The failure characteristics around shallow buried tunnels under rainfall conditions

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\textbf{ABSTRACT}

The instability of weak surrounding rock around shallow buried tunnels induced by rainfall is a challenge for tunnel engineering and threatens construction safety. To reveal the influence of rainfall on the rock surrounding a tunnel, the results of experiments on the failure of surrounding rock under different rainfall intensities and durations using a self-developed test system are presented. First, the stress and seepage behaviors of the surrounding rock under rainfall were analysed, and the results showed that the stress increased while the pore water pressure decreased as the rainfall intensity decreased. It was more difficult to maintain vault collapse as rainfall intensity increased, and the particle erosion in the model intensified as the rainfall duration increased. The change in pore water pressure was greater than the change in stress, but the stress and pore water pressures influenced each other during rainfall. The influence of rainfall on the rock at the top of the tunnel was greater than that at the two sides of the tunnel because the seepage channels at the top of the tunnel were more developed and collapsed more easily due to smaller stressess. According to the phenomena of the surrounding rock observed during the test, the evolution of progressive failure under rainfall was roughly divided into eight stages: stability, water drop, continuous water flow, partial collapse, mud and water mixture, vault collapse, throughgoing collapse, and massive water and mud gushing. Furthermore, the final failure pattern of the surrounding rock consists of an excavation disturbance zone, vault damage zone and collapse failure zone. This research helps to reveal the progressive failure of surrounding rock around tunnels under rainfall conditions and can be used as a reference for designing disaster prevention strategies in practical engineering.

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1. Introduction

Engineering practice shows that rainfall often triggers water and mud inrush; water is an important factor that induces the instability of rock surrounding tunnels (Li et al. 2009; Lin et al. 2019). Water infiltrates into the surrounding rock of a tunnel through rock interfaces such as joints and cracks, which lead to the surrounding rock losing its stability and deteriorating under the action of softening, soaking and erosion, which is then followed by collapse and even water gushing and mud bursting (Fan et al. 2020; Xu and Li 2010; Yu et al. 2020b). In addition, water and mud inrush will seriously affect the progress of tunnel construction and may even result in casualties, and most underground geological disasters pose a risk to surface subsidence and affect the water environment (Li et al. 2016, 2017; Parise and Lollino 2011; Song et al. 2012). Moreover, rainfall and water infiltration in a rock mass is a dynamic process with strong spatiotemporal variation, with seepage transitioning between saturated and unsaturated conditions (Wang et al. 2017, 2019b; Zou et al. 2019).

Therefore, it is of great urge but difficulty to understand the stability of the surrounding rock under the water-rich condition during the construction and operation of underground engineering.

To date, many scholars have carried out relevant research on the stress and seepage behaviors of surrounding rock. Abundant research results have been obtained for the failure mechanism of surrounding rock of underground engineering, such as tunnels (Lü et al. 2017; Wang et al. 2020c). Sun et al. (2015) conducted a detailed analysis of the deformation and stress characteristics of surrounding rock from the perspective of rheological properties. Time-dependent deformation and fracture evolution around underground excavation with different shapes were numerical studied by stress corrosion theory from the view of the rheological model (Fu et al. 2020). Keawsawasvong and Ukritchon (2020) proposed a new design method for stability analyses of shallow buried tunnels with no liner, considering the generalized Hoek-Brown failure criterion. Tang et al. (2018) obtained an analytical expression of groundwater flow in circular tunnels with anisotropic soils, which is helpful for predicting pore water pressure distribution. Shahin et al. (2004) established a 2D plane strain finite element model to analyze the strata deformation and earth pressure around the tunnel in different excavation modes. Yin et al. (2020) applied the coupled FDM-DEM method to simulate the failure process of the excavation face and analyzed the behaviors of the soil, ground surface and supporting pressure of the rock. However, theory and numerical simulation clearly simplify practical engineering conditions, which are more complex and variable. Therefore, it is a feasible method to adopt geological model tests of the recurrence of engineering disasters and collect relevant data for further research. Kirsch (2010) prepared a series of small-scale models to study the stability and failure of tunnel excavation surfaces in sandy soil layers and found that the estimation of the support force based on results is smaller than that of the theoretical model. With the help of a large-scale model test, Liu et al. (2018) discussed the support force and ground settlement caused by the migration of soil particles of shallowly buried tunnels in dry sand. Xu et al. (2018) studied the progressive failure process, deformation and stress variation of surrounding rock around large sections and shallow buried tunnels by means of model tests and numerical
simulations. The stability of the surrounding rock under the disturbance of excavation was mainly the focus of these studies, while some influencing factors, such as water, have received little attention.

Furthermore, in view of the influence of water infiltration on the failure of rock masses in underground engineering, a considerable amount of relevant research has been conducted with theoretical calculations, numerical simulations, and model tests (Lei et al. 2019; Wang et al. 2020a, 2020b). Erguler and Ulusay (2009) designed laboratory tests to study the physical and mechanical properties of rock with different water contents. Fang et al. (2016) obtained the influence of external water pressure on tunnel liners under rainfall with the help of a self-developed apparatus. Zeng (2014) focused on the analysis of the characteristics of tunnel surrounding rock and supporting structure internal force characteristics under the condition of rainfall. Yu et al. (2014, 2020a) proposed analytical expression of the surrounding rock stress based on a simplified seepage field and researched the characteristics of the stress distribution under the effect of water infiltration and the time-dependent deformation mechanism in soft-rock tunnels was investigated in depth based on the humidity field theory and the 3D Hoek-Brown yield criterion. These authors quantitatively found that water seepage has a great impact on the surrounding rock and supporting structure of tunnels. Li et al. (2020) studied the seepage-failure coupling effect in the process of unloading in underground excavation. Yang et al. (2019) developed a model test system and fluid-solid coupled material, and the law of occurrence of water inrush was summarized by analyzing the interaction between groundwater and surrounding rocks during excavation. Zhang et al. (2019) have investigated seepage erosion around shield tunnels with the CFD-DEM model. Wang et al. (2019a) researched particle migration with water flow with a 3D solid-water flow. These previous studies have successfully acquired abundant results under the multifarious conditions of water-rock interaction.

In summary, outstanding achievements have been made in studies on the stability of tunnel surrounding rock via seepage analysis, mechanical research and numerical simulation under conditions of water infiltration. However, most of the previous studies have focused on the influence of water infiltration on the supporting state, deformation and stress of the surrounding rock (Dadashi et al. 2017; Hsiung 2018; Li et al. 2019), while few experimental studies have been conducted considering hydraulic coupling and the time-space effect during the failure of weak surrounding rock under rainfall (Liu et al. 2019). In addition, the time effect of the rainfall infiltration process is noticeable in practical engineering (Jiang et al. 2020; Liang et al. 2016). Therefore, the dynamic change process of weak surrounding rock under different rainfall conditions should be further explored. Thus, to investigate the progressive failure characteristics of weak surrounding rock under rainfall conditions, a series of rainfall tests for unsupported tunnels of surrounding rock with grade IV are carried out by using an independently developed apparatus that can simulate rainfall. According to the test results, the stress and pore water pressure characteristics of the surrounding rock are studied first, and then the effect of rainfall duration on the stability of the weak surrounding rock is examined. Finally, the failure evolution process of weak surrounding rock under the action of rainfall is presented. Moreover,
reasonable suggestions for tunnel engineering are proposed based on test results and analysis.

2. Experimental methods and procedures

2.1. Materials and apparatus used in the experiments

Weak tunnel surrounding rock is usually characterized by broken rock masses, low strength and large deformation, which are greatly affected by unfavorable geological conditions such as underground water (Santi 2006; Li et al. 2017). Thus, accidents such as water inrush, collapse and surface settlement easily occur, which leads to great difficulty in construction. Considering the limitation of experimental conditions and to satisfy the self-stability of surrounding rock during tunnel excavation, grade IV surrounding rock, which is common in practical engineering, is considered to define the mechanical parameters of the raw rock in this study.

In engineering practice, tunnel collapse and water inrush usually occur at an excavation section because of delay in supporting or insufficient support strength in weak rock masses, especially affected by rainfall in shallow buried tunnel. Therefore, experiments on the progressive failure of weak surrounding rock around tunnels without support structures under different rainfall conditions were conducted in this study. As the basis of the model test and to satisfy the grade IV rock mechanical parameters, the properties of the similar materials used should not only meet the basic geometric
similarity conditions of the model but also meet the fluid-solid coupling similarity conditions. Combined with the previous research results and following the principles of convenient material sourcing, simple manufacturing process and safety, similar materials of tunnel surrounding rock are prepared with river sand, clay, cement and water.

Similar materials are commonly used for simulating surrounding rock in experiments, and the similarity ratios of geometry \( C_l = 50 \) and bulk density \( C_c = 1 \) have been designed for this model test. According to similarity theory, the similarity ratios of Poisson’s ratio, strain and internal friction angle can be obtained \( (C_{\mu} = C_e = C_\varphi = 1) \). Moreover, the similarity ratios of the strength, stress, cohesion, elastic modulus and permeability coefficient between the raw rock and similar material also can be calculated \( (C_{\sigma} = C_c = C_k = 50, \text{ and } C_k = \sqrt{C_l C_c}) \). In addition, the permeability coefficient is regulated by the clay proportion and hydraulic oil, the material strength is controlled by the cement and hydraulic oil, and the cohesion is obviously affected by cement proportion and hydraulic oil proportion. Finally, the components of the similar materials for the tests were determined after several times of preliminary proportioning tests (sand:cement:clay:water:hydraulic oil = 8.0:0.6:0.4:0.8:0.1). The test specimens of \( \varphi50 \times 100 \text{ mm} \) were designed and fabricated (see Figure 1), and according to the data of laboratory experiments on rocks and similar materials, and the physical and mechanical properties are listed in Table 1.

|                  | Density (g/cm\(^3\)) | Compressive strength (MPa) | Elasticity modulus (GPa) | Poisson’s ratio | Cohesion (MPa) | Internal friction angle (\(^{\circ}\)) | Permeability coefficient (cm/s) |
|------------------|----------------------|----------------------------|--------------------------|-----------------|---------------|----------------------------------------|---------------------------|
| Raw rock mass    | 2.50                 | 15.00                      | 2.0000                   | 0.35            | 1.500         | 37                                     | \(2.85 \times 10^{-5}\)   |
| Similar materials| 2.46–2.58            | 0.28–0.32                  | 0.0384–0.0439            | 0.33–0.36       | 0.031         | 36–41                                  | \(4.36 \times 10^{-6}\)   |
| Mass ratio       |                      |                            |                          |                 |               |                                        |                           |

Adopting the plane strain model, the model test system of tunnel collapse under the conditions of rainfall and groundwater seepage (see Figure 2) with independent design and processing is used for the experiments to investigate the failure characteristics of weak surroundings under rainfall. The schematic layout of the experimental setup is shown in Figure 2(a). The test system mainly consists of three parts: rainfall equipment, seepage system and measuring system. The seepage system is mainly composed of a steel framework box with a net size of \(1000 \times 1000 \times 300 \text{ mm}\), and it is filled with similar material for simulating surrounding rock, providing the basic conditions of the experiment. Transparent PMMA with a thickness of 12 mm is applied to the front of the model box for visualization, therefore, the water seepage, deformation and failure of the surrounding rock can be observed during the experiment. A reserved hole with a net width of \(a\) and net height of \(h\) for simulating tunnel excavation and is located at the middle-lower area of the transparent PMMA. Moreover, the model box is not covered, rainfall equipment is set above the box, and an outlet is set on the right wall of the bottom of the test box for discharging water.

As shown in Figure 2(b), rainfall simulation is implemented by the rainfall equipment above the test box. The rainfall equipment is made of galvanized plate iron with the size of \(1000 \times 300 \times 30 \text{ mm}\), and the bottom of the plate has 200 evenly
distributed small holes of $\varnothing 1\text{mm}$. The uniform and dense distribution of the small holes in the rainfall equipment ensures the uniformity of rainfall so that rain will fall across the entire surface of the similar materials in the model box. Water pipes and valves are installed on both sides of the rainfall equipment, the water tank is connected by pipes and the flow rate can be adjusted by these valves. Since the water inlets are located at the middle of both sides of the rainfall equipment, the uneven rainfall caused by the internal air pressure of the rainfall equipment is alleviated, and the water flow in the rainfall equipment is accelerated; therefore, the rain falling into the test box is uniformly distributed. The measuring systems mainly include micro earth pressure cells, osmometers, displacement meters and digital photography (for non-contact measurement). The whole process of monitoring the strain, pore water pressure and deformation fields of the surrounding rock under the condition of rainfall is realized.

Based on similarity theory, a shallow buried roadway in practical engineering is experimentally simulated in this study. As shown in Figure 3(a), there is a reserved tunnel cross section with the net span and net arch height are $a$ and $h$, respectively, and locates about $3h$ from the bottom of the glass plate. The height of the surrounding rock of the model is designed to be $0.83\text{m}$ and the burial depth of the roadway in the model is about $4.6h$. The top of the surrounding rock is set as a free boundary, while the other boundaries are fixed by the model box; a layer of hydraulic oil is applied inside the box before the test to prevent water from flowing along the inner wall of the model box during the experiments.

### 2.2. Testing methods and procedures

There are two steps in the experiments. The excavation of the tunnel section is carried out first under the condition of the low water content in surrounding rock. After the completion of excavation, a stable water supply is provided by the rainfall equipment installed above the model box to simulate rainfall and water infiltration. Thus, the surface of the model is evenly covered with water that falls from the rainfall
equipment vertically, and then rainwater infiltrates the cracks of the rock mass to replenish the groundwater, which results in the continuous accumulation and flow of underground water. The groundwater eventually drains out of the tunnel with the help of seepage action after a period accumulation, leading to the further destruction of the tunnel.

With reference to the standard for rainfall intensity of China Meteorological Administration, 10.0 mm/hr was selected for the intensity of heavy rain, 4.0 mm/hr for the intensity of moderate rain, and 0.4 mm/hr for the intensity of light rain for laboratory model tests in this study. Different levels of water supply flow are adopted in the rainfall system to simulate different levels of rainfall intensity in the experiments; thus, the specific scheme of the test is shown in Table 2.

The sensors arrangement around the tunnel is shown in Figure 3(a). Sensors T1, T3, T5, T7, T9 and T11 are earth pressure cells for measuring the stress of surrounding rock, sensors T2, T4, T6, T8, T10 and T12 are osmometers for measuring the pore water pressure of surrounding rock, and sensors T13, T14 and T15 on the top of the model are displacement meters for measuring the displacement of the surface of the model. The earth pressure cells and osmometers are alternatively arranged on the top and sides of the tunnel cross section. For the displacement meters on the ground surface of the model, sensor T14 is set directly above the tunnel axis, and the other two are each arranged 200 mm from the tunnel axis.

This test is roughly divided into two procedures, tunnel excavation and failure due to hydraulic loading. The whole cross section is excavated and formed once, and after the monitoring data acquired from the sensors in the model reach stable conditions, simulations of different levels of rainfall intensity are realized through the flow control of water entering into rainfall equipment according to different test schemes.

It can be seen from Figure 3(b) that although the stable state of the surrounding rock could be achieved in the excavation process, the inner wall surface of the cave is...
rough, and partial collapse occurs because of the insufficient bearing capacity of the weak surrounding rock.

During the test, the model is left for a period of time after the completion of excavation, and rainfall is carried out when the data collected by the acquisition instruments achieve stability. The variation characteristics of various factors in the failure process of tunnel surrounding rock under rainfall conditions are obtained based on the analysis of the test results, and the progressive failure characteristics of the weak surrounding rock of a shallow buried tunnel under the condition of rainfall are revealed.

3. Stress and pore water pressure characteristics of surrounding rock under different rainfall intensities

To explore the variation in pore water pressure and stress in the rock surrounding the tunnel during different levels of rainfall intensities, representative stress measuring points T1 and T9 and representative pore water pressure measuring points T2 and T10 were selected for analysis. The variation characteristics of the data of the selected points at different times under different rainfall intensities are plotted in Figure 4 and analysed as follows.

When the rainfall duration is 10 min (shown in Figure 4a), it is clear that the stress of the rock surrounding the tunnel increases approximately linearly with the decrease in rainfall intensity. Moreover, the stress at the top (T9) of the rock surrounding the tunnel is greater than that at the arch wall (T1). However, the pore water pressure of the surrounding rock decreases approximately linearly with the decrease of rainfall intensity, and the pore water pressure at the top (T10) of the surrounding rock is lower than that at the arch wall (T2). This indicates that rainfall has little influence on mechanical and hydraulic state of the rock surrounding the tunnel at the beginning of rainfall infiltration.

When the rainfall duration is 20 min (see Figure 4b), analysis was conducted based on the monitoring values of stress measuring point T9 and pore water pressure measuring point T10. The results are different from those in Figure 4(a), suggesting that the pore water pressure of the surrounding rock at the top of the tunnel shows a slight increase with the decrease of rainfall intensity, and the stress and pore water pressure at the top of the tunnel both decrease greatly. The result demonstrates that particles of surrounding rock at the top of tunnel loss occurred initially as rainfall duration increased.

As seen in Figure 4(c), when the rainfall duration is 30 min, considering the stress at measuring point T9 and the pore water pressure at measuring point T10, the stress and pore water pressure of the surrounding rock at the top of tunnel...
furtherly due to rainfall infiltration but perform a slowly increase with the reduction in rainfall intensity. Specifically, the stress at the top of the tunnel surrounding rock becomes 0 kPa under the rainfall intensity of 10.0 mm/hr, which suggests that collapse has occurred at the top of tunnel.

Figure 4(d) shows that at the rainfall duration of 40 min, based on measuring points T9 and T10, the pore water pressure and stress of surrounding rock at the top of the tunnel are both 0 kPa under the rainfall intensity of 10.0 mm/hr. This implies that the surrounding rock at the top of the tunnel has been completely collapsed. Moreover, the pore water pressure of the surrounding rock on the two sides of the tunnel (T2) increases first and then decreases with decreasing rainfall intensity. It should be noted that the stress magnitudes at the sides of the tunnel show little change with rainfall intensity and duration, only a small decrease as the rainfall intensity and duration increase. This observation demonstrates that the influence of rainfall on the surrounding rock at the top of tunnel is greater than that at the sides and that the change in pore water pressure occurs prior to the change in stress.
4. Effect of rainfall duration on the stability of tunnels in weak surrounding rock

To investigate the variation characteristics of pore water pressure and stress in the tunnel surrounding rock throughout the rainfall process with different rainfall durations, the measured data corresponding to a rainfall intensity of 0.4 mm/hr are selected for analysis as an example. Therefore, sensors T1, T3, T9 and T11 are adopted to monitor the stress changes in surrounding rock of the tunnel. Sensors T2, T4, T10 and T12 are used to monitor the pore water pressure changes in surrounding rock of the tunnel. It should be noted that the time when the similar materials reach saturation is defined as the beginning time of the tests, and the measured soil stress is negative based on the assumption that the stress is positive upward. Therefore, the changing characteristics of the detailed measure data are presented in Figure 5 for different rainfall durations.

According to the pore water pressure and stress monitoring data of the surrounding rock during rainfall shown in Figure 5, the influence of rainfall duration on the stability of tunnel surrounding rock can be analysed as follows.

The stress and pore water pressure of measuring points T1 and T2 decrease by 1.28% and 24.02%, respectively, from the maximum value to the end of the test. This indicates that the change in pore water pressure in the surrounding rock is greater at the tunnel sides than it is at other locations, while the stress of the surrounding rock is relatively stable under the rainfall intensity of 0.4 mm/hr. The results at measuring points T9 and T10 at the top of tunnel decrease by 6.91% and 34.76%, respectively, from the beginning to the end of the experiment. The influence of rainfall on the stability of the top of the tunnel is distinctly greater than that at both sides. With the increase in rainfall duration, there are several times of fluctuations in the stress values monitored at measuring point T3 and pore water pressure values monitored at measuring point T4, which implies that a certain fluctuation in the stress and pore water pressure occurred due to the effect of groundwater in the surrounding rock. This observation suggests that the pore water pressure in the rock surrounding the tunnel
is changed by rainfall via rainfall infiltration. The change in pore water pressure leads to the change in stress in the surrounding rock, which then influences the pore water pressure, resulting in the fluctuation in the pore water pressure curves. This demonstrates that there is a mutual influence between the pore water pressure and stress of the rock surrounding the tunnel. Meanwhile, the stress and pore water pressure data at measuring points T3 and T4 remain steady after the rainfall duration of 20 min with the increase in rainfall duration, suggesting that the pore water pressure and stress are nearly unaffected by rainfall in the surrounding rock at about 1.5 h from the sides of the tunnel.

Affected by rainfall, the pore water pressure of the surrounding rock around the tunnel is gradually changed rather than abruptly changed. During rainfall, the pore water pressure fluctuates slightly at the beginning, then generally slightly increases to the peak at about the rainfall duration of 10 min, and finally decreases gradually. Moreover, the pore water pressure generally decreases and surrounding rock stress tends to become relatively stable with the increase in rainfall duration and continuous development and expansion of the seepage channel in the surrounding rock. Compared with the surrounding rock of the tunnel arch (T1, T2, T3 and T4), the surrounding rock at the top of the tunnel (T9, T10, T11 and T12) corresponds to a lower stress and pore water pressure, which indicates that the seepage channels in the surrounding rock above the tunnel are more developed than that on the sides. The top of the tunnel is prone to collapse because the stress of the surrounding rock is lower and an unloading zone easily forms there.

Taking the example of the rainfall intensity of 0.4 mm/hr, the effect of tunnel collapse damage on surface settlement under different rainfall durations is investigated. The amount of settlement of the model surface obtained from measuring points T13,

![Graph](image_url)
T14 and T15 under the different test conditions described previously and the other monitoring data are summarized in Figure 6.

The settlement of the ground measuring points continuously increases with rainfall duration. Moreover, the variation in the final settlement at the ground measuring point T13 20 cm from the left side of the tunnel was almost synchronous with that of measuring point T15 20 cm from the right side of the tunnel in rainfall test. It could be concluded that the uniform rainfall leads to the surface settlement distribution that is approximately symmetric across the tunnel axis.

This finding conforms to the observations: not only is the settlement of measuring point T14, which is directly above the tunnel, the largest but also the rate of increase in the settlement there is consistently greater than that at the sides of the tunnel under the condition of the same rainfall duration.

5. Progressive failure analysis of tunnels in weak surrounding rock under the action of rainfall

The evolution process of surrounding rock failure in tunnels affected by rainfall is presented in this section based on the phenomena of model test (see Table 3 and Figure 7), combining the pore water pressure and stress data of the surrounding rock during rainfall (see Figure 5). To facilitate the recording of the phenomena during rainfall and considering the rheology of weak surrounding rock, rainfall was suspended after every 5 min of rainfall, and the state of the surrounding rock was recorded. The test phenomena observed at different rainfall intensities are listed in Table 3, among which the phenomena that occurred under the rainfall intensity of 10.0 mm/hr are shown in Figure 7.

| Rainfall duration/min | 10.0 mm/hr | 4.0 mm/hr | 0.4 mm/hr |
|-----------------------|------------|-----------|-----------|
| 15                    | No obvious phenomenon | / | / |
| 20                    | Water droplets on top of the tunnel | / | / |
| 25                    | Continuous water flow from the top of the tunnel | / | / |
| 30                    | A local collapse in the tunnel | No obvious phenomenon | / |
| 35                    | A mixture of mud and water upwelling | Water droplets on top of the tunnel | / |
| 40                    | Vault collapse | Continuous water flow from the top of the tunnel | / |
| 45                    | Throughgoing collapse | A local collapse in the tunnel | / |
| 50                    | Large-scale of water and mud gushing | A mixture of mud and water upwelling | No obvious phenomenon |
| 55                    | / | Vault collapse | Water droplets on top of the tunnel |
| 60                    | / | Throughgoing collapse appeared | Continuous water flow from the top of the tunnel |
| 65                    | / | Large-scale water and mud gushing | Local collapse in the tunnel |
| 70                    | / | / | A mixture of mud and water upwelling |
| 75                    | / | / | Vault collapse |
According to Table 3 and Figure 7, the surrounding rock around the tunnel can basically be self-stable after excavation. Taking the rainfall intensity of 10.0 mm/hr as an example, water droplets can be observed at the top of tunnel after 20 min of rainfall, which indicates that the seepage channel initially formed along the rock mass fractures. More concretely, the initial formation of the seepage channel in the rock mass takes that 35 min at the rainfall intensity of 4.0 mm/hr and 55 min at the rainfall intensity of 0.4 mm/hr. These results indicate that rainfall intensity plays a relatively significant role in the failure of tunnels caused by rainfall. Furthermore, seeping water gradually develops into a continuous flow with the increase of rainfall duration, accompanied with erosion of the surrounding rock. The outflowing fluid changed from the clear water to the muddy water mixture, worse that local collapse ulterior occurred at the top of tunnel, as shown in Figure 7(a). The collapse developed upward, and collapse occurred on both sides of the tunnel as the rock and soil particles were further carried into the tunnel by water flow (see Figure 7b and 7c). It can be considered that the unloading zone at the top of the tunnel and the deadweight of the surface water of the model play a dominant role in the vault collapse at the top of the tunnel.

The corresponding ground surface at the top of the tunnel presented a funnel-shaped subsidence distribution (see Figure 7d), this implies that stress readjustment
occurred at the top of the tunnel. In other words, a certain thickness of rock mass with a certain capacity to resist the hydraulic disturbance formed in the tunnel surrounding rock. Subsequently, the rock mass of the model surface subsided along the crack in the weak surrounding rock mass with continuous rainfall. With further rainfall, the particles of the surrounding rock around the tunnel were consistently dragged away by the groundwater, resulting in the gradual weakening of the self-stability ability of the surrounding rock mass. This promoted the coalescence of the bottom of surface subsidence area and the top of tunnel collapse area (see Figure 7e). Finally, the tunnel surrounding rock further deteriorated because of the infiltration of rainwater, and vault collapse gradually developed, penetrating the surface (see Figure 7f). In addition, under the condition of different rainfall intensities, three final failure modes of tunnel collapse were recorded after the data collected during the test became stable and shown in Figure 8.

During the development of the failure of the rock surrounding the tunnel caused by the seepage action of the rainwater under different rainfall intensities, three regions form in the surrounding rock, as Figure 8 clearly shows: the excavation disturbed zone, the vault damage zone and the collapse failure zone. Among them, the area of the excavation disturbance zone is mainly regarded as the unloading area of surrounding rock caused by excavation, and it is rational identified by the cracks around the rock mass of the tunnel after excavation. The vault damage zone is induced by the internal pressure-arch effect, and it is identified by the scope of the intermittent cracks and collapse during the rainfall experiment. In addition, the collapse failure zone is formed by the gradual expansion of cracks to the surface of the model. The sequential failure process of the rock surrounding the tunnel was analyzed in detail on the basis of the test results of three kinds of rainfall intensity, and the following modest rules are proposed.

The destruction of the surrounding rock begins at the top of the tunnel firstly, and then the collapse at the top of the tunnel occurs and gradually develops upward symmetrically along the two sides of the tunnel with the increasing rainfall duration. Furthermore, it is considered that the main reasons for the failure of surrounding rock are the deadweight of the water on the model surface and rainwater infiltration...
that expands the cracks in the rock mass. Thereafter, water gushes are clearly observed, the scouring effect of the groundwater as well, and the water output gradually turns into a muddy water mixture that includes particles of the surrounding rock. This leads to serious water and soil loss in the interior of the model, as well as the formation of cracks, resulting in a change in the original stable state of the tunnel surrounding rock. The damage degree of mud inrush worsens, which leads to large-scale collapse of tunnel surrounding rock and significant ground subsidence of model surface.

Considering the deformation process diagram of the tunnel model collected during the test, the dynamic collapse evolution of the tunnel develops along the two large main cracks that formed in the upper part of the tunnel surrounding rock with rainfall. It should be noted that the shape of collapse zone on either side of the tunnel is symmetrical due to the uniform distribution of rainfall. Furthermore, it is more difficult to maintain the state of vault collapse with increasing rainfall intensity. The larger the rainfall intensity is, the shorter the rainfall duration needed for through-going collapse.

The primary reason for the initiation of the collapse of tunnel surrounding rock is the collapse of the unloading zone caused by excavation cracks and infiltration in the cracks. Thus, tunnel collapse develops upward during vault collapse with increasing rainfall, which leads to the distinct ground subsidence of model surface. Concretely, the largest surface settlement and the widest scope of influence of the surface occur with the rainfall intensity of 10.0 mm/hr, followed by the rainfall intensity of 4.0 mm/hr. For the rainfall intensity of 0.4 mm/hr, partial collapse occurs at the top of the tunnel for only a limited time during the experimental observation. Although rainwater flows out of the tunnel along the stable seepage channel and the surface subsidence of the model appears, the collapse does not penetrate the surface of the model, and the main fracture in the surrounding rock does not extend to the surface; therefore, stable arched failure ultimately occurs.

The above analysis shows that the collapse modes of the surrounding rock around the tunnel are not only determined by rainfall intensity, but also closely related to rainfall duration. Therefore, it is of strongly necessary to monitor the tunnel surrounding rock during construction and operation. Meanwhile, measures such as the redirection and discharge of surface rainwater should be taken in a timely manner to reduce the infiltration of rainwater, particularly in the case of continuous rainstorms. Therefore, it is important to weaken the adverse effect of groundwater seepage on rock and soil structure at the source to further reduce the probability of water and mud inrush disasters.

### 6. Conclusions and discussions

To investigate the effect of rainfall infiltration on weak surrounding rock around tunnels, the surrounding rock of grade IV that common in practical tunnel engineering was selected, and the failure of surrounding rock was been experimentally simulated with an independently developed laboratory test system. The mechanical and hydraulic behaviors, as well as the evolution characteristics of the tunnel surrounding
rock, were analyzed under different rainfall conditions. Several conclusions are summarized based on the above results and analysis as follows.

With the reduction in rainfall intensity, the stress of surrounding rock tends to increase while the pore water pressure decreases. In addition, particle erosion of the model interior intensifies as rainfall duration increases, which leads to local collapse occurring initially at the top of the tunnel. Moreover, the pore water pressure of surrounding rock changes gradually rather than abruptly during failure caused by rainfall infiltration, and the changes in pore water pressure occur earlier than the change in stress. There is a mutual influence between the pore water pressure and stress of surrounding rock, which is more evident at the beginning of the rainfall.

In addition, with the increase in rainfall duration and gradual enlargement of the seepage channels of surrounding rock, the pore water pressure of surrounding rock decrease in general, while the stress tends to remain stable. Notably, the influence of rainfall on surrounding rock at the top of the tunnel is greater than that at the two sides of the tunnel. In other words, the seepage channels in the surrounding rock at the top of the tunnel are more developed compared with those at the two sides of the tunnel under the condition of rainfall. Moreover, the stress of the surrounding rock at the top of tunnel is relatively low and prone to collapse when the unloading zone forms. Therefore, it becomes more difficult to maintain vault collapse of the surrounding rock at the top of tunnel with the increase in rainfall intensity.

Finally, the evolution of the failure of surrounding rock under rainfall conditions is proposed based on the test results: stability, water drop, continuous water flow, partial collapse, mud and water mixture, vault collapse, throughgoing collapse, and massive water and mud gushing. Furthermore, the final failure zone of surrounding rock roughly consists of an excavation disturbance zone, vaulted damage zone and collapse failure zone.

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