Application Study on Treatment Technology of Geological Disasters Caused by Water and Mud Inrush in Ningchan Tunnel

Danfeng Zhang¹, Shilai Xiao², Liang Cheng²*

¹Qinghai Communications Construction Management Co, Ltd., Xining, Qinghai, 810003, China
²China Merchants Chongqing Communications Technology Research & Design Institute Co., Ltd., Chongqing, 400067, China
*Corresponding author’s e-mail: lightcheng@126.com

Abstract: In the process of tunnel construction, water and mud inrush are engineering disasters which are extremely difficult to deal with and have great harm. With Ningchan Tunnel as the background, and combined with the actual situation of the project site, the causes of water and mud inrush in tunnels with weak geological structure are analyzed. Through safety risk analysis, a comprehensive treatment scheme of "advance pipe-shed reinforcement and curtain grouting" is put forward. By selecting the accumulated vault settlement and accumulated peripheral convergence of 4 typical monitoring sections before and after treatment, the deformation laws of Ningchan Tunnel before and after treatment are summarized: The accumulated vault settlement and accumulated peripheral displacement convergence of the monitoring section after treatment is far less than those before treatment. It shows that reasonable grouting reinforcement, advance pipe-shed reinforcement and other methods are suitable for the treatment of sections with water and mud inrush, and the treatment effect is obvious. It has certain guiding significance for similar tunnel projects.

1. Introduction
Mud bursting and water bursting are a common geological disaster during underground construction in karst area, which seriously threatens the construction progress and personnel safety, and some underground construction may even be forced to stop or reroute [1–4]. Only in the first decade of the 21st century, the safety accidents caused by water and mud inrush accounted for 77.3% of the major safety accidents during the construction of large-scale infrastructures in China. Karst areas in China are widely distributed, with a total area as high as 3.44 million square kilometers, accounting for 15.6% of the total karst areas in the world. Besides, karst is also abnormally developed in various countries and regions along "the Belt and Road Initiative", covering 2/3 of the total karst area in the world.

Relevant project cases show that the seepage instability of filling medium in solution cavities (solution caves) is one of the main precipitating factors of water and mud inrush disaster during underground construction in karst area [5]. Sandy filling medium with good permeability is constantly eroded underground under the action of strong seepage, making the seepage channel gradually extend, expand until connect, which leads to the occurrence of water and mud inrush disaster [6]. Its manifestation has obvious hysteretic and unknown natures, and it is concealed and destructive.
Li Liping et al. [7, 8] proposed a "three-stage" evolution model of porous medium seepage instability regarding the above catastrophic characteristics of water and mud inrush, which consists of slow flow (Darcy flow) in water inrush inoculation section, rapid flow in pore evolution section (Briikinan flow) and free flow in water inrush burst section (N-S flow). Its rationality has been preliminarily verified by related laboratory seepage tests. Yang Ping et al. [9–11] systematically analyzed the influence of grout ratio and grouting parameters, etc. on grout diffusion form and reinforcement range through grouting reinforcement model test. Wang Kai et al. [12, 13] prepared triaxial specimens with different grout filling ratios by mixing method and carried out systematic mechanical tests, and established the quantitative relation between grout filling ratios and specimen strength and permeability parameters. Zhang Weijie et al. [14, 15] used model tests to conduct grouting reinforcement for the fault fracture zone, and found that the cohesion of the grout-rock (soil) interface was greatly improved, but the internal friction angle had no obvious change.

Water and mud inrush are very harmful to tunnel construction. If the risk identification is not well done and the comprehensive treatment technology or the construction scheme formulated is inappropriate, the construction environment will be further deteriorated, leading to secondary disasters. This paper takes Ningchan Tunnel as a project case for analysis, puts forward the comprehensive treatment technology, and analyzes the effect of the treatment technology.

2. Project Overview

2.1 Tunnel overview
Ningchan Tunnel is a super long separated tunnel, and the interval between the left and right tunnel lines is about 21.5–44.7m. The tunnel lengths of the left and right lines are 6,044m and 5,963m, respectively. Both the entrance and exit of the tunnel are in Xianmi Township, Menyuan County, Qinghai Province, and the general strike of the tunnel axis is 135°. The tunnel adopts gable slope, and the longitudinal slopes along the left line are 3.00%/800, 1.938%/5950 and -2.304%/600 in sequence. The longitudinal slopes along the right line are 1.937%/5955 and -2.30%/597.998 in sequence.

2.2 Hydrogeological conditions
Groundwater in the tunnel site area is mainly bedrock fissure water, which is mainly distributed in water-bearing rock groups of sandstone and coal measures strata. Atmospheric precipitation is the main supply source. The structure in the area is comparatively developed, and the bedrock is damaged by compression in different degrees. The joints and fissures are developed, which are generally interconnected with the pore water in the overlying slope wash, and recharge and discharge each other. In addition to commonly developed joints and fissures, fault fracture zones are the structures with greater influence in the area, where groundwater is rich. Groundwater had great influence on tunnel construction.

2.3 Water and mud inrush
At 23:28 p.m. on October 17, 2017, when the upper bench of the right tunnel face of Ningchan Tunnel was constructed to YK37+500, There was sudden debris flow appeared on the springing line at the left side of the face, and the personnel and machinery were quickly evacuated. Two minutes after the evacuation, water gushing and debris flow erupted from the face, and large-scale mud burst lasted for one minute, resulting in a mud burst cavity with a diameter of about 8m and a depth of about 30m on the surface. At 9:10 a.m. on October 18, 2017, mud burst occurred again, and the mud burst cavity on the surface expanded, with a diameter of about 25m and a depth of about 15m. The total volume of the two-time mud burst was about 8000m³, and the lining trolley (weighing 100t) 30m away from the tunnel face was pushed out for about 60m, resulting in serious overall deformation. See Fig. 1 for the scene of the mud outburst.
3. Cause Analysis of Water and Mud Inrush

After water inrush and mud gushing, detailed supplementary exploration was made on the geological conditions of this tunnel section, and a borehole was arranged at K37+520. According to the geological data of the initial survey and this detailed survey, the following reasons were obtained through analysis:

(1) The surrounding rocks of the left and right tunnels at the entrance side of Ningchan Tunnel were mainly gravelly soil of accumulation horizon, and the integrity and self-stability of the surrounding rocks were extremely poor. Through supplementary survey, it was revealed that the strata were gravel, rock block, silty clay gravel mixed with pebbly silty clay. There were large strands of water and scattered water flowing out of the tunnel faces of both lines. According to the measurement, the total water volume at the entrance of Ningchan Tunnel was about 17,155 m$^3$/d, and the surrounding rocks were weak at nearly Grade V;

(2) According to the topography and geological structural conditions of the tunnel site area, the tunnel site was divided into two relatively independent hydrogeological units along the mountain heights and the tectonic line direction. There were certain differences between the hydrogeological units, which were manifested in the diversity of groundwater types, inconsistent recharge, runoff, discharge location and direction, independent hydrogeological system, and complex hydrogeological conditions;

(3) The gravel soil of the accumulation body had strong water permeability, and the rock mass contained water supply channels. The water-rich rock mass plus continuous rain and snow weather also increased the water volume in the tunnel, which increased the tunnel construction risk. In addition, due to the limitations of geophysical exploration, there may be a hidden mud cavity structures outside the tunnel contour line. This water and mud inrush were a sudden geological disaster.

(4) According to the monitoring result of the water flow in the tunnel, the variation of the water flow in the tunnel was small during the monitoring period, which indicated that the groundwater volume was fairly abundant in the short term, and the average flow along the left line was about 10,537 m$^3$/d, and the average flow along the right line was about 6,648 m$^3$/d.

4. Treatment of Water Inrush and Mud Gushing

4.1 Treatment principle

The daily drainage at the tunnel entrance had a flow of 17,000 m$^3$/d, the front of the tunnel face was the gravel soil of the accumulation body, and the right tunnel YK37+500 was under construction, so the serious geology disaster of water and mud inrush occurred. Therefore, it was necessary to increase drainage to reduce the flow, and at the same time, to reinforce the surrounding rock by curtain grouting to form a safer construction environment. Through multi-angle advance grouting, the bottom of the mud burst cavity formed a relatively tight bearing arch, which created favorable conditions for re-excavation and erection of steel arch.
4.2 Treatment measures

(1) Grouting reinforcement: Curtain grouting was carried out in the unfavorable geological sections with water-rich gravel soil of the accumulation body for the section from ZK37+477 to +519 on the left line and the section from YK37+494 to +536 on the right line of Ningchan Tunnel. The scope of grouting reinforcement was a circle with a radius of 10m. In the grouting section, each cycle was 24m long. The grouting section was divided into two cycles. The first cycle was 18m long, and the second cycle was 24m long. After one grouting section was completed, 6m was left without excavation, which would serve as the grouting-stopping rock plate for the next grouting section.

The grouting holes were arranged in an umbrella-like radial shape from the working face to the excavation direction, which were arranged in several circles, with the inner and outer circles arranged in a blossom shape, and the long and short holes integrated, so as to achieve the purpose of sufficient grouting without leaving a dead space. The diffusion radius of grout was 2m, and the spacing between bottom holes was not more than 3m. If the surrounding rock condition was still unfavorable geology after the curtain grouting of the left and right lines was completed, curtain grouting could be continued. Fig. 2 shows the grouting parameters.

(2) Advance pipe-shed reinforcement: Three rows of φ108 pipe sheds for grouting treatment were used for the emergency geological disaster at YK37+500. After grouting, a row of φ108 drainage pipes were constructed above the grouting body. Double-spliced steel arch frames were set at the mud-bursting mouth to serve as one, and the spacing between the steel frames was 50cm. Φ108 large advance pipe sheds were constructed above the arches of the curtain grouting sections on the left and right lines. Fig. 3 shows detailed parameters.

Fig. 2 Design Drawing of Full-Face (Curtain) Advance Pre-Grouting
In the section from YK37+494 to YK37+536(42m)—the unfavorable geological section with water-rich gravel soil of the accumulation body, curtain grouting was adopted, and φ108 conduits of 24m long were used, with a cycle length of curtain grouting of 24m, a lap length of 6m for each cycle, which served as a grouting-stopping rock plate for the next cycle. Because the tunnel face of the left line was close to the mud-burst point on the right line, the surrounding rock was very similar to the condition at the time the mud burst occurred on the right line, which was water-rich surrounding rock of gravel soil of the accumulation body, and the water flow was gradually increasing, so two cycles of curtain grouting was set in the section from ZK37+477 to ZK37+519. The two cycles were overlapped for 6m, and φ108 pipe-following method was used to drill holes for the grouting pipes. At the same time, the large advance pipe shed was also the main channel for drainage of water and mud inrush cavities.

(3) Treatment of mud outburst cavity: The mud burst cavity was covered with colored strips in advance to prevent a large amount of rainwater from entering the cavity during raining/snowing. For the accumulated water in the cavity, a water pump was installed to pump it out. After the treatment of mud outburst in the cavity was completed and the secondary lining reached the design strength, it was backfilled. Before backfilling, the surrounding area of the cavity was backfilled in layers with in-situ topsoil, which was 150cm away from the surface of the earth, and then C25 concrete with a thickness of 150cm was poured as the surface covering to prevent rainwater infiltration. Finally, a clay layer with a thickness of 50cm was laid on the surface.

5. Analysis of Treatment Effect
In order to evaluate and analyze the treatment effect, the accumulated vault settlement and accumulated peripheral convergence of 4 typical monitoring sections before and after treatment were selected, and the deformation laws of Ningchan Tunnel before and after treatment were summarized according to the characteristics of monitoring curves. YK37+445 was a monitoring section before treatment, and YK37+505, YK37+525 and YK37+545 were monitoring sections after treatment.

5.1 Layout of monitoring points
The measuring point for vault settlement was selected at the vault, and one measuring point was set. The measuring points for peripheral convergence were selected at the waist position of the left and right arches, as shown in Fig. 4.
5.2 Comparison of monitoring section data before and after treatment: vault settlement (representative point) and peripheral convergence

(1) Monitoring data processing

Monitoring and measuring in tunnels will be affected by many external factors. The original data obtained from field measurement have some discreteness to a certain extent, including reading errors and even test errors. Moreover, there is no linear relation among the data obtained from tunnel monitoring and measurement. The displacement-time diagram drawn according to the data obtained from actual tunnel measurement will be in a very unstable state and there is no regularity at all. So, it is particularly difficult to analyze the variation law of the measuring points based on this diagram. Therefore, in order to better analyze the regular changes, it is necessary to apply mathematical methods to carry out regression analysis on the data obtained from monitoring and measurement.

In this paper, exponential function $u = ae^{(-b/t)}$ is used for regression analysis. Where $u$ is the displacement (mm); $a$ and $b$ are regression constants. The steps of converting it into a linear function by exponential function are as follows:

It can be obtained by exponential function: $\ln u = \ln a - \frac{b}{t}$

Let $Y = \ln u, \ X = -\frac{1}{t}, \ A = \ln a, \ B = b$, then it can be converted into a linear equation: $Y = A + BX$

Coefficients $A$ and $B$ can be estimated by the least square method:

$$A = \bar{Y} - B\bar{X} = \frac{\sum_{i=1}^{n} Y - B \sum_{i=1}^{n} X}{n} \quad (1)$$

$$B = \frac{\bar{X}\bar{Y} - \bar{X}\bar{Y}}{\bar{X}^2 - \bar{Y}^2} = \frac{n \sum_{i=1}^{n} XY - \sum_{i=1}^{n} X \sum_{i=1}^{n} Y}{n \sum_{i=1}^{n} X^2 - (\sum_{i=1}^{n} X)^2} \quad (2)$$

Correlation coefficient:

$$r = \frac{n \sum_{i=1}^{n} XY - \sum_{i=1}^{n} X \sum_{i=1}^{n} Y}{\sqrt{[n \sum_{i=1}^{n} X^2 - (\sum_{i=1}^{n} X)^2][n \sum_{i=1}^{n} Y^2 - (\sum_{i=1}^{n} Y)^2]}} \quad (3)$$

After the above coefficient is obtained, the values of $a$, $b$, $u$ can be obtained, i.e. $a = e^A, \ b = B, \ u = e^{A+B/t}$

(2) Result analysis
Fig. 5 are graphs showing the monitoring data of the Monitoring Sections YK37+445 (monitoring section before treatment) and YK37+505 (monitoring section after treatment) as well as the exponential fitting data V.S. time.

Calculation results: The theoretical maximum vault settlement of Monitoring Section YK37+445 was 36.966mm, the maximum peripheral displacement was 32.720mm, and the vault settlement on the 45th day was 31.10968mm, which was 84.2% of the theoretical final settlement. By taking the derivative of the fitting formula, the settlement rate on the 45th day was 0.0154 mm/d; the peripheral displacement on the 45th day was 26.205mm, which was 92.3% of the theoretical final peripheral displacement. The convergence rate of peripheral displacement on the 45th day was 0.0129 mm/d.

For Monitoring Section YK37+505, the theoretical maximum vault settlement was 28.392mm, the maximum peripheral displacement was 22.680mm, and the vault settlement on the 45th day was 24.691mm, which was 87.0% of the theoretical final settlement. By taking the derivative of the fitting formula, the settlement rate was 0.012 mm/d; the peripheral displacement on the 45th day was 19.874mm, which was 92.4% of the theoretical final peripheral displacement. The convergence rate of peripheral displacement on the 45th day was 0.0098 mm/d.

Comparing the data of two monitoring sections, compared with Monitoring Section YK37+445, the maximum vault settlement of Monitoring Section YK37+505 is 8.57mm smaller and the peripheral displacement is 10.04mm smaller. In addition, the settlement rate and peripheral displacement convergence rate of Monitoring Section YK37+505 are lower than those of Monitoring Section YK37+445 on the 45th day of face excavation.

According to the above data analysis, it can be concluded that the surrounding rock of Monitoring Section YK37+505 after treatment is better than that of Monitoring Section YK37+445 which has not been treated. This suggests that the design of parameters for grouting reinforcement and advanced pipe shed reinforcement, etc. in this project was reasonable and the treatment effect was obvious, which can
provide reference for the treatment of mud burst and water gushing in similar tunnel projects in the future.

6. Conclusions
The control the unfavorable hydrogeological disaster of water gushing and mud bursting in Ningchan Tunnel is a long-term and complicated systems engineering. In order to ensure the normal tunneling during the tunnel construction and the permanent safety of the structure during the operation, the construction organization organized multiple expert consultation meetings and implemented a series of treatment measures. Finally, grouting reinforcement and advance pipe shed were adopted. Therefore, some experience has been accumulated during the implementation of the scheme, and the following conclusions have been drawn.

(1) The design parameters of grouting reinforcement and large advance pipe shed in this project are reasonable and the treatment effect is obvious, which can be used for reference in similar projects in the future.

(2) The main reason for the water and mud inrush disaster in the tunnel is that the unfavorable geology was uncovered rashly without taking advance geological prediction measures. To prevent disasters, advance geological prediction should be strengthened, and the technical scheme of "first treatment, then excavation" should be strictly implemented.

(3) After water and mud inrush, it is necessary to carry out evaluation on the safety of desilting to prevent secondary disasters during desilting.

(4) After water inrush occurs in a deep-buried karst tunnel, the treatment measures of the combination of blocking and drainage must be taken. Water inrush and mud gushing caused by tunnel excavation will change the original drainage channel of groundwater. Meanwhile, the discharge of sediment will form new drainage channels of groundwater and aggravate the infiltration of surface water, so comprehensive treatment measures should be taken: sealing and strengthening the surface rivers and valleys, and reducing the infiltration of surface rivers; Appropriate plugging measures shall be taken in the tunnel to control the discharge of groundwater.

Acknowledgments
This work is jointly supported by the Science and Technology Project of Transportation Department of Qinghai Province (No. 2020-01).

References
[1] ZHOU Y. Study on water inrush mechanism and early warning of filled piping-type disaster and its engineering applications in tunnels [D]. Ji’nan: Shandong University, 2015.
[2] Liu Z G, Liu X F. TSP application and development in tunnel lead forecast [J]. Chinese Journal of Rock Mechanics and Engineering, 2003, 22(8):1399-1402.
[3] Lin C N. Research on application of comprehensive advanced prediction for karst tunnels [J]. Chinese Journal of Underground Space and Engineering, 2008, 4(6): 1086-1090.
[4] Zhang M Q, Sun G Q. Technology for treating mud and water bursts in tunneling [J]. Modern Tunneling Technology, 2011(12):117-123.
[5] Li S C, Li X Z, Jing H W, etc. Research progress on disastrous mechanism, prediction, early warning, and control theory of deep and long tunnels [J]. China Basic Science, 2017, 19(3): 27-43.
[6] Zhou Z Q. Evolutionary mechanism of water inrush through filling structures in tunnels and engineering applications [D]. Ji’nan: Shandong University, 2016.
[7] Yang T H, Chen S K, Zhu W C, etc. Water inrush mechanism in mines and nonlinear flow model for fractured rocks [J]. Chinese Journal of Rock Mechanics and Engineering, 2008, 27(7):1411-1416.
[8] Yang T H, Tang C A, Tan Z H, etc. State of the art of inrush models in rock mass failure and developing trend for prediction and forecast of groundwater inrush [J]. Chinese Journal of Rock Mechanics and Engineering, 2007, 26(2):268-277.

[9] Yang P, Tang Y Q, Peng Z B, etc. Study on grouting simulating experiment in sandy gravels [J]. Chinese Journal of Geotechnical Engineering, 2006, 28(12):2134-2138.

[10] Zhang Z M, Zou J, He J Y, etc. Laboratory tests on compaction grouting and fracture grouting of clay [J]. Chinese Journal of Geotechnical Engineering, 2009, 31(12): 1818 - 1824.

[11] Zhu M T, Zhang Q S, Li S C, et al. Numerical simulation and experimental study on soil split grouting reinforcement mechanism [J]. Journal of Central South University (Science and Technology), 2018, 49(5): 1213 -1220.

[12] Wang K, Li S C, Yang L, etc. Tests on physic-mechanical properties of grouted completely weathered granite Journal of Tianjin University: Natural Science and Engineering Technology, 2017, 50(11):1199-1209.

[13] Yuan J Q, Chen W Z, Huang S W, et al. Experimental study on physic-mechanical properties of grouted completely weathered granite [J] Chinese Journal of Rock Mechanics and Engineering, 2016, 35 (Supplement1):2876 - 2882.

[14] Zhang W J, Li S C, Wei J C, etc. Model tests on curtain grouting in water-rich broken rock mass [J]. Chinese Journal of Geotechnical Engineering, 2015, 37(9): 1627 - 1 634.

[15] Zhang Q S, Li P, Zhang X, etc. Model test of grouting strengthening mechanism for fault gouge of tunnel [J]. Chinese Journal of Rock Mechanics and Engineering, 2015, 34(5):924 - 934.

[16] Li M B, Xu M, Wang Y H. Analysis of structural characteristics and causes of karst channel fillings [J]. Yellow River, 2011, 33(4): 144 – 146.