Experimental Research on Destruction Characteristics of Mud Inrush on Tunnel in Argillaceous Fault Fracture Zone

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Abstract. The argillaceous fault fracture zone is a special area which bears the most concentrated stress when it forms and develops. Therefore, the tunnel under construction is subject to serious water and mud inrush when excavated through this area. In order to explore the destruction characteristics of mud inrush, a large-scale three-dimensional geological model test was carried out, which overcomes the "black box" problem of the traditional test, and a cone-shaped and parabolic body model were proposed to depict the shape of soil disturbance. In addition, the evolution law of displacement field inside medium was studied and the change regulation of actual disaster influence area also was been revealed. Finally, the tunnel mud inrush mechanics were revealed according to destroyed characteristics. As the results showed, the location of the initial mud inrush occurred at the spandrel of the tunnel face, the displacement of soil near the location of mud inrush increased with proceeding time, but there was a sudden saltation of the increasing rate when the disaster occurred. Besides, the shape of surface subsidence above the location of the inrush gradually transferred from “W” to “V” in the process of mud inrush. With the increase of the number of mud inrush, the soil disturbance develops from the local to the whole. When the local disturbance occurs, the soil form is cone, while when the whole disturbance occurs, the soil form is parabola. In addition, it is found that soil displacement is related to the seepage pressure under different disturbance modes. Finally, the conclusion of the model test may shed light on the catastrophic process and evolution law of the mud inrush in fault fracture zone, which has certain guidance and reference significance for the prevention of mud inrush in similar projects.

Keywords. Argillaceous fault fracture zone; mud inrush; geological model test; destroyed characteristics.

1. Introduction

With the rapid development of traffic infrastructure construction in China, a large number of tunnel projects have been put on the construction agenda. Among them, a large number of tunnel construction projects are located in the southwest mountainous area with complex geological conditions. When the tunnel passes through the fault fracture zone, karst, high stress soft rock and other unfavorable geological areas, large-scale mud inrush disaster is very easy to occur, which often leads to casualties, construction period delay and environmental damage. For example, Yesanguan Tunnel [1] of Yiwan railway has experienced many large-scale mud inrush disasters, with the cumulative mud inrush volume of about 5.3×10⁴ m³; Six mud inrush disasters have occurred in Xiangshan tunnel [2] of Longxia railway, and the maximum instantaneous mud inrush volume is 1000
m³. At present, how to carry out targeted, rapid and effective treatment of frequent mud inrush disasters has become a bottleneck restricting the development of tunnel and underground engineering construction.

Because the occurrence of mud inrush is often accompanied by water inrush disaster, most of the existing studies [3-5] focus on water inrush, or simply classify mud inrush disaster as the associated disaster caused by water inrush through the idea of “water inrush with mud”, and then equate the disaster characteristics of these two disasters. However, due to the huge differences in the nature of water and mud, mud inrush and water inrush are two different types of disasters. Therefore, the relevant disaster control theories which study on water inrush cannot provide scientific and effective guidance for the prevention and control, early warning and grouting treatment of mud inrush.

In view of the above problems, some scholars have carried out targeted research on the mechanism of mud outburst. In terms of experimental research, Zhang [6] and Wang [7] developed large-scale three-dimensional mud outburst model test systems respectively, studied the evolution process of mud outburst in tunnels. In the aspect of numerical simulation, Wang [8] and Geng [9] established a three-dimensional numerical model of tunnel mud inrush by using the discrete element method, which revealed the mechanism of disaster. In theory, Liu [10] proposed the critical starting formula of particles in the process of mud inrush and Yao [11] established the coupling dynamic model of broken rock mass. These achievements have greatly promoted the development of the research on the mechanism of mud bursting, but most of them are limited to the starting criteria and evolution characteristics of disasters. Although it has an important guiding role in disaster prevention and early warning, but limited by the "black box" problem, it is impossible to study the morphological characteristics, damage scope and disturbance mode of mud outburst. Therefore, in the post disaster treatment, grouting design still mainly depends on experience, resulting in poor treatment effect, low treatment efficiency and repeated mud inrush disasters. Tunnel construction often falls into a passive situation of “mud inrush-treatment-excavation-mud inrush again-treatment again”.

Based on the mud inrush disaster of Yonglian tunnel, this paper carries out further research on the basis of Wang [8] and Zhang [12]. Through the large-scale three-dimensional tunnel mud inrush model test, the evolution law of displacement field in the medium was monitored, the disturbance morphology and evolution mode of mud inrush body in the process of disaster were studied, and then the mechanism of mud inrush was revealed from the perspective of disaster disturbance characteristics. The research results have certain guiding significance for the disaster pre-warning and post disaster management.

2. Model Test of Mud Inrush Disturbance

2.1. Engineering Background
Yonglian Tunnel is located in Jiangxi Province, China. Yonglian Tunnel was designed for two-way separation of the tunnel with the left tube 2486 m long, along with the right 2494 m long. The tunnels pass through 4 secondary fault zones, including the representative fault F2. The rock mass structure in the fault F2 was crushed to a near-to-complete fragmented state, in which the filling mainly contained argillaceous substance with a poor binding form. In contrast, mainly composed of mudstone and shale, the rock in common zone had some water-conducting capacity, could resist the disintegration, and therefore, the fault was well developed here. The area was rich in water and high in both ground and water pressure. When the tunnel was excavated to F2 fault, there were 15 water and mud inrush disasters with the total amount of emission properties approaching about 35,000 m³, which leads to a large range of lining damage, surrounding rock collapse and surface collapse, as shown in figure 1. It is a serious threat to construction safety and greatly delays the construction progress.

2.2. Model Test System of Mud Inrush
In order to reproduce the catastrophic process of mud inrush and explore its mechanism from the perspective of disaster disturbance characteristics, a large-scale three-dimensional geological model
A test system was developed [7]. Using this system, the process of mud inrush can be reduced. By monitoring the earth pressure, seepage pressure, displacement and strain, the shape changes of geological disaster variants were analyzed, and the time effect characteristics of mud inrush were studied, so as to reveal the activation mechanism of surrounding rock under the comprehensive action of Engineering Disturbance and groundwater.

Figure 2 shows a simple model of the test system. The model test system consists of four parts: test model frame, crustal stress loading system, water pressure loading system and information monitoring system. Similar materials are divided into ordinary surrounding rock and fault surrounding rock. The angle between the fault and the tunnel axis is 85°, the dip angle is 90°, the fault width is 0.3m and runs through the whole model. The layout of monitoring section and monitoring points is shown in figure 3. In particular, the number of monitoring points on each ring from the vault is arranged as 1, 2, 3, 4, 5, 6, 7, 8 clockwise. Taking IZ12 as an example, the number of monitoring points is defined as follows: 1 stands for monitoring section, Z stands for left hole, 1 stands for 1 times of tunnel diameter, and 2 stands for right arch shoulder position.
2.3. Experimental Scheme

2.3.1. Experiment Principle. Under the action of long-term groundwater seepage damage, a part of the rock and soil medium in the tunnel site will be activated and the solid-plastic-liquid phase transition process will be completed. As a result, the rock and soil body is transformed from normal rock and soil medium to disaster-causing medium, the cohesion and internal friction angle are greatly reduced, and the mechanical strength of the medium is significantly reduced [13]. When the Yonglian Tunnel was excavated to expose the above-mentioned disaster-causing media, a large amount of water-sand mixture immediately poured out, leading to mud-bursting disasters. With the outburst of disaster-causing media during the mud burst process, a large-scale cavity destruction area is formed behind the tunnel face. Over time, under the combined action of groundwater, own gravity and in-situ stress, un-activated rock and soil media will migrate to the destruction zone, and repeatedly completes the above activation process. Due to the periodic “activation-inrush-migration-reactivation” process, the failure area continues to expand, eventually penetrating the surface to form a large area of collapse (figure 1c).

In summary, the destruction zone formed by the flooding of the pre-order disaster-causing medium provides a space foundation for the activation and migration of the subsequent disaster-causing medium during the mud burst, forming an unstable area for the next mud-burst disaster. Therefore, it is of great significance to clarify the morphological changes and range characteristics of the destruction zone during the mud inrush process for post-disaster grouting treatment. In this paper, the model test is carried out to simulate the actual reality of the project. Through the monitoring of soil mass displacement and seepage pressure in the process of mud inrush, the disturbance mode and morphological characteristics of mud inrush were studied.

2.3.2. Experiment Conditions. In actual engineering, the disaster-causing media and groundwater volume characteristics can be obtained through hydrogeological exploration, geophysical exploration and core drilling, and then the in-situ stress and groundwater pressure can be obtained. After finishing the model body, seal the top of the model and open the hydraulic control station, so that the model body is loaded. Finally, use the water supply system to fill the model body with water, adjust the in-situ stress and the water level to the initial state of the actual project, keep the water and pressure until the monitoring data is stable, then conduct tunnel excavation and data collection. And the disturbed shape and influence range of the rock and soil body after mud inrush are studied.

According to the actual tunnel excavation method and progress, the upper and lower bench excavation method was adopted in the test [14]. The height of the upper step is 6.5 cm, the height of the lower step is 8.6 cm, the trial excavation one cycle footage is 2.5 cm, which is equivalent to the actual project footage of 1.5 m, and the excavation step length is 12.5 cm, which is equivalent to the actual project distance of 7.5 m. Considering the continuous water seepage in the tunnel during the experiment, the water source was continuously added to the water supply tank during the excavation, keeping the water level height unchanged. When the excavation surface completely exposes the chasm, stop the excavation and observe the data and changes in the surrounding rock of the tunnel until the instability and damage of the surrounding rock of the chasm occur mud inrush.

3. Analysis of Test Results

The disturbance characteristics such as the morphology, displacement and influence range of the mud inrush are closely related to the amount of mud inrush and the evolution characteristics of the disaster, which directly affect the hazard degree of the disaster and the design of grouting treatment after the disaster.

3.1. Disturbance Morphology of Mud Inrush Body

The displacement can reflect the settlement and deformation state of rock mass at different time and position in the process of mud inrush. Figure 4 shows the subsidence curve during the first disaster. In
the initial stage of tunnel excavation, the subsidence of the tunnel vault was larger than the middle region. With the advance of excavation, the settlement at the vault of two tunnels was larger than that at the opening of the water and mud inrush. Moreover, the influence of weakening of groundwater on the fault rock got increasingly obvious, the settlement value of rock in the middle area increased and its deformation state changed from shape “W” to “V” observed from cross section. When the first disaster occurred, a large number of water-mud mixture gushed, resulting in a large-scale subsidence of rock, and the collapse state of shape “V” formed eventually. At the final stage of a sequence of disasters, the rock mass tended to be stable, and its displacement was basically coherent with the disturbance form.

With the passage of time, the rock mass continues to lose stability and deformation under the weakening effect of groundwater, and the pressure arch is destroyed, forming the second mud bursting. As shown in figure 5, the displacement of IZ11, IZ22 and IZ33 increased abruptly, while that of IZ38 was relatively small, while that of IZ18 and IY01 were stable without cataclysm. The distribution of monitoring points where saltation appeared is shown in figure 6, in which the area “AOB” formed by the line between monitoring points denoted the main influencing scope of the mud inrush. It is suggested that the closer the monitoring point was to the tunnel surface and the excavation contour line, the larger displacement the surrounding rock could produce. When the second and third mud inrush occurs, the shape of this area has formed and is stable, which is the main disturbance area.

