Article

Damage to the Microstructure and Strength of Altered Granite under Wet–Dry Cycles

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Received: 6 November 2018; Accepted: 24 November 2018; Published: 4 December 2018

Abstract: This paper presents an analytical method for surrounding rocks in symmetrically shaped tunnels or roadways, with the symmetrical rise and fall of groundwater over a certain period. The influence of reservoir water level on wet–dry cycles were studied. The changes in the microstructure and strength of altered granite and its evolution were explored using mechanical tests and scanning electron microscopy (SEM). The results showed that: (1) the wet–dry cycles weakened the strength of altered granite. Furthermore, the uniaxial compressive strength, elastic modulus, cohesion, and internal friction angle decreased with the increase of the number of cycles, while the maximum reduction in these parameters reached 50.22%, 63.84%, 93.76%, and 53.90%, respectively. (2) The wet–dry cycles damaged the microstructure of altered granite. The SEM analysis showed that, under wet–dry cycles, the structure of altered granite changed from a smooth and integrated internal structure to the initiation, development, and expansion of pores and cracks. The porosity and fractal dimension of rock were determined using the SEM results. The degree of damage to altered granite under wet–dry cycles was quantitatively analyzed. (3) According to the rock mechanics strength tests and SEM and X-ray diffraction analyses, the damage mechanism of altered granite subjected to wet–dry cycles was discussed. The results provide the basis for a stability analysis of symmetrically shaped tunnels, especially symmetrical tunnels constructed in water-rich areas such as symmetric circular tunnels and symmetric horseshoe tunnels.

Keywords: wet–dry cycles; scanning electron microscopy (SEM); microstructure; macroscopic strength; damage mechanism

1. Introduction

Due to the fluidity and permeability of water, the stability of a large number of geotechnical structures is closely related to water. Examples of such structures include the Three Gorges Dam [1,2], submarine slopes, underwater structures, tailings, pond slopes, and other water conservation projects [3,4]. The water level of a reservoir or of groundwater changes cyclically due to the replenishment of various hydraulic paths. Because of this, the rock and the soil body experience a state of wet–dry cycles over a long period of time, which weaken the mechanical strength of the rock. Recently, many researchers have focused on studying the weakening of rock due to water–rock interaction. Zhao et al. studied the variation in clay’s tensile strength under wet–dry cycles and analyzed its weakening mechanism [5]. Liu et al. studied the changes in sandstone’s mechanical parameters [6]. A. Özbek studied the variation in rock’s mass, apparent porosity, water absorption, and uniaxial compressive strength under the action of wet–dry cycles [7]. G. Khanlari et al. reported that, under the action of wet–dry cycles, the main factors affecting the rock’s strength were the...
rock’s particle pore size and its argillaceous interlayer [8]. Chen et al. quantitatively analyzed the damage to rock’s strength under wet–dry cycles [9,10]. Ciantia studied the degradation of the strength calcarenites under wet conditions prevailing for various time periods [11]. Stoltz performed porosity and strength tests and studied changes in the strength and internal structure of lime-treated soil under the action of wet–dry cycles [12]. Bian et al. studied the meso-damage mechanism and proposed a damage-related model based on the rock’s X-ray and scanning electron microscopy (SEM) results under water–rock interaction [13]. Doostmohammadi and Maximiliano studied the variations in the expansion, deformation, and strength of mudstone and volcanic rocks under the action of wet–dry cycles, and analyzed their impact on building stability [14,15]. Takuya performed a sink experiment to study the effects of wet–dry cycles on the tensile strength of rock and the rate of bedrock erosion [16]. Ekrem studied the expansion behavior of modified expanded clay under the action of wet–dry cycles and found that silicon powder can reduce progressive deformation during wet–dry cycles [17]. Furthermore, various techniques, including MRI (magnetic resonance imaging), AE (acoustic emission), and NMR (nuclear magnetic resonance) were used to study the structural damage and reservoir wettability of rock subjected to water–rock interaction or wet–dry cycles [18].

The damage to the internal structure of rock is the root cause of the deterioration of its strength. Therefore, the relationship between the damage to rock’s meso-structure and the weakening of rock’s strength under wet–dry cycles needs further research and understanding. In this paper, the relationship between the strength and the meso-structure of a rock under wet–dry cycles were studied. Uniaxial and triaxial compressive tests and SEM analysis were used to analyze the weakening of the rock’s strength, whereas the changes in meso-structure were studied to investigate the essential reasons for the weakening of the rock’s strength. The relationship between the strength and the evolution of the meso-structure was established, and the mechanism of the rock’s damage under the influence of wet–dry cycles was analyzed.

2. Materials and Methods

2.1. Engineering Geology

The San Shandao open pit was used as a tailings store for the San Shandao Gold Mine Concentrator. With the discharge of waste tailings into the pit, the water level in the open pit continues to rise, which has a serious impact on slope stability, as shown in Figure 1.

![Figure 1. (a) Open pit with no water. (b) Open pit with rising water level. (c) Open pit with falling water level. (d) Open pit slope deformations.](image-url)
Granite heavily altered by sericite is the main rock of the open pit slope. Due to the geological diagenesis period, the flow of high-temperature hydrothermal fluid invades and some substances inside the rock body are dissolved, which results in various defects in the interior of rock, including pores and fissures. Due to these defects, the rock exhibits less strength than the unaltered granite.

In order to eliminate the stress concentration phenomenon, symmetrical cylindrical rock samples are used during compressive tests. Therefore, the samples tested in this work were also symmetrical cylinders. A standard sample was 50 mm in diameter and 100 mm in length. The samples were obtained through core drilling and sawing. Figure 2 shows the preparation of the rock samples.

According to the results of the moisture content tests [9], a wet–dry cycle consisted of freely submerging the specimen in water until it was saturated (24 h), then placing it into a 105 °C oven for 12 h, and then cooling it to room temperature.

2.2. Rock Compressive Tests

In view of the weakening of rock’s strength due to wet–dry cycles, some basic mechanical tests were conducted on the rock. These tests included a uniaxial compression test and a triaxial compression test. Meanwhile, the essential cause for the weakening of the macroscopic strength was analyzed using scanning electron microscopy (SEM). The fracture morphology of the rock specimens was analyzed, and the relationship between the macroscopic strength and the meso-structure was established. Figure 3 shows the tree diagram of the basic experimental design adopted in this work.
The main constituents of the rock specimens were determined using an X-ray diffractometer. Figure 4 shows the results of the X-ray diffractometer. According to the test results, the altered granite mainly consisted of SiO$_2$ and K$_2$O·Al$_2$O$_3$·6SiO$_2$.

The rock mechanics tests included a uniaxial compression test and a conventional triaxial compression test. The variations in the rock’s compressive strength, elastic modulus, cohesion, and internal friction angle under different wet–dry cycles were studied. In this regard, SHIMADZU’s uniaxial compression test machine was used to conduct the uniaxial compression test, while for the triaxial compression tests, the MTS servo triaxial test machine was used. Figure 5 shows the two instruments.

![Diagram of experimental design](image)

**Figure 3.** Tree diagram of the basic experimental design.

![X-ray diffraction results](image)

**Figure 4.** Results of X-ray diffractometer.
2.3. Analysis of Microstructure Using SEM

In order to analyze the fracture of the rock under different wet–dry cycles, the effect of these cycles on the internal structure of the rock was obtained. The scanning electron microscope test instrument was a Nova Nano SEM 450, as shown in Figure 6.

![Nova Nano SEM450 scanning electron microscope.](image)

A high-resolution scanning electron microscope was used to analyze the microscopic pore characteristics. The magnification was set to 500 times.

3. Results

3.1. Rock Mechanics Test Results

According to the characteristics of the rock’s uniaxial compression stress–strain curve, the peak strength and elastic modulus of the rock under different wet–dry cycles can be obtained. According to the results of the rock’s triaxial compression test under different confining pressures, the rock cohesion and internal friction were obtained. The results are presented in Table 1.
Table 1. Parameters used to study the rock mechanics.

| Number of Cycles | Compressive Strength/MPa | Elastic Modulus/GPa | Cohesion/MPa | Internal Friction Angle φ/° |
|------------------|--------------------------|--------------------|--------------|-----------------------------|
| 0                | 40.80                    | 10.98              | 5.61         | 49.24                       |
| 5                | 36.54                    | 7.71               | 4.45         | 46.67                       |
| 15               | 32.63                    | 6.56               | 3.58         | 42.30                       |
| 20               | 28.72                    | 5.15               | 2.28         | 37.95                       |
| 30               | 24.11                    | 4.71               | 0.62         | 28.37                       |
| 60               | 20.31                    | 3.97               | 0.35         | 22.70                       |

According to the results presented in Table 1, the wet–dry cycles deteriorated the compressive strength, elastic modulus, and shear strength of the rock. The maximum compressive strength of the rock was 50.22%, while the maximum elastic modulus was 63.84%. According to the results of the triaxial compression test under different wet–dry cycles, the cohesion of the rock was reduced from 5.61 MPa to 0.35 MPa after 60 cycles, showing a reduction of about 93.76%. The internal friction angle was reduced from 49.24° to 22.70°, indicating a reduction of approximately 53.90%.

3.2. Rock’s SEM Results

According to the SEM results of the rock under wet–dry cycles, the microstructure of the rock changed significantly. The surface of the rock was relatively smooth, while the overall structure was complete. However, with the increase in the number of cycles, the effect of wet–dry cycles on the internal erosion of the rock deepened. Due to hydraulic intrusion, the bonding between the rock particles weakened. As a result, some of the rock particles appeared to fall off. The test results are shown in Figure 7.

As the number of wet–dry cycles increased, a cluster of flocculent material appeared within the rock’s mass structures, indicating that the rock was dissolving. Finally, with the dissolution of the flocculent material filled within the rock mass structures, the rock’s interior became native. The pores expanded and secondary pores developed. Furthermore, the pore distribution within the rock gradually expanded, which may have led to abrupt instability in the rock’s strength.

According to the theory of continuum damage mechanics, the damage to the rock’s meso-structure was the essential reason for the weakening of the rock’s macroscopic strength [19,20]. Therefore, the evolutionary relationship between the rock’s meso-structure and macroscopic strength can be studied. The results of the rock’s SEM analysis can be qualitatively analyzed to study the changes in the rock’s internal structure. For this purpose, the relevant digital processing software was used. The two indices of the fractal dimension and porosity were used to study the effect of wet–dry cycles on the strength and meso-structure of the rock. PCAS software was used to describe the quantitative characterization of the rock’s damage [21,22]. The binarized images are shown in Figure 8, while the results of the mesoscopic parameters are presented in Table 2.

The results presented in Table 2 and Figure 8 show that, with the increase in the number of cycles, the fractal dimension and porosity gradually increased, and the areas of the maximum region and average region first increased, then decreased, and finally increased again. This was consistent with the results of the rock’s SEM analysis. When the number of cycles was 15 or 20, the clustered flocculent material appeared between the rock mass structures. The rock was dissolved and the areas of the maximum region and average area regions significantly decreased.
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Table 2. Identification of rock's SEM results.

| Number of Cycles | Porosity/% | Fractal Dimension | Maximum Region Area | Average Region Area |
|------------------|------------|-------------------|----------------------|---------------------|
| 0                | 11.96      | 1.246             | 7002                 | 147.39              |
| 5                | 19.84      | 1.289             | 19,365               | 185.79              |
| 15               | 28.94      | 1.352             | 240,247              | 513.94              |
| 20               | 34.70      | 1.445             | 81,021               | 402.04              |
| 30               | 39.86      | 1.462             | 99,429               | 362.23              |
| 60               | 45.82      | 1.513             | 201,454              | 633.6               |

Figure 7. (a) SEM image of rock without a wet–dry cycle. (b) SEM image of rock after five wet–dry cycles. (c) SEM image of rock after 15 wet–dry cycles. (d) SEM image of rock after 20 wet–dry cycles. (e) SEM image of rock after 30 wet–dry cycles. (f) SEM image of rock after 60 wet–dry cycles.
According to the results of the rock’s SEM results, the increase in the rock’s fractal dimension and porosity indicates the damage to the rock’s internal structure. The relationships between the number of cycles and the fractal dimension as well as between the number of cycles and the porosity are shown in Figure 9.

4. Discussion

4.1. Relationship between Strength and Micro-Parameters

According to the results of the rock’s SEM results, the increase in the rock’s fractal dimension and porosity indicates the damage to the rock’s internal structure. The relationships between the number of cycles and the fractal dimension as well as between the number of cycles and the porosity are shown in Figure 9.
The relationship between the macro–micro evolution under the action of wet–dry cycles was also explored in this work. Furthermore, the quantitative relationships among the fractal dimension, porosity and rock’s compressive strength, elastic modulus, cohesion, and internal friction angle were also analyzed. The evolutionary relationship between the rock’s mesoscopic parameters and its macroscopic intensity is shown in Figure 10.

It can be seen from Figure 10 that the evolutionary relationships among the fractal dimension, porosity, rock’s compressive strength and elastic modulus, rock’s cohesion, and its internal friction angle are all linear relationships. As the number of cycles increases, the fractal dimension and porosity gradually decrease, whereas the rock’s mechanical parameters also decrease linearly. This indicates that the decrease in the macroscopic strength of the rock is closely related to the change in its meso-structure.

According to the above analysis, the evolutionary relationship between the rock’s mesoscopic parameters and macroscopic strength under the action of wet–dry cycles can be characterized using a linear relationship, whereas the results also show that the wet–dry cycles cause damage to the rock’s meso-structure. The fractal dimension and porosity increase with the increased number of cycles, which leads to damage to the rock’s internal structure. Based upon the changes in the macroscopic
strength of the rock, the compressive strength, elastic modulus, cohesion, and internal friction angle were gradually reduced.

![Mechanical parameters and Fractal dimension](image)

Figure 10. (a) Relationship among the porosity, uniaxial compressive strength, elastic modulus, cohesion, and internal friction angle. (b) Relationship among the fractal dimension, uniaxial compressive strength, elastic modulus, cohesion, and internal friction angle.

### 4.2. Damage Mechanism under Dry and Wet Cycles

According to the basic mechanical tests and the SEM results under wet–dry cycles, it is possible to obtain the rock’s meso-structural damage, which leads to the weakening of the rock.

(1) Fundamentally, the wet–dry cycles result in the expansion and penetration of primary pores inside the rock. Meanwhile, the development of secondary pores is also an essential reason for the loss of the rock’s strength. The hydraulic intrusion produces a lubricating effect between the rock particles, reduces the friction, and promotes the movement of rock particles. According to the SEM results, the wet–dry cycles cause the internal microstructure of the rock to gradually transition from an overall uniform compact stage to the stage in which the primary pores expand and the porous flocs develop. Finally, the transition to the pore and fracture development stage is reached.
(2) Due to the dissolution of soluble salts inside the rock, the internal pores develop or even penetrate, thus affecting the macroscopic strength of the rock. According to the XRD (X-ray diffraction) results, the main constituents of the altered granite are SiO$_2$ and K$_2$O·Al$_2$O$_3$·6SiO$_2$. The main chemical reactions occurring in rock under different chemical environments are given as follows.

Acidic environment:

$$\text{KAlSi}_3\text{O}_8 + 4\text{H}^+ = \text{Al}^{3+} + 3\text{SiO}_2 + 2\text{H}_2\text{O} + \text{K}^+$$

$$\text{SiO}_2 + 2\text{H}_2\text{O} = \text{H}_4\text{SiO}_4$$

Alkaline environment:

$$\text{KAlSi}_3\text{O}_8 + 8\text{H}_2\text{O} = \text{H}_4\text{AlO}_4^- + 3\text{H}_4\text{SiO}_4 + \text{K}^+$$

As the various constituents dissolve and differ in water, the pores develop and expand, which also decreases the strength of the rock.

(3) During the rise and fall of the water level, the pore water inside the rock mass of the slope cannot be eliminated. The increase in the pore water pressure inside the rock mass results in the development of micro-fracture and cracks. Due to this reason, the adhesion between the rock particles is weakened and the rock particles are exacerbated from the rock mass skeleton, causing the expansion of primary pores and fissures and the development of secondary pores and fissures.

5. Conclusions

In this paper, the influence of reservoir water levels on altered granite was studied. The changes in rock's microstructure and strength were explored using mechanical and SEM tests. The meso-structural damage to rock and the mechanism of the weakening of rock’s strength were studied based upon the effect of wet–dry cycles. The relationship between the structural damage and the evolution of macroscopic strength supports the following conclusions.

Wet–dry cycles weaken the strength of rock, while different mechanical strength parameters have various sensitivity levels towards the wet–dry cycles. In this paper, the sensitivity levels for altered granite were found to be in the following order: cohesion > elastic modulus > internal friction angle > compressive strength. The weakening of the rock’s shear strength parameters was found to have adverse effects on the stability of hydropower station slopes or symmetrical tunnels.

Wet–dry cycles damage the rock’s meso-structure. The scanning electron microscopy (SEM) results of the rock showed that the wet–dry cycles resulted in changes in the internal microstructure of the rock, which included the overall uniform compact stage, the primary pore expansion stage, the porous gradual transition of the flocculation stage, and the pores and fissure development stage. With PCAS digital image recognition software, a quantitative analysis of the degree of damage under the action of wet–dry cycles was performed based upon analyses of the rock’s porosity and fractal dimension. As the number of cycles increased, the fractal dimension and porosity gradually decreased, and the relationship among the fractal dimension, porosity, and the rock’s mechanical properties appeared to be linear.

The mechanism of the rock’s damage under wet–dry cycles was also analyzed. The damage mechanism was analyzed from the perspective of the rock’s internal structural changes, chemical composition, and pore water pressure. The results of this study can provide a reference for the analysis of hydropower stations or of the stability of tailings and pond slopes. In view of the influence of water–rock interaction on rock’s strength, the strength of slopes and tunnels surrounding rock under wet–dry cycles was studied. This work provided the mechanical basis for the stability analysis of symmetrical tunnels. This is particularly true for symmetrical tunnels constructed in large water-rich mountain slopes, such as symmetrical circular tunnels and symmetrical horseshoe tunnels.
Author Contributions: X.C. and Z.Q designed and directed the project. X.C. processed the experimental data, performed the analysis, drafted the manuscript and designed the figures. P.H. provided critical revision and acquisition of the financial support for the project leading to this publication. All authors contributed to the final version of the manuscript.

Funding: This research was funded by Shandong Provincial Natural Science Foundation grant number NO. ZR2017BEE014 and Scientific Research Foundation of Shandong University of Science and Technology for Recruited Talents grant number 2017RCJJ050.

Conflicts of Interest: The authors declare that there is no conflict of interest regarding the publication of this paper.

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