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STUDY ON THE STABILITY EVOLUTION LAW OF EXPANSIVE SOFT ROCK ROADWAY AFFECTED BY SEASONAL WET-DRY CYCLE

Many open-pit mines are gradually converted to underground mining, the problem of roadway surrounding rock damage caused by expansive soft rock is becoming increasingly problematic. To study the seasonal evolution of expansive rock mass containing clay minerals, an underground mine transferred from an open-pit was selected as the experimental mine. The experimental results of SEM electron microscopy and X-ray diffraction confirmed that the surrounding rock of the main haulage roadway contains a large number of expansive clay minerals. The expansive grade of the main transport roadway's surrounding rock could then be identified as the medium expansive rock mass, which has a large amount of exchangeable cation and strong water absorption capacity, based on the combined test results of dry saturated water absorption and free expansion deformation. The water swelling can cause the roadway to considerably deform, and then the surrounding rock will have strong rheological characteristics. From the research results in the text, the seasonal evolution law of the main haulage roadway in the experimental mine was obtained, and the deformation law of the expansive rock mass under different dry and wet conditions was revealed. The research results provide a reference for studying the stability evolution law of expansive soft rocks in underground mines.

Keywords: Underground mine; expansibility; rheology; clay minerals; seasonal evolution

1. Introduction

With the continuous advancement of the economy, the quantity of large-scale geotechnical engineering in China is increasing. Among them, the Three Gorges Hydropower Station, Qinling

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Tunnel and the planned Bohai Tunnel are known to the world. Many rock mass projects such as water conservancy, deep mining roadways and subsea tunnels are always in the water environment, and the surrounding rock is always in a saturated state. During the construction and operation of rock mass engineering, rocks interact with groundwater. Therefore, studying the stability of rock mass engineering under the influence of water and its time dependence is of great significance to ensure the long-term stability of rock mass engineering in a water environment.

Natural rock masses are mostly anisotropic discontinuous media, and inevitably there are fissures with different characteristics. In a water environment, water will move along the fissures in the rock mass, resulting in an interaction between rock and water. The groundwater in the fissure changes the fissure structure in the rock mass through osmotic pressure and physical & chemical action. The hydrostatic pressure and hydrodynamic pressure are applied to the rock mass. Finally, groundwater affects the fissure structure and stress field of the rock mass. The fissure expansion caused by engineering disturbance accelerates the water flow along the fissure in the discontinuous medium. The influence of rock-water interaction on the stability of rock mass is further aggravated due to the continuous engineering construction and blasting vibration disturbances, the structural plane of the rock mass is developed ceaselessly, and the seepage field in the rock mass changes correspondingly. The expansive rock mass mineral expands rapidly with water, and this expansion stress accelerates the expansion of the structural surface. Next, the stress field and structural plane distribution of the original rock are changed. It is precisely because of the interaction between the rock mass and the water environment, and the stability of the rock mass engineering under the water environment needs to be solved urgently.

In recent years, domestic and foreign experts have begun to focus on the strain-softening problem of expansive rock masses. The influence of expansive minerals on the stability of surrounding rock in rock mass has gradually become a research hotspot. The earliest country to study the interaction between rock and water was the former Soviet Union. Bridgman (1949) first discovered and proposed the expansion mechanism of the expansive rock mass. He proposed that the fissures in the soft rock block continue to expand after the interaction between rock and water in the air with the development of time. The whole rock mass gradually disintegrates and breaks, and the volume increases continuously with the expansion. Burshtein [14] studied the effect of water content on the uniaxial compressive strength of rock. Atkinson et al. [3] studied the effect of water on quartzite fracture from the perspective of stress corrosion. The research results of Logan et al. [11] show that water can significantly affect the friction properties between rocks. Feucht et al. [13] studied the effects of different chemical solutions on the strength and friction properties of rocks. Karfakis et al. [16] studied the effect of water chemistry on rock fracture toughness. Hawkins et al. [1] found that the sandstone strength in the saturated state is 31% lower than that in the dry state. The change of pore water pressure has a great influence on the attenuation of strength. Zhou et al. [6] conducted an experimental study on soft rocks in saturated conditions and found that the mechanical strength index of soft rock decreases with the increase of time until it reaches a stable value, which obeys the exponential change law. Tang et al. [15] studied the propagation law of rock mass fissures with rock-water interaction and discussed the fracture strength of rock mass in a saturated environment. The ageing characteristics of various mechanical indexes were analysed by experiments on mechanical and fracture effects of rock mass in various chemical solutions. According to the experimental results, the quantitative method of rock mass mechanical effect with rock-water interaction is proposed. Yang and Cao [8] studied the meso-mechanical model of equivalent fissure propagation with rock-water interaction and discussed the meso-mechanism of fissure growth. Rashdi et al. [9] conducted a series of destructive and non-destructive tests on sandstone samples and studied the engineering property change characteristics of sandstone in porosity, permeability, water absorption, density, Q factor, elastic modulus (E) and unconfined compressive strength (UCS).

In addition to the chemical and physical effects of rock and water, the mechanical action of rock and water is also a key issue in the research of rock engineering. Since the Soviet Union scholars conducted rock mass fissure hydraulic tests in the 1940s, rock mechanics researchers around the world have done a lot of experimental and theoretical research on the mechanical effects of rock-water interaction. Louis et al. [5] carried out a water flow model test using a single-fracture test piece to analyse the influence of the fracture surface characteristics on the water flow. Through testing and analysis, it is considered that the effect of the osmotic pressure on the fractured rock mass is composed of tangential force, hydrostatic pressure and hydrodynamic pressure generated by the viscosity of water. Louis first proposed the concept of rock hydraulics. Afterwards, Raven et al. [12] studied the relationship between seepage and stress and obtained the corresponding curve. To study the detailed relationship between seepage and stress, rock mechanics researchers have proposed various seepage models for fractured rock masses. While studying the seepage model of rock mass, the researchers also studied the effect of osmotic pressure on rock mass and the coupling of the osmotic field and stress. Walsh [10] and Morrow [4] studied the effective stress law of rock mass with osmotic pressure. It is believed that water pressure is an essential element affecting the performance of fractured rock mass, and its changes can lead to stress changes in rock materials. Maslia [17] pointed out that effective stress is related to the confining pressure and osmotic pressure of the rock mass, and a correlation relationship is proposed. Priest et al. [18] also believed that the effect of osmotic pressure on the rock mass is also reflected in the damaging effect of the rock mass. Vázquez-Silva et al. [19] designed and optimised the support of two typical roadways affected by mining in low-quality rock mass under complex geological conditions. Skrzypkowski et al. [20] have proved through experiments that rocks are more easily damaged and cracked under high temperatures and that rocks are more vulnerable when exposed to water. Sun et al. [21] used a crushed rock deformation-seepage test system to test the compressive deformation of crushed sandstone under different saturated conditions. Ram et al. [2] studied the slope failure characteristics affected by rainfall in Viti Levu area of Fiji.

