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RESEARCH ARTICLE

# Effect of the Water-Rock Interaction on the Creep Mechanical Properties of the Sandstone Rock

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***Abstract***

*After the commencement of the Three Gorges hydropower project, the reservoir water level has been fluctuating by 30 m (145–175 m) annually. The stability of the bank slope has been highlighted since the reservoir water level has been repeated. Apart from that, the long-term effect of the water-rock interaction on the rheological and mechanical properties of the rock was not studied sufficiently. Therefore, a typical sandstone rock was brought from the Three Gorges reservoir area, to meet the purpose of this study. Then, a series of water-rock interaction tests were conducted to simulate the fluctuations in the reservoir water level. Based upon the experimental results, the following points were pointed out: 1) for the first three successive water-rock interaction cycles, the long-term strength of the rock was dramatically reduced. In contrast, the rate of reduction on the long-term strength of the rock was getting a steady state after six successive water rock interactions.2) At the failure stress level, the rock specimens exhibited similar characteristics under different water-rock interaction cycles. 3) The densely compacted micro structures of the sandstone rock were transformed into loose and porous state.*

***Keywords***

*reservoir bank slope, creep, water-rock interaction, sandstone, deterioration mechanism*

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## 1 Introduction

Bank slopes have become common as a result of rapid hydropower constructions. For instance, the Three Gorges reservoir has been fluctuating by 30 m (145–175 m). Hence, the rock mass is highly vulnerable to a cyclic water-rock interaction. Meanwhile, this repeated action will reach a state of fatigue, and its effect on both the rock mass and the soil mass will gradually reduce. However, the cumulative effect will result a catastrophic damage [1–4]. After subsequent progressive failures, the stability of the bank slope has been dramatically affected by the cyclic fluctuations in the reservoir water level.

In practice, creep deformation is the predominant type of failure in rock masses. Creep is one of the most important mechanical characteristics of the rock mass. It describes the time-related deformation, slip and failure characteristics of rock materials. Creep and the long-term stability of the rock mass are closely related to each other. In the design and analysis, one should properly address these problems to avoid a catastrophic damage of structures. Due to the rapid development of large scale constructions (hydro powers) the effect of cyclic water rock interaction on the stability of the bank slope will be an inevitable and challenging practical problem. The hydro-fluctuation belt is a governing and a critical zone which can determine the stability of the bank slope [5]. An experimental study was conducted by [6], to investigate the varieties in the uniaxial compressive strength of sandstone rock at dry and saturated conditions. The results revealed that, a significant amount of strength loss (78%) was recorded for the Cretaceous Green-Sand when the siliceous sandstone exhibited relatively small amount of strength loss (8%). The extent of sensitivity to water content is predominantly governed by the mineralogical properties of the rocks (proportions of quartz and percentage of clay minerals). Moreover, weak sandstones were less sensitive to moisture. According to [6], the influence of pore water pressure on the mechanical properties of the sandstone rock was negligible. Similarly, a detailed literature review [7] has been done to investigate the effect of moisture content on the strength and modulus of different types of rocks. It was concluded that [7], considerable discrepancies were noticed among the previously published papers due to the variations in the testing procedures and data interpretations. Generally, the degree of reduction in the mechanical properties of sedimentary rocks is mainly governed by the mineralogical compositions (percentage of clay fraction). According to [7], a stronger bond (silca-oxygen) can be converted into a weak hydrogen bond due to the presence of water. Comparatively, sedimentary rocks are more vulnerable for strength loss than igneous and metamorphic rocks. The physical and mechanical degradation of the rock mass properties under a cyclic water rock-interaction have also been studied by many scholars. The deformation and the fracture properties of sandstone rock specimens under a variable water pressure were studied by using an immersion air dry circulation function test [8–10]. The effects of cyclic wetting and drying on the sandstone strength were studied [11–15]. Similarly, other experiments were also conducted to investigate the effect of water-rock interaction on the mechanical properties of rocks [16–19]. The above studies revealed that, the degradation in the mechanical parameters such as: compressive strength, tensile strength, elastic modulus, shear strength, fracture toughness and so on are caused by the cyclic water rock interaction. A series of uniaxial compression tests on both dry and saturated sandstones were done to examine the creep characteristics of the rock [20–22]. Beside, some new constitutive models were proposed to handle the creep deformation and the effect of saturation [23–25]. The results showed that the presence of water exacerbated the creep characteristics of the rock.

In the previous studies, the effects of moisture content on the mechanical properties of rocks were studied on both dry and saturated specimens. However, the long-term effect of the water-rock interaction on the creep and mechanical properties of the rock was not studied sufficiently. Therefore, a typical sandstone rock was brought from a land slide affected area (in the vicinity of Three Gorges reservoir), to achieve the objectives of this study. A series of tests under the effect of water-rock interaction were carried out, to simulate the fluctuations in the reservoir water level. Moreover, rheological triaxial compression tests and analysis of microstructures were done at different water-rock interaction stages, to scrutinize the weakening and degradation mechanism of the sandstone. Based upon the macrostructures, microstructures and analysis of the mechanical properties the degradation mechanism of the sandstone was studied under the immersion-air dry cyclic water-rock interaction.

## 2 Project background

After the impoundment of the Three Gorges reservoir area, the reservoir water level has been fluctuating by 30 m (145–175m). The reservoir water affects 4 counties in Hubei Province and 16 counties (districts) in Chongqing, with a total length of about 600km. There are many types of rocks in the affected area, such as sandstone, mudstone, limestone, breccia and so on. Different types of rock slopes exhibited different deformation and failure criterion under the long term reservoir water, And a detailed literature review [7] has been done to investigate the effect of moisture content on the strength and modulus of different types of rocks. Statistics showed that many bank slope instabilities were occurred after subsequent fluctuations in the reservoir water level. Since the commencement of the Three Gorges project in June 2003, the bank slopes have been subjected to cyclic wetting and drying conditions. Based upon the water level changes, each cycle can be divided into three stages: rise period; relatively stable period, drop period. Due to cyclic fluctuations in the reservoir water level, the rock mass of the bank slopes will be in a dry or a saturated state. The change of the seepage field will not only change the mode of dissolution and the intensity of the water, but it also repeatedly changes the direction of dissolution-precipitation. This phenomenon exacerbated the water-rock interaction (physical and chemical), and yielded sharp drop in the strength of the rock. Figure 1 shows typical bank slopes in the Three Gorges Reservoir area. As it can be seen from Figure.1, the sandstone rock mass is highly weathered and eroded due to the change in the reservoir water level (145–175 m).

**Fig. 1** Typical failure of the sandstone rock mass in the vicinity of hydro-fluctuation belt (Three Gorges reservoir area, 2015)

## 3 Experiments

### 3.1 Specimen Preparation

A number of cylindrical sandstone specimens (Φ 50mm × 100mm) were prepared from the rock sample brought from the Three Gorges reservoir area (Figure 2). Besides, samples with noticeable defects were screened and rejected. The P-wave velocities and the rebound values were used to eliminate the samples with large discreteness [26].


**Fig. 2** Sandstone specimens

### 3.2 Simulation approach

The aim of this experiment is to simulate the effect of cyclic reservoir water fluctuation on the sandstone rock mass.

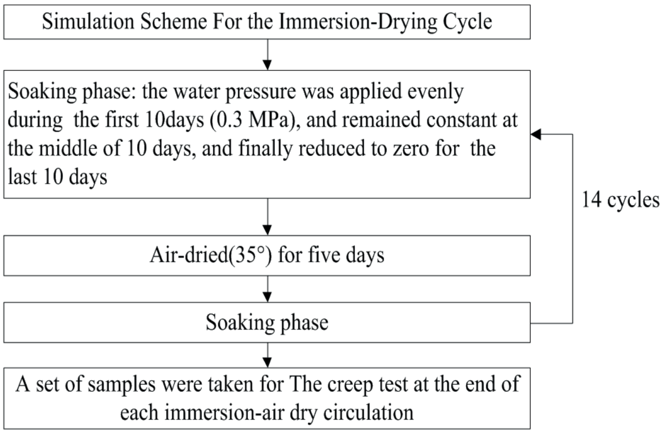



**Fig. 3** Flow chart that shows the immersion-air dry circulation process

The simulation procedures are presented in Figure 3. Hence, the basic objectives of this paper were simulation of the reservoir water fluctuation and the resulting immersion - air dry circulation. A rock dissolution apparatus was used to place the rock specimens. A uniform water pressure (0.3MPa) was applied for the first 10 days to replicate the rise in the reservoir water level. This is because the reservoir water level has been fluctuating by 30m head difference. In the next 10 days, a relatively steady state of the reservoir water level has been simulated. In the last 10 days, the water pressure was uniformly reduced to 0MPa to simulate the drop in the reservoir water level. The immersion stage took for a total of 30 days. Then soaked specimens were air-dried at 35°C for 5 days. This is to demonstrate the air-dried rock mass in the dry season. A total of 14 cycles were designed during the experimental program. The dissolution and air drying devices are shown in Figure 4. The devices were used to prepare the rock specimens for the water-rock interaction tests. The fluctuations in the water pressures were efficiