 \times 2.61 \times 10^7}{4} = 3654.8 \text{ m}^3/\text{d}$$  \hspace{1cm} (9)

Prediction of dynamic reserves

The dynamic reserves of flood season $Q_f$ is calculated by:

$$Q_f = \frac{\alpha N A F}{T}$$  \hspace{1cm} (10)

where $N$ is the coefficient of water inrush, the values of $N$ is the same as of Equation (8); $\alpha$ is infiltration coefficient, $\alpha = 0.4$ because of some water outflow in this region; $A$ is rainfall, $A_1 = 100$ mm and $A_2 = 150$ mm according to the local weather information; $T$ is rainfall cycle, its value is 2 d; $F$ is the recharge area, its value is 1.01 km$^2$ according to the tunnel hydrogeological conditions.

The values of water inflow in flood season can be calculated by:

$$\begin{align*}
\Sigma Q_{f1} &= Q_s + Q_{f1} = 17794.6 \text{ m}^3/\text{d} \\
\Sigma Q_{f2} &= Q_s + Q_{f2} = 24864.8 \text{ m}^3/\text{d}
\end{align*}$$  \hspace{1cm} (11)

The results show that when the rainfall is 100–150 mm and rainfall cycle is two days, the value of water inflow is 17794–24864 m$^3$/d. When the rainfall is less than 100 mm, water inflow will decrease
exponentially. When the rainfall is more than 150 mm or the rainfall cycle is more than two days, water inflow will be multiplied.

3.3. Advanced geological prediction program

According to Figure 6, the karst fractures develop strongly and groundwater storage is ample in the ZK19+420~ZK19+539 section of Jigongling Tunnel. This section is in the interface of Shilongdong group limestone and Shipai group shale. The Shilongdong group limestone karst develops strongly and the shale is an impermeable layer, therefore this specific geology may result in great water inrush accident. According to Table 2, the calculated result of the water inflow is 741.42 m³/h~1036 m³/h (17794~24864 m³/d) rated in class b. Therefore, the TSP, TEM, IP and advanced geological drilling method are used for geological detection.

3.3.1. TSP prediction

The TSP detection was taken at the tunnel working face of ZK19+410 with the detection range of ZK19+410~ZK19+510. Prediction results are presented in Figure 7. The physical properties of rock mass presented in Figure 7(a) shows that Vp increase dramatically while Vs remain almost unchanged at ZK19+462~ZK19+510 (regions marked with ellipse), the Poisson ratio and Vp/Vs both increase. On the contrary, both the density and the dynamic Young’s modulus (Dyn. Young modulus) decrease. In the diagram of S-waves depth migration (see Figure 7(b,c)), negative and positive reflected waves appeared alternately from ZK19+462 to ZK19+510, which means the rock mass in this section was fissure developed. All the variation tendency of the reflected waves, S-waves migration and rock properties agree well with the judging criteria of TSP technique for water. Therefore, it can be inferred that fissure water may be encountered during the tunnel construction in this section.

Figure 7. Prediction results of TSP203 system. (a) Physical properties of rock mass, (b) S-waves depth migration and (c) S-waves reflector extraction.
In order to ensure the construction safety, TEM detection was taken at the tunnel face in ZK19+423 and ZK19+467 sections. The prediction result is shown in Figures 8 and 9.

(1) Result of first detection at ZK19+445~ZK19+483 section

Prediction result shows that there were no karst cavities filled with water and mud or other large water-bearing structures in K19+445~K19+483 sections, but the quality and integrity of the rock mass is poor and the fissure water develops at ZK19+463~K19+483.

(2) Result of second detection at ZK19+467~ZK19+504 section

Prediction result shows that the rock mass ahead of the tunnel face is fragmented and the fissure develops, but there are no large water-contained structures.
As can be seen in Figure 10, when the tunnel was excavated to ZK19+487 section, much fissure water appeared at the tunnel face. The fissure water pressure is small, so the tunnel excavation continued combining with the advanced blast-hole.

### 3.3.3. IP prediction

The IP prediction method was used at the tunnel face of ZK19+509 section, the detection range was ZK19 +509~ZK19 +539. In IP detection, we focus on water-bearing structure and rich water area of 3D space location. The prediction results are shown in Figure 11.

![Figure 10. The fissure water at the tunnel face (ZK19+480).](image1)

![Figure 11. The map of 3D resistivity.](image2)
(1) The electrical resistivity decreases at ZK19+510, it can be inferred that the water occurrence in surrounding rock increase. The low resistivity anomalous objects exist at the top right of ZK19+513~ZK19+517 section, it can be inferred to be cavities or fissures filling with water. (2) The resistivity of ZK19+521~ZK19+527 section is low (lower than 100 Ωm, partial lower than 40 Ωm), it can be inferred that surrounding rock fractures there is rich water and mud.

As can be seen from Figure 12, in the process of the advanced blast-hole prediction at the tunnel face of ZK19+509 section, when the advanced drilling goes forward about 4 m, the pressure water sprays from the hole. When the water inflow is about 35~45 L/S, tunnel construction stops.

### 3.3.4. Advanced geological drilling

Based on the detection results mentioned above, the RPDS-150-c multi-function drilling rig was used for advanced drilling detection at the tunnel face of ZK19+509 to verify the detection results. As shown in Figure 13, four advanced geological drilling holes (ZK1~ZK4) have been drilled at K19

![Figure 12. Tunnel face of ZK19+509.](image)

![Figure 13. Position of advanced geological drilling hole at K19+509.](image)
+509, and the drilling depth, drilling angle and drilling direction can be seen in Table 3. The drilling records are shown in Figure 14–Figure 20, where failure energy means the energy release from the interaction of drill pipe and rock, the greater failure energy means the harder rock, and vice versa. The investigation results are represented in Table 3. ZK2, ZK3, ZK4 are not to expose the groundwater in the drilling process. At the mileage of ZK19+515~ZK19+517, drilling speed increases sharply and failure energy reduces greatly in ZK1, we can infer the fractured surrounding rock in this section with filler of karst conduit. At the mileage of ZK19+523.5~ZK19+549, drilling speed and failure energy are low, there is a small amount of fissure water exposed. Combined with the analysis of the curve and the detection results of IP, there could be a large crack existing and the groundwater type belongs to fissure water. The water inflow mainly exists above the vault at ZK19+509~ZK19+527 section where may have a water connection with surface water, the fissure (see

| Drilling hole | Depths (m) | Mileage | Drilling angle and direction | Prediction results |
|---------------|------------|---------|-------------------------------|-------------------|
| ZK1           | 0~2.5      | K19+509~K19+511.5 | Same to excavation direction; drilling upwards with inclination of 6° | Drilling speed and failure energy are low; fractured surrounding rock; ground- water is not exposed. |
| ZK1           | 2.5~6      | K19+511.5~K19+515 | Same to excavation direction; drilling upwards with inclination of 6° | Drilling speed and failure energy change frequently; hard and soft rocks alternate; groundwater is not exposed. |
| ZK1           | 6~8        | K19+515~K19+517 | Same to excavation direction; drilling upwards with inclination of 6° | Drilling speed increases sharply and failure energy reduces greatly; fractured surrounding rock; fault fracture zone or filler of karst conduit. |
| ZK1           | 8~14.5     | K19+517~K19+523.5 | Same to excavation direction; drilling upwards with inclination of 6° | Drilling speed is low and failure energy is high; strength of rock mass is high but fissures also develop. |
| ZK1           | 14.5~36    | K19+523.5~K19+549 | Same to excavation direction; drilling upwards with inclination of 6° | Drilling speed and failure energy are low; The rock is soft and fissures develop; groundwater is exposed in this section. |
| ZK2           | 0~6.6      | K19+509~K19+515.2 | Same to excavation direction; drilling upwards with inclination of 20° | Drilling speed is low and failure energy change frequently; hard and soft rocks alternate and groundwater is not exposed. |
| ZK2           | 6.6~15     | K19+515.2~K19+523 | Same to excavation direction; drilling upwards with inclination of 20° | Drilling speed is low and failure energy change frequently; hard and soft rocks alternate and groundwater is not exposed. |
| ZK3           | 0~10.2     | K19+509~K19+516.2 | 45° to excavation direction; drilling horizontally | Drilling speed and failure energy change frequently; the rocks is soft and fissures develop; groundwater is not exposed. |
| ZK3           | 10.2~14    | K19+516.2~K19+519 | 45° to excavation direction; drilling horizontally | Drilling speed is fast and failure energy is low; fractured surrounding rock, strength of rock mass is low; groundwater is not exposed. |
| ZK4           | 0~3.9      | K19+509~K19+511.8 | 45° to excavation direction; drilling horizontally | Drilling speed and failure energy are low; the rock is soft and fissures develop; groundwater is not exposed. |

Figure 14. Drilling speed and failure energy of ZK1 at ZK19+509~ZK19+519.
Figure 15. Drilling speed and failure energy of ZK1 at ZK19+519—ZK19+529.

Figure 16. Drilling speed and failure energy of ZK1 at ZK19+529—ZK19+539.

Figure 17. Drilling speed and failure energy of ZK1 at ZK19+539—ZK19+549.

Figure 18. Drilling speed and failure energy of ZK2 at ZK19+509—ZK19+523.

Figure 19. Drilling speed and failure energy of ZK3 at ZK19+509—ZK19+523.

Figure 20. Drilling speed and failure energy of ZK4 at ZK19+509—ZK19+513.
Figure 13) extending down to ZK19+543.2, with good filling and poor water permeability, resulting in only a small amount of drilling water outflow.

4. Tunnel excavation condition

In Figure 21, when the tunnel is excavated to ZK19+515, a large fissure appears at the tunnel face and is extended to the tunnel bottom. Fissure water flows along the fissure.

In Figure 22, when the tunnel is excavated to ZK19+525, the surrounding rocks crush filled with water and mud at the tunnel face.

The excavation results show that the method has achieved good forecasting effect on fissure water occurrence and location. It ensures a successful tunnel construction.
5. Conclusion

(1) To ensure the safety of tunnel construction, a three-stage prediction method for complex karst area tunnel fissure water inrush is proposed. In the investigation stage, the engineering geological and hydrogeological conditions of Jigongling tunnel, including the fracture structures, the main karst water systems and the principal lithology crossed by the tunnel, were succinctly analysed and investigated.

(2) Based on the analysis of hydrogeological condition of Jigongling tunnel, the equalization method was selected to calculate water inflow. The inflow calculation results (about 3654.8m3/d) are consistent with the actual inflow (about 3628m3/d), which provide a basis for the selection of advanced geological prediction method.

(3) To make an accurate prediction, the TSP, TEM and IP methods were comprehensively applied. The TSP detection was adopted firstly to estimate the fissure water condition which might be encountered in section ZK19+410~ZK19 +510. In this case, TSP was not conclusive and additional techniques such as TEM and IP were employed to evaluate the specific location of fissure water. In addition, advanced geological drillings were also applied for the verification of fissure water regions. After tunnel excavation, fissure water revealed at ZK19+515 and ZK19+525, which agreed well with the comprehensive prediction results.

(4) Practice proved that the three stages forecasting the method effectively predict the occurrence of fissure water in front of the tunnel face, and sequentially avoid the water inrush and mud gushing during construction period. This method has provided a reference for the similar engineering constructions.

Disclosure statement

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