In summary, the rock-water interaction cannot be ignored in rock engineering. Factors such as strain softening, fissure propagation and intrinsic stress of rock and water have been thoroughly studied by scholars. However, the rock sample used in the indoor experiment cannot represent the property of the rock mass in the on-site engineering. The properties of the expansive soft rock encountered in the on-site engineering are affected by many factors such as structure, weathering layer, environment, etc. Therefore, the on-site rheological characteristics of the expansive surrounding rock were explored in this paper, and the creep characteristic curve of the expansive rock mass was obtained. This lays a foundation for the prevention and control of the harmful deformation of the expansive rock mass under the influence of the rock-water interaction of this type of mine.

2. Geology and Engineering Background

The experimental mine is located about 45 km away from Beipiao City, Liaoning Province. The centre of the mining area is located at 42.5° north latitude and 121.8° east longitude (as shown in Fig. 1). The mine is adjacent to the east side of Inner Mongolia, and the mining area is about 1,200 m long and 820 m wide. The lithology of this ore is mainly mixed rock and slanted amphibolite. The majority of the surrounding rocks are black-green, with massive structures and flaky crystal formations. The roadway characteristics used in this experiment's strata control are fairly clear. The lithology of the surrounding rock is mainly migmatite and amphibolite. The early exploration results show that the mineral composition is as follows: 55% potassium feldspar, 20% potassium feldspar, 22% biotite and 3% garnet.

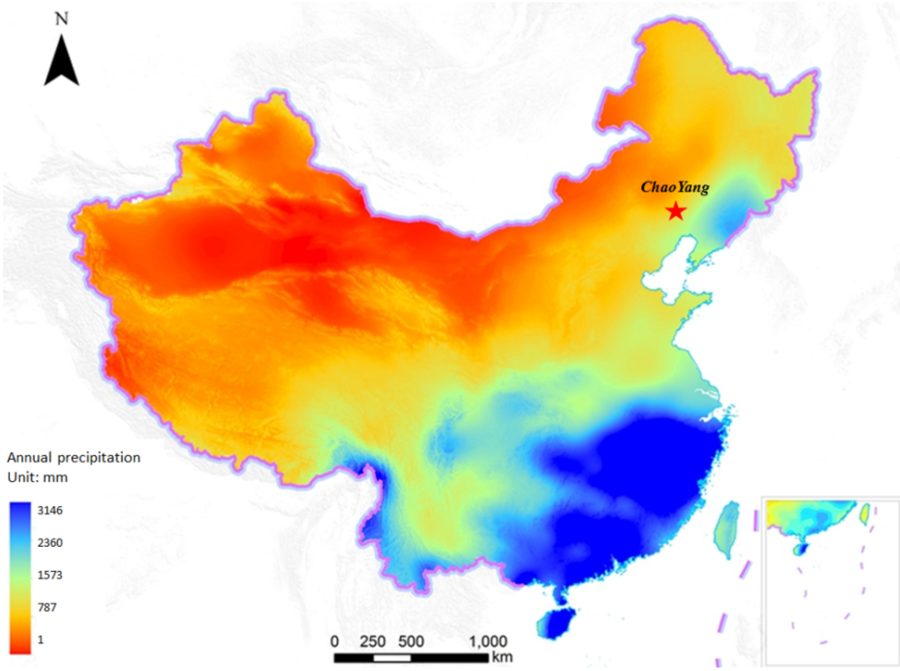


Fig. 1. Experimental mine location and annual average precipitation

The main rivers within the mining area are 2~10 m wide (up to 300 m when flooding), the flow rate is 0.1~50 m^3/s, and the total length of the river is 42 km. The water-filling factor during the open-pit mining of experimental mines was mainly atmospheric precipitation, and the underground water-filling factor was mainly the structurally confined water of the rock layer itself. With the development of open-pit to underground mining, the collapse subsidence area continually increased, and the surface atmospheric precipitation seepage gradually became the main source of groundwater. The average rainfall in the mine range is 490 mm/a, and the rainy season is from June to August. The location of the mine is the north temperate monsoon climate zone. The rainfall varies greatly from season to season. Fig. 2 shows a comparison of different environmental humidity of the experimental mine roadway during the rainy and dry seasons. Fig. 2(d) illustrates the phenomenon that the water mist in the roadway adheres to the roof and freezes when the humidity of the ventilation roadway reaches 100% in the rainy season. At this time, the air's saturability is insufficient, and excess water will form a water mist, as shown in Fig. 2(c).

(a) The humidity of roadway in dry season

(b) The humidity of roadway in rainy season

(c) Water mist in the roadway during the rainy season

(d) Frozen ventilated roadway in rainy season

Fig. 2. Comparison of different humidity in rainy and dry seasons of experimental mine roadway

After on-site investigation, it was found that the ore body has complicated conditions, and the surrounding rock of the ore body belongs to the expansive rock mass containing clay minerals. It is prone to expansion deformation with the action of structural alteration. The surrounding rock of the lower plate has the characteristics of low compressive strength, large deformation, rapid pressure and easy swelling with water. These characteristics lead to the extremely low stability of the main haulage roadways, which seriously affects the mining and transportation of the mine. In the expansion and deformation of many roadways in the mine, the most typical are the fissures caused by the expansion of the surrounding rock and the serious deformation of the roadway bottom drum (as shown in Fig. 3).

Due to the extensive distribution of soft rock, the strain softening problem of the expansive rock mass has become a key issue that underground engineering technicians and researchers have to focus on. According to incomplete statistics, more than 50% of all types of rock on the earth's surface are composed of mudstone and shale. In the previous study, the research team studied the failure mechanism of the expansive soft rock roadway in underground mines. At the same time, Jing et al. [7] obtained the effect of cyclic mining blasting on the stability of the soft

(a) Side wall convergence (b) Roadway floor heave

(c) Roof subsidence (d) The whole deformation of surrounding rock

Fig. 3. Different destruction modes of expansive soft rock roadway during the rainy season

rock roadway. However, the failure modes of underground engineering gradually developed over time, and the rheological properties of expanded rock mass containing clay minerals in water-rich mines become the Achilles' heel that controls the stability of this lithologic rock mass. It is imperative to study the expansion law of the expansive rock mass with different stresses and in different environments.

3. Study on expansion mechanism of soft rock roadway

The swelling of clay minerals in soft rock underground engineering is a difficult problem in the fields of civil transportation, water conservancy, hydropower and mining. The basic factors affecting the properties of the expansive soft rock are mainly composed of internal and external factors. Internal factors mainly include rock components (mineral composition, chemical composition and particle size composition), natural water content and humidity status, and degree of cementation. The external causes are mainly composed of changes in moisture and internal stress caused by human activities. The unique geological conditions of soft rock mines cause the volume expansion of clay minerals to become the main reason for the deterioration of rock mass quality (As shown in Fig. 4). The essence of soft rock expansion is caused by the hydrophilicity of the clay minerals. The hydrophilic ability of clay minerals varies with the composition. According to the findings of earlier investigations, montmorillonite has a significant capacity for expansion, whereas illite and kaolinite have the least. The significant expansion capacity of montmorillonite is due to its strong cation exchange capacity, and the volume will expand rapidly after absorbing moisture. The volume of montmorillonite in the expansion stage of the crystal layer can be doubled. In the permeation hydration stage, the volume of montmorillonite will continue to increase several times as the water permeates under the osmotic pressure. Studying the deformation mechanism of soft rock roadways containing clay minerals in the underground mining environment is extremely important because of the considerable expansion capacity of clay minerals.

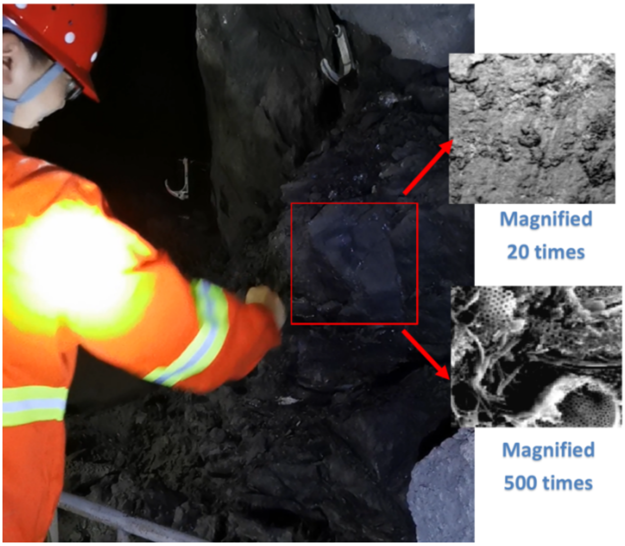


Fig. 4. Collection of soft rock samples in underground mines

The ore body type of the experimental mine is the Anshan-type sedimentary metamorphic iron deposit in Chaoyang, Liaoning Province. Randomly selected samples were scanned by an electron microscope and clay mineral X-ray diffraction experiments in the main haulage roadway of the mining level. The model of the scanning electron microscope is CD-SEM S-8840, and the secondary electron image resolution is 5 nm (50 A). The model of XRD is XRD-6100, with an optical resolution of 0.01. The results of scanning by electron microscopy are shown in Fig. 5. The specific mineral composition statistics are shown in Table 1, and the X-ray diffraction experimental results are shown in Table 2. The sample rock name is garnet-biotite-plagioclase-gneiss. The rock is black-green, with a large structure. The characteristics of some minerals are as follows. The jointed potash feldspar is not easily clayed, and the particle size distribution is

0.3-20 mm. The plagioclase is a double crystal structure with weak sericitisation, and its particle size is mostly 0.5-1 mm. The biotite is in the form of flake, reddish-brown, unevenly aggregated, and the particle size is mostly 0.2-1.5 mm. The garnet is granular and light brown, and the cleavage is relatively developed, with a particle size between 0.2-0.5 mm.

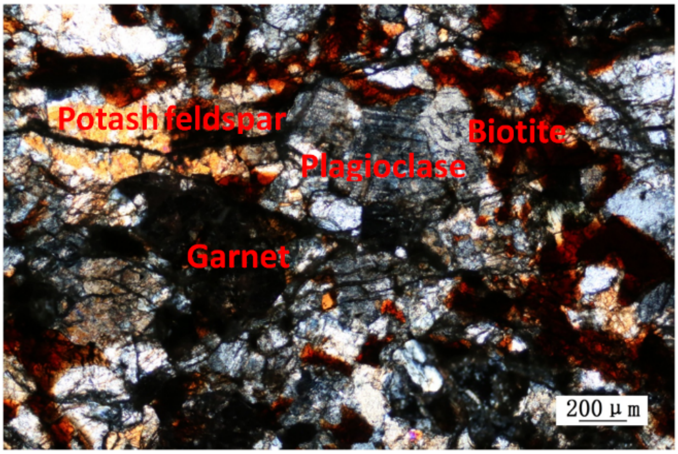


Fig. 5. Results of SEM scanning in Baoguo iron mine

TABLE 1

SEM mineral composition analysis results

	Mineral composition relative content (%)				
Minerals	Plagioclase	Potash feldspar	Biotite	garnet	clay minerals
Content	37.7%	10%	22.5%	13%	16.8%

TABLE 2

Clay mineral X-ray diffraction analysis results

	Clay minerals relative content (%)			
Clay minerals	Smectite	Illite	Kaolinite	Chlorite
Content	15.624%	0.336%	0.336%	0.504%

Clay minerals are mainly crystal minerals. Crystal is the regular arrangement of atoms and ions in space. The internal atomic arrangement has a fixed regularity. The spacing between atomic layers is characteristic of mineral crystal structure. Diffraction occurs when X-rays are injected into the crystal lattice of clay minerals. Different clay minerals have different lattice structures, which will produce different diffraction patterns. XRD analysis is based on the characteristics of the layered structure of clay minerals and the principle of X-ray diffraction. The interplanar spacing is calculated from the diffraction peaks. Thereby, the mineral type could be judged. Finally, the percentage of various clay minerals in the sample is inferred semi-quantitatively. The expansion of soft rock has a direct relationship with the content of clay minerals. Previous research results show that when the montmorillonite content is more than 7% or the illite content is more than 20%, the soft rock has obvious expansion and contraction characteristics. The higher the content is, the greater the expansion ratio will be. The X-ray diffraction analysis method can be used to determine the types of clay minerals and their percentages, thus revealing the influence of clay minerals on the stability of underground soft rock roadway engineering. Based on the test results, the composition and percentage of clay minerals in the surrounding rock of the main haulage roadway can be obtained.

According to clay mineral X-ray diffraction analysis results, the clay mineral composition of this mine is mainly montmorillonite, and the content of montmorillonite exceeds 7%. The content of other clay minerals is insignificant, so the expansibility of the soft rock in this mine is mainly affected by montmorillonite. There are two main expansion forms of soft rock: ① The reduction of cohesive force will lead to softening, disintegration and fragmentation, while the mineral particles do not expand. The mineral composition of this rock is mainly kaolinite and illite; ② The expansion of mineral particles will lead to softening and fragmentation, and the composition of this rock is mainly montmorillonite. Therefore, according to the above analysis results, the expansion property of rock mass studied in this paper is the second form.

Based on the proportion of expansive clay minerals, the swelling grade of soft rock containing clay minerals could be classified by the grading standard of expansive soft rock in Table 3 (Sun et al., [22]). Determining the expansion level of soft rock roadway has a significant effect on the deformation mechanism of the large deformation soft rock roadway.

TABLE 3

Standard for classification of expansive soft rock

Classification	Dry saturated water absorption ratio /%	Montmorillonite content /%	Free expansion deformation ratio /%
Strong expansibility	>50	>30	>15
Medium expansibility	20~50	10~30	10~15
Poor expansibility	<20	<10	<10

In addition to the content of montmorillonite, the expansion rock determination index also has a dry saturated water absorption rate and free expansion deformation amount. The samples of the expansive rock used in the dry saturated water absorption test were taken from the main haulage roadway at –40 m below the mine to ensure that the samples weren't weathered. In the test, 50 g of the above intact samples were taken respectively for the dry saturated water absorption and the free expansion deformation. After the test, the average montmorillonite content of the sample was 15.624%, the average dry saturated water absorption rate was 32.947%, and the average free expansion ratio was 21.236%. Applying the expansive soft rock grading standard proposed by Professor He Manchao, the surrounding rock of the main haulage roadway of Baoguo Iron Mine belongs to medium expansion soft rock. This type of soft rock is prone to be clastic or destructive after water immersion. It has a large water absorption capacity, which is clearly controlled by the exchangeable cation composition.

The expansive rock mass will cause a rheology effect under engineering stress, which is mainly composed of creep, relaxation and elastic aftereffects. Among them, creep refers to the phenomenon of the deformation increasing with time when the load is constant. Relaxation refers to the phenomenon when the stress decreases with time, and the strain remains unchanged. Elastic aftereffect refers to the phenomenon that elastic strain lags behind stress when loading or unloading. Therefore, the expansion of the rock is caused by its rheological constitutive characteristics. It is well known that the nature of rocks cannot explain rock masses, and the environmental conditions of underground engineering are more complex and variable. Therefore, to study the seasonal deformation law of large deformation soft rock roadway, it is necessary to obtain both the macroscopic response law of the surrounding rock of the roadway under the overall action of various daily production disturbances as well as the physical and structural characteristics of the rock mass through laboratory experiments.

4. Study on Seasonal Evolution Law of Expansive Soft Rock Roadway

The damage of rock engineering projects is often controlled by the rheological properties of the rock mass. In order to study the seasonal evolution law of the underground mine, it is necessary to first analyse the rock-water interaction law of the expansive soft rock roadway in the experimental mine. First, the mine's areas of rock and water deformation and destruction were meticulously counted. Detailed statistical results show that the water seepage of the surrounding rock corresponds to the damage to the roadway. The statistics of roadway damage caused by the rock-water interaction in the mine are shown in Fig. 6.

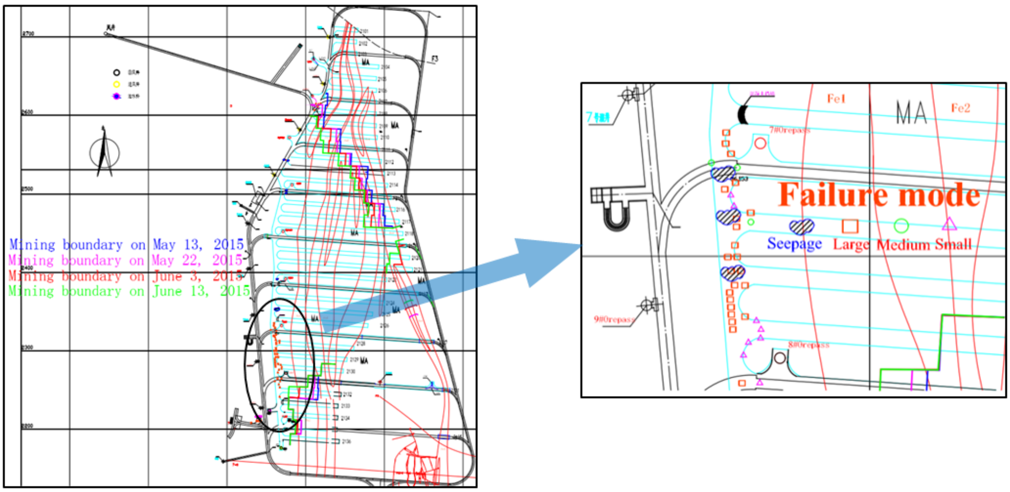
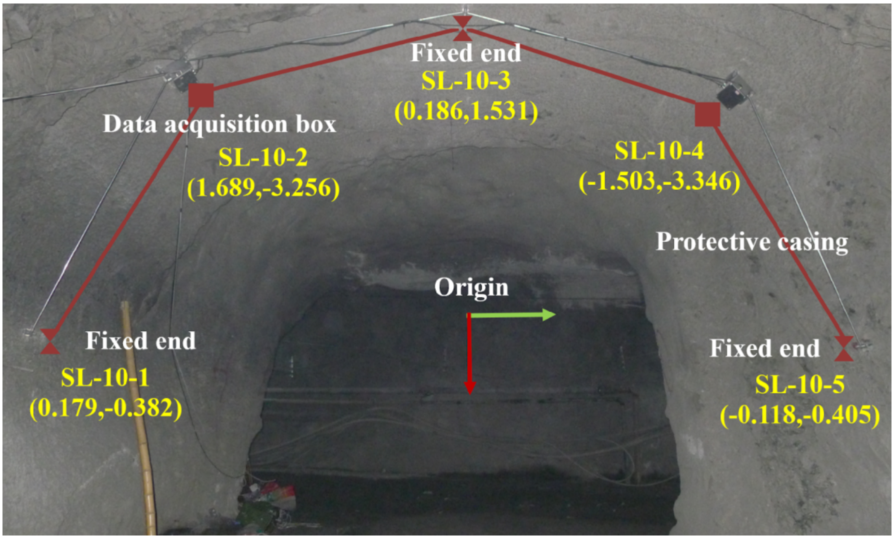
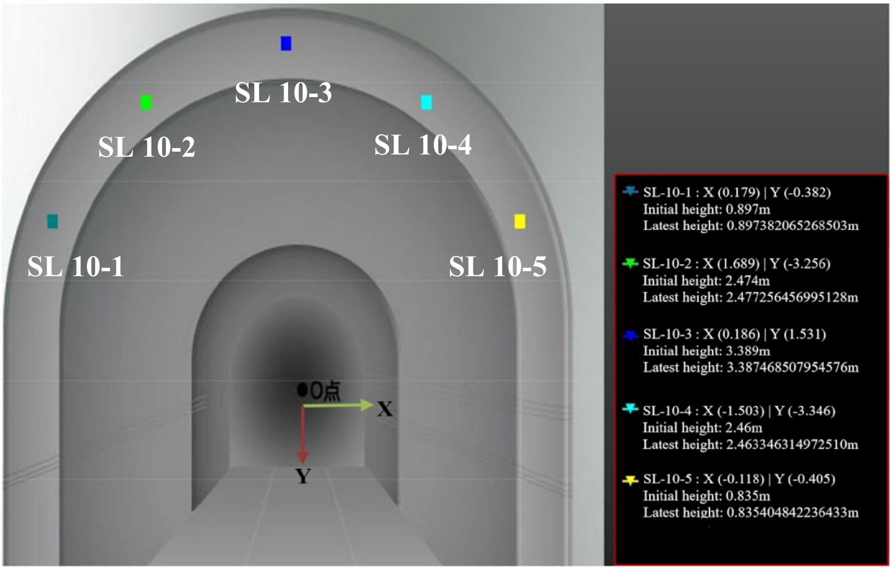


Fig. 6. Statistics on the damage caused by rock-water reaction in the expansive surrounding rock roadway

In order to study the seasonal evolution law of the expansive rock roadway containing clay minerals, and explore the deformation characteristics of the expansive rock mass under the rock-water interaction, Jing et al. (2018) independently developed the underground mine roadway deformation continuous monitoring system "MineTCS" to obtain continuous and complete roadway surrounding rock deformation monitoring data. Fig. 7 shows the equipment installed at the SL-10 monitoring point in the surrounding rock and the real-time convergence deformation data.



(a) Installation of equipment in roadway



(b) Mine-TCS data real-time display interface

Fig. 7. Real time convergence deformation data of SL-10 monitoring point

Ten sets of Mine-TCS monitoring equipment were deployed across the entire mining roadway in order to get the comprehensive and precise deformation law of the expansive soft rock roadway. Fig. 8 depicts the equipment's installation scheme. The device has a once-per-minute sampling rate. The centralised collecting point will receive the data that was gathered at each monitoring point.

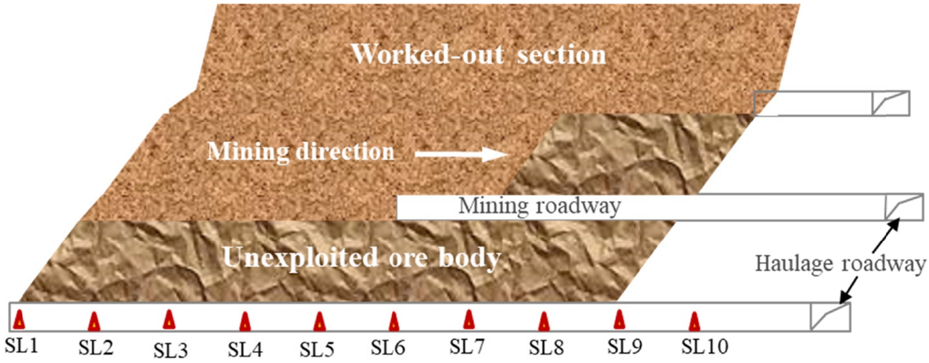


Fig. 8. Layout plan of Mine-TCS monitoring equipment

The survey results of rock mass structural surface information show that the joints and fractures of the rock mass are relatively developed, and the structure is broken, which means the groundwater can easily infiltrate. The mine belongs to an open pit for underground mining, and the depth of mining is shallow. The underwater seepage of the open pit surface in the rainy season makes the underground rock mass saturated. Due to the temperate monsoon climate in the region, the four seasons are distinct. The atmospheric precipitation of spring, autumn and winter are quite small, and the climate is dry. On the contrary, the amount of precipitation in summer is considerable. So, the distribution of precipitation during the year is extremely uneven. According to the data of the meteorological monitoring station, the distribution of precipitation in the experimental mine during the year is shown in Fig. 9.

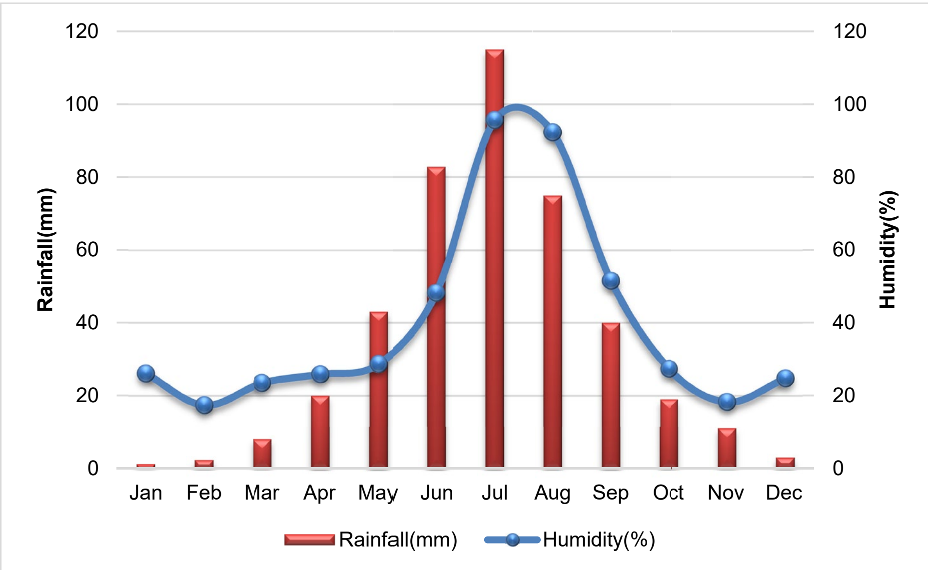


Fig. 9. Precipitation in experimental mine and humidity changes in underground roadway

The average annual precipitation of the experimental mine is 421.2 mm, of which 75.9% of the annual precipitation is concentrated from May to August, and the total precipitation during this period reaches 319.5 mm. From January to April, it only accounts for 7.3% of the annual precipitation of 30.6 mm. From September to December, it accounts for 16.8% of the annual precipitation of 71.1 mm. It can be seen that the precipitation of the mine is mainly concentrated from June to August and is characterised by a unimodal distribution. During the rainy season, the humidity increases from 15%~30% to 90%~100%, as shown in Fig. 8, whilst the humidity of the air will stay saturated for several days. It should be noted that precipitation infiltration needs to go through a process after the arrival of the rainy season in June. Surface precipitation gradually converts into pore water, which moves along the rock mass cracks and finally reaches the mining level. As the air at the mining level gradually saturates, water mist appears in the roadway. Therefore, combined with rainfall and humidity data, it can be seen that there is a significant delay in the roadway humidity relative to the precipitation.

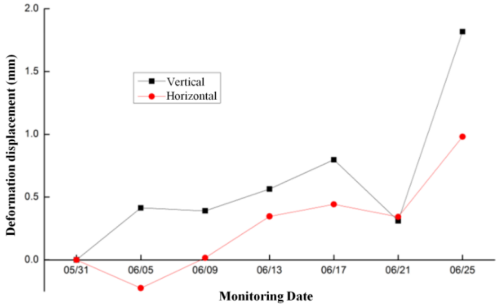
The installed 10 sets of MineTCS deformation monitoring equipment obtained a similar trend of roadway surrounding rock deformation. Some monitoring data collected over time are shown in Table 4.

TABLE 4

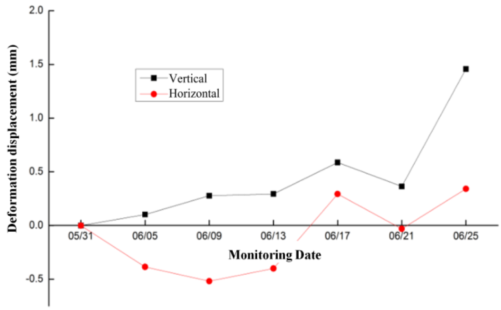
Deformation data of partial monitoring points of 2210# roadway

Monitoring Date		5.31	6.05	6.09	6.13	6.17	6.21	6.25
SL-1 (mm)	Vertical	0.000	–0.225	0.016	0.346	0.442	0.343	0.981
	Horizontal	0.000	–0.057	0.390	0.564	0.797	0.311	1.817
SL-2 (mm)	Vertical	0.000	–0.386	–0.518	–0.400	0.293	–0.031	0.341
	Horizontal	0.000	–0.096	0.277	0.294	0.587	0.364	1.457
SL-3 (mm)	Vertical	0.000	0.217	0.309	0.188	0.238	–0.029	0.866
	Horizontal	0.000	–0.010	0.315	0.483	0.472	0.403	1.434
SL-4 (mm)	Vertical	0.000	0.161	0.249	0.374	0.223	0.107	1.024
	Horizontal	0.000	0.160	0.445	0.476	0.868	0.560	1.831
SL-5 (mm)	Vertical	0.000	0.351	0.289	0.879	0.831	0.438	1.387
	Horizontal	0.000	0.107	0.566	0.329	0.808	0.553	1.686
SL-6 (mm)	Vertical	0.000	0.002	0.148	0.325	0.199	–0.469	0.772
	Horizontal	0.000	0.230	0.487	0.492	0.767	1.182	1.790
SL-7 (mm)	Vertical	0.000	0.256	0.155	0.474	0.636	0.046	0.935
	Horizontal	0.000	–0.047	0.399	0.349	0.851	1.199	1.558
SL-8 (mm)	Vertical	0.000	0.103	0.128	0.339	0.758	–3.868	–2.948
	Horizontal	0.000	0.787	1.990	2.336	3.106	2.646	4.085
SL-9 (mm)	Vertical	0.000	0.406	0.567	0.569	0.868	0.384	1.329
	Horizontal	0.000	0.090	0.248	0.339	0.749	0.449	1.328
SL-10 (mm)	Vertical	0.000	0.265	–0.024	0.733	0.311	0.160	0.948
	Horizontal	0.000	0.167	0.242	0.665	0.879	0.481	1.460

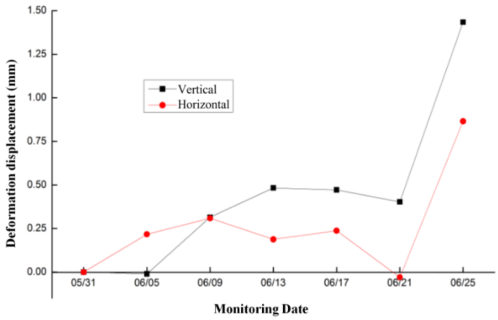
The following is a summary and analysis of the displacement changes of each monitoring point. The displacement of each monitoring point over time is shown in Fig. 10.



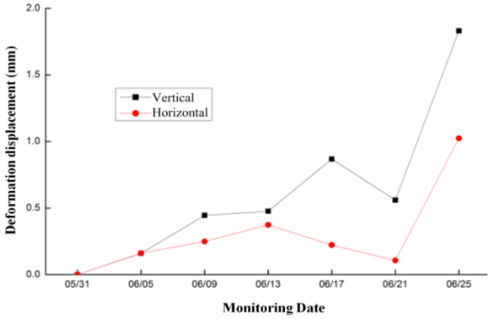
a. SL1-3 monitoring point



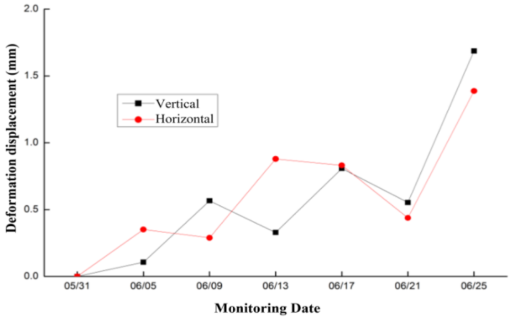
b. SL2-3 monitoring point



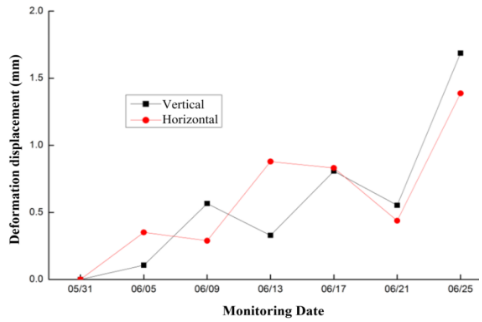
c. SL3-3 monitoring point



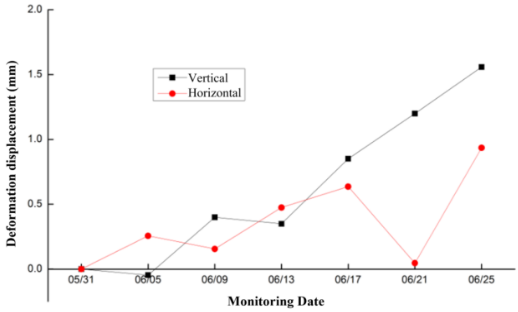
d. SL4-3 monitoring point



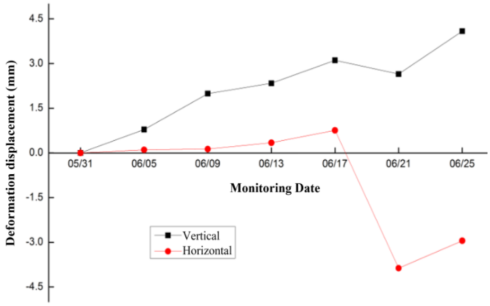
e. SL5-3 monitoring point



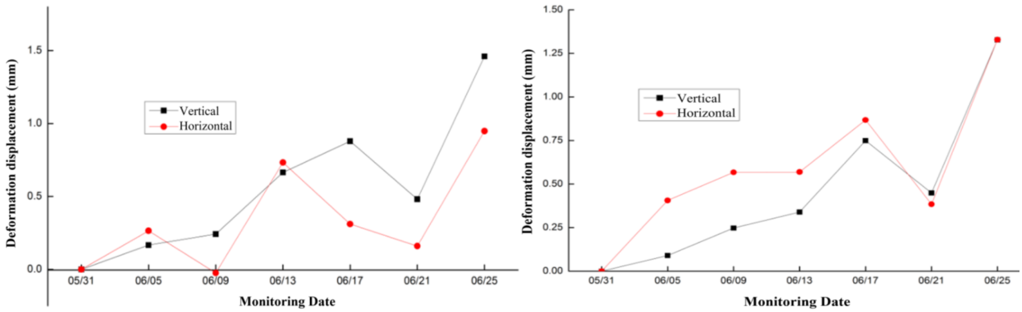
f. SL6-3 monitoring point



g. SL7-3 monitoring point



h. SL8-3 monitoring point



i. SL9-3 monitoring point

j. SL10-3 monitoring point

Fig. 10. SL1-3 to SL10-3 monitoring point displacement curves varied with time

To sum up, the displacement change trend of each monitoring surface is consistent. Considering the geological factors, there is an ore rock contact zone near SL9 measuring point, with relatively poor stability. Therefore, SL9 should be emphatically observed, recorded and analysed in the following monitoring work. Moreover, the ground pressure changed significantly from June 17 to June 25, so monitoring should be strengthened to prevent accidents.

The seasonal evolution law was further studied by the SL9-2 monitoring points in the expansive soft rock roadway combined with the precipitation distribution. The obtained displacement curve is shown in Fig. 11.

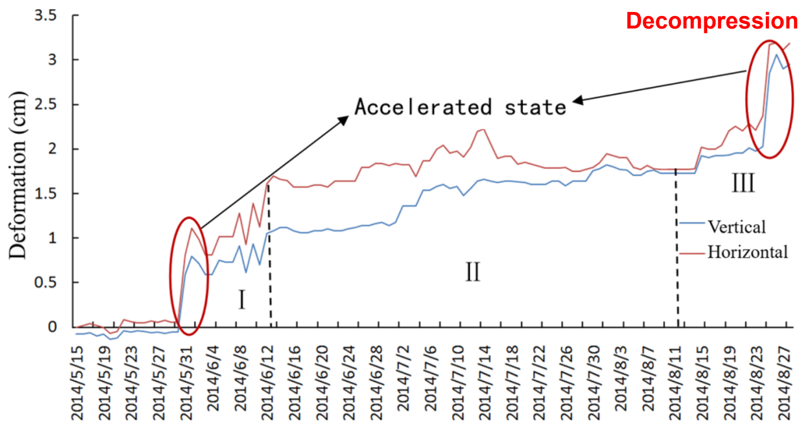


Fig. 11. SL9-2 monitoring point displacement curve varied with time

The deformation of the soft rock roadway in the experimental mine is not significant, except for the months of June to August, according to the annual monitoring data. During this time, seasonal rainfall not only causes an increase in environmental humidity but also increases the pore pressure inside the rock mass.

As shown in Fig. 11, according to the monitoring data of continuous deformation in the rainy season, there are two deformation acceleration stages in the deformation monitoring curve of the expansive fractured rock mass roadway in the experimental mine. The first part of the roadway monitoring point convergence curve is the attenuation creep phase, with the continuous increase of environmental water and deformation, the deformation potential energy of the roadway gradually decreases, which leads to the reduction of the deformation rate. Then, during the steady-state creep phase, the rock mass was in a water-saturated environment for a long time. Finally, during the accelerated creep phase, more and more water-rock interactions and the expansion of joints accelerate the plastic deformation rate. On August 28th, a large-scale surrounding rock damage occurred near the SL9 monitoring point (as shown in Fig. 12).

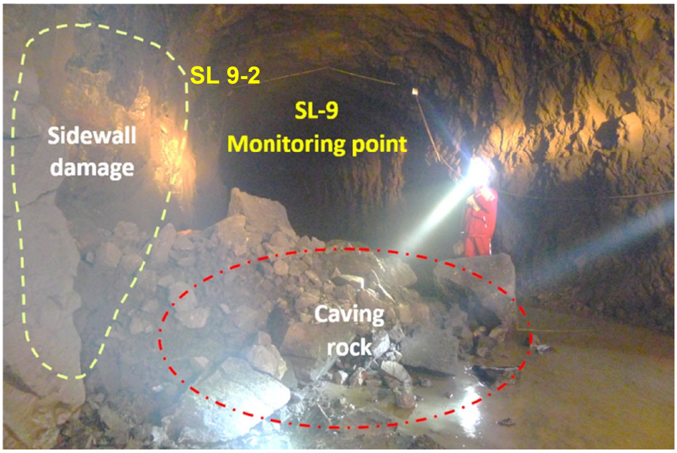


Fig. 12. SL9 monitoring point displacement curve varied with time

The complete curve shape from the first deformation acceleration phase on May 28 to the end of the second acceleration deformation phase on August 28 is similar to the creep curve. The creep-like curve obtained from the on-site monitoring data completely shows the three creep stages of decay creep, constant velocity creep and accelerated creep. The above data shows that the expansive rock mass is a rheological material, as it has the associated material properties. On the one hand, it is due to the obvious rheological properties of the structure and composition of the engineering rock mass itself. On the other hand, it is also due to the stress conditions that make the rheological properties more prominent. The mechanical phenomena such as earth pressure, deformation and damage exhibited in underground mine roadway engineering are inseparable from time. Instantaneous and difficult to quantify, the deformation and stress of the road as determined by elastic and elastoplastic mechanics. Rheology causes measurable deformation and stress, which can be controlled using support measures. As a result, the foundation for resolving real-world issues in mining engineering is the study of rheological characteristics in underground rock masses.

According to the research results, the managers of the mine focused on the key support of the ore rock contact zones. Based on anchor mesh support, the shotcrete technology was used to quickly seal the surrounding rock to reduce the water-rock interaction. In addition, the anchor cables have been used to reduce the separation of surrounding rock, and the plastic failure of rock mass has been significantly reduced.

5. Conclusions

In summary, the fundamental cause of the expansion deformation in the experimental mine is the rock-water interaction. After the excavation of the underground mine roadway, the original rock in its natural state loses water easily. Due to the increased precipitation in the rainy season, the clay minerals absorb more water, which accelerates the expansion deformation of the surrounding rock. Therefore, the seasonal evolution law of the expansive soft rock roadway is of great significance for analysing the deformation mechanism of an engineering rock mass.

In order to study the seasonal evolution law of the expansive rock mass containing clay minerals under the rock-water interaction, the underground mine roadway continuous deformation monitoring system "MineTCS" was independently developed to obtain continuous and complete roadway deformation monitoring data. Based on the above research results, the seasonal evolution law of the main haulage roadway of the mine had been studied, and the rheological characteristics of the expansive rock mass with dry and wet conditions in the underground mine were revealed. Finally, the creep characteristic curve of the expansive rock mass containing clay minerals in the experimental mine was obtained. The research results provide a reference for preventing and controlling the harmful deformation of the expansive rock mass under the interaction of rock and water.

In future underground mining activities, more attention should be paid to the influence of water-rock interaction. It is crucial to adopt effective means to reduce the probability of water-rock interaction and to study the specific treatment scheme for the damage caused by it.

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