3.2. Disturbance Model of Mud Inrush Body

With the increase of the times of mud inrush, the upward extension range of the rock mass in the fault zone can be obtained from the change of displacement and morphology of mud inrush body. By analyzing the displacement of rock mass from excavation to the third mud inrush, we can see the change process of the disturbance mode. The deformation of rock mass in the region of mud inrush was analyzed, and the curves of different typical stages were drawn. It can be seen from figure 7 that the local “conical” failure mode caused by the first occurrence of water and mud inrush had developed into a “parabolic” mode. With the increase in the disasters, the disturbance range of the rock mass in the fault fracture zone persistently extended until the top rock was affected and triggered the surface subsidence and collapse, as shown in figure 8. In the figure, the first stage is the excavation of normal surrounding rock, the second stage is the initial stage of exposing fault, the third stage is the first mud inrush, and the fourth and fifth stages are the second and third mud inrush respectively. It can be seen from the analysis that in the first three stages, the rock mass at the top has basically not changed, only a small displacement occurs when the first mud inrush disaster occurs.

Figure 4. Subsidence curves of section I in every period of the first mud inrush. Figure 5. Displacement changes of several monitoring points.
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4. Influencing Factors of Destruction Characteristics
The different deformation morphology of rock mass in the process of tunnel excavation and mud inrush was studied, and the different disturbance model in different stages was tracked. In the late stage of the disaster, the disturbance morphology of mud inrush is stable, and it is a cone when it is damaged locally, and a parabola rotorator when it is overall damaged.

4.1. Local Disturbance Mode
In order to study and describe the influence of disasters on rock mass, the failure point was set as the coordinate origin, the distance from the mud inrush mouth was set as the abscissa (x-axis), the vertical displacement of the rock mass was set as the ordinate (Y-axis). After the mud inrush disaster, the rock and soil tend to be stable. When the height exceeds a certain level, the top of the disturbed area becomes a curved surface. Because its shape is symmetrical about the coordinate axis, the local failure mode shape is described in two dimensions, as shown in figure 9.

It can be seen from the above analysis of displacement curve, the displacement of rock mass in the area of mud inrush is large, while the displacement at the boundary is smaller, and it tends to be stable in the later stage of the disaster. In order to study the disturbance mechanism and influence analysis of mud inrush from rock mass, within the scope of rock failure, the influence height is h, n is the height difference between the disturbed area and the mixed critical area of the upper rock mass.
Based on the description of the rock disturbance morphology and boundary in the fracture zone of multiple groups of tests, the rock mass change law of local disturbance mode is summarized.

(1) The failure range of mud inrush results in local rock mass disturbance, which is similar to the shape of cone, and the two-dimensional expression is consistent with formula (1);

(2) The disturbance morphology and boundary of rock mass are related to the influence radius \( r \) and the influence height \( h \), which are determined by the mechanical parameters of rock mass under the load, especially the seepage pressure;

(3) When \( z > h - n \), the top of the disturbance area changes from a plane to a curved surface.

After mud inrush occurred in the tunnel, when the scale of the disaster is small or the early stage of multiple disasters causes local damage to the rock mass in the fault fracture zone, the rock mass disturbance morphology is shown in figure 10. Based on the test displacement data, the disturbance boundary morphology is fitted, which has a high correlation, as shown in table 1.

### Table 1. Fitting function of the disturbance morphology in different positions.

| Position | Fitting function | Correlation coefficient |
|----------|------------------|-------------------------|
| Both sides | \( x \geq r \) | \( z = -1.37 - 0.0035x \) | 0.9378 |
| | \( x \leq r \) | \( z = -1.29 + 0.002x \) | 0.8698 |
| Top | \(-r \leq x \leq r \) | \( z = -0.59 - 5.3 \times 10^4 x - 3.14 \times 10^6 x^2 \) | 0.865 |

The expression can be described as
\[
\begin{align*}
&z = a + bx(-r \leq x \leq r, z \leq h) \\
&z = c + dx + fx^2(-r \leq x \leq r, z \geq h - n)
\end{align*}
\] (1)

where the coefficients \(a, b, c, d\) and \(f\) are functions related to the seepage pressure \(P\). Because it is symmetrical about axis, the left displacement is taken as the research object, and the relationship between \(a, b, c, d, f\) and \(p\) is fitted through the test data, as shown in table 2.

**Table 2.** Fitting function between displacement of the left rock mass and distance to mud mouth.

| Seepage pressure (KPa) | Fitting formula | Correlation coefficient |
|------------------------|-----------------|------------------------|
| 9.15                   | \(z = -0.637 - 0.002x\) | 0.895                  |
| 13.31                  | \(z = -1.38 - 0.0038x\) | 0.95                   |
| 15.94                  | \(z = -1.37 - 0.0035x\) | 0.938                  |

The fitting relationship between the seepage pressure \(P\) and \(a, b\) is shown in formula (2), and the fitting curve is shown in figure 11.

\[
\begin{align*}
& a = 3.96 - 0.74p + 0.025p^2 \\
& b = 0.01 - 0.02p + 0.00007p^2
\end{align*}
\] (2)

The displacement of rock mass on both sides can be expressed as

\[
z = 3.96 - 0.74p + 0.025p^2 + (0.01 - 0.02p + 0.00007p^2)x
\] (3)

In the same way, the fitting function and correlation coefficient between the displacement of the top rock mass and the distance to mud mouth are shown in table 3.

**Table 3.** Fitting function between displacement of the top rock mass and distance to mud mouth.

| Seepage pressure (KPa) | Fitting formula | Correlation coefficient |
|------------------------|-----------------|------------------------|
| 14.32                  | \(z = -1.71 - 2 \times 10^{-4}x + 1.8 \times 10^{-5}x^2\) | 0.973                  |
| 14.85                  | \(z = -1.94 - 2.4 \times 10^{-4}x + 2 \times 10^{-5}x^2\) | 0.989                  |
| 16.23                  | \(z = -4.35 - 3 \times 10^{-4}x + 5.4 \times 10^{-5}x^2\) | 0.975                  |

The relationship between seepage pressure \(p\) and \(c, d, f\) is:

\[
\begin{align*}
& c = 19.36 - 1.46p \\
& d = 5.19 \times 10^{-4} - 5.06 \times 10^{-5}p \\
& f = -2.72 \times 10^{-4} + 2 \times 10^{-8}p
\end{align*}
\] (4)

The displacement of the top rock mass can be expressed as

\[
z = 19.36 - 1.46p + (5.19 \times 10^{-4} - 5.06 \times 10^{-5}p)x + (-2.72 \times 10^{-4} + 2 \times 10^{-8}p)x^2
\] (5)

**4.2. Overall Disturbance Mode**

With the increase of the number of mud inrush, the failure range of rock mass is expanding to the surface, the disturbance mode is gradually transformed from local to overall, and the morphology is evolved from cone to parabola rotating body, as shown in figure 12. Except for the boundary state of both sides, the change of internal rock mass is same as that of local disturbance mode. Therefore, the research on the displacement of rock mass at the boundary is focused.
Figure 11. Fitting curve of coefficient $a$ and $b$ with seepage pressure.

Figure 12. Two dimensional model of overall disturbance mode.

The fitting functions of the top rock mass morphology and the influence of seepage pressure on the boundary rock mass on both sides under overall disturbance mode are shown in table 4 and 5 respectively.

| Table 4. Fitting function of the disturbance morphology of the top rock mass. |
|--------------------------------------|-----------------|-----------------|
| Position               | Fitting function            | Correlation coefficient |
|------------------------|-----------------------------|-------------------------|
| Both sides $-r \leq x \leq r$ | $z = -7.57 + 6.1 \times 10^{-5} x + 9.9 \times 10^{-5} x^2$ | 0.969                   |
| Top                 | $z = -4.46 - 0.002 x + 9.3 \times 10^{-6} x^2$ | 0.992                   |

| Table 5. Fitting function of seepage pressure and displacement of rock mass on both sides of boundary. |
|--------------------------------------|-----------------|-----------------|
| Seepage pressure (KPa)              | Fitting formula            | Correlation coefficient |
|--------------------------------------|-----------------------------|-------------------------|
| 16.23                                | $z = -4.35 - 3 \times 10^{-4} x + 5.4 \times 10^{-5} x^2$ | 0.975                   |
| 20.34                                | $z = -4.43 - 5.3 \times 10^{-4} x + 5.4 \times 10^{-5} x^2$ | 0.961                   |
| 31.08                                | $z = -7.57 + 6.1 \times 10^{-5} x + 9.9 \times 10^{-5} x^2$ | 0.969                   |

The fitting function in table 4 can be abstracted as follows:

$$z = g + ix + mx^2$$  \hspace{1cm} (6)

The relationship between seepage pressure $p$ and $g$, $h$ and $i$ is as follows:

$$\begin{align*}
g &= -0.22 - 0.23 p \\
i &= 0.003 - 3.29 \times 10^{-4} p + 7.47 \times 10^{-6} p^2 \\
m &= -4.61 \times 10^{-6} + 3.26 \times 10^{-6} p
\end{align*}$$  \hspace{1cm} (7)

The displacement of rock mass on both sides of the overall disturbance mode can be expressed as follows:

$$z = -0.22 - 0.23 p + (0.003 - 3.29 \times 10^{-4} p + 7.47 \times 10^{-6} p^2)x + (-4.61 \times 10^{-6} + 3.26 \times 10^{-6} p)x^2$$  \hspace{1cm} (8)

The influence of seepage pressure on the top rock mass fitting function and correlation are shown in table 6.

The relationship between $g'$ and $i'$ and $m'$ is as follows:
\[
\begin{align*}
g' &= 4.2 - 0.28p \\
i' &= 0.002 - 1.22 \times 10^{-4}p \\
m' &= -8.7 \times 10^{-6} + 5.91 \times 10^{-7}p
\end{align*}
\] (9)

**Table 6.** Fitting function of seepage pressure and displacement of the top rock mass.

| Seepage pressure (kpa) | Fitting formula | Correlation coefficient |
|------------------------|-----------------|------------------------|
| 16.23                  | \(z = -0.11 -8 \times 10^{-3}x + 3.5 \times 10^{-7}x^2\) | 0.853                  |
| 20.34                  | \(z = -1.95 -1 \times 10^{-3}x + 4.2 \times 10^{-6}x^2\) | 0.941                  |
| 31.08                  | \(z = -4.5 -2 \times 10^{-3}x + 9.5 \times 10^{-6}x^2\) | 0.999                  |

The displacement of the top rock mass under the condition of the overall disturbance mode can be expressed as

\[
z = 4.2 - 0.28p + (0.002 - 1.22 \times 10^{-4}p)x + (-8.7 \times 10^{-6} + 5.91 \times 10^{-7}p)x^2
\] (10)

Through the test, it is found that after the rock mass softens under the action of groundwater, the relationship between seepage pressure and displacement is close, and the influence of seepage pressure on displacement is different in different stages of rock mass. From the test results, both the local disturbance mode and the overall disturbance mode show that the closer the mud inrush mouth is, the greater the seepage pressure is, the greater the displacement of the rock mass is, so that the rock mass has different disturbance morphology in different stages.

### 5. Conclusions

(1) Through the model test of mud inrush disaster, it is found that the displacement of the rock mass in the middle of the two tunnels is larger, and the closer to the mud inrush mouth, the more obvious the settlement of the surrounding rock. The settlement curve of rock mass near the mud inrush mouth gradually develops from “W” type to “V” type.

(2) With the increase of mud inrush times, the rock mass develops from local failure to overall failure. In the local failure mode, the disturbance morphology of rock mass is cone, while in the overall failure mode, the disturbance morphology of rock mass is parabola.

(3) Based on a series of experimental data, the shape and boundary of the rock mass disturbance were described, and then the fitting function of morphology and the fitting function of displacement with the change of seepage pressure under different disturbance modes are obtained. It is found that the influence of seepage pressure at different time and position on the displacement of rock mass is different, which makes the rock mass produce different disturbance characteristics at different stages.

### References

[1] Xu H and Deng Y 2010 Analysis of hydrogeology problems related to water bursting in area of DK124+602 at Yesanguan tunnel of Yichang-Wanzhou railway *Journal of Railway Engineering Society* 139 (4) 29-34.

[2] Zhang M, Zhang M, Huang H and Sun G 2011 Research on construction technology in karst area of Xiangshan tunnel of Longyan-Xianmen railway *Journal of Railway Engineering Society* 28 (9) 75-82.

[3] Li S, Wu J, Xu Z and Li L 2016 Unascertained measure model of water and mud inrush risk evaluation in karst tunnels and its engineering application *KSCE Journal of Civil Engineering* 24 1-13.

[4] Li L, Rong X, Wang M, Lu H, Xia Y and Zhang Z 2016 Development and application of 3D model test system for water inrush geohazards in long and deep tunnels *Chinese Journal of Rock Mechanics and Engineering* 35 (3) 491-7.

[5] Gu Y, Li X, Zhao Y and Ren S 2005 Analysis of forming reason of mud breakout in Tong-Yu tunnel *Rock and Soil Mechanics* 26 (6) 920-3.
[6] Zhang Q, Wang D, Li S, Zhang X, Tan Y and Wang K 2017 Development and application of model test system for inrush of water and mud of tunnel in fault rupture zone Chinese Journal of Geotechnical Engineering 39 (3) 417-26.

[7] Wang D, Zhang Q, Zhang X, Wang K and Tan Y 2016 Model experiment on inrush of water and mud and catastrophic evolution in a fault fracture zone tunnel Rock and Soil Mechanics 37 (10) 2851-60.

[8] Wang Y, Lu Y, Ni X and Li D 2011 Study on mechanism of water burst and mud burst in deep tunnel excavation Journal of Hydraulic Engineering 42 (5) 595-601.

[9] Geng P, Quan Q, Wang S, An J and Yan Q 2015 Study of the formation process of mud and water bursts during tunnel construction and the influence of fault dip angles Modern Tunneling Technology 52 (5) 102-9.

[10] Liu J, Yang D, Chen W, Yuan J, Li C and Qi X 2017 Research on particle starting velocity in the expansion of water inrush channel in completely weathered granite Rock and Soil Mechanics 38 (4) 1179-87.

[11] Yao B, Mao X, Wei J and Wang D 2014 Study on coupled fluid-solid model for collapse columns considering the effect of particle transport Journal of China University of Mining & Technology 43 (1) 30-35.

[12] Zhang Q, Jiang Q, Zhang X and Wang D 2019 Model test on development characteristics and displacement variation of water and mud inrush on tunnel in fault fracture zone Natural Hazards 99 (1) 467-92.

[13] Yang T, Zhang Q, Zhang X, Li X and Yin Z 2019 Cohesion variation during instability evolution of disaster medium in mud inrush of mountain tunnel Journal of Mountain Science 16 (11) 2519-31.

[14] Li X, Liang F, Lu Y, Kang Y, Fu C and He Z 2007 Analysis and prevention of geologic disasters caused by leakage in tunnel construction: Taking Huanshanping span tunnel as an example Chinese Journal of Rock Mechanics and Engineering 26 (Supp.1) 2718-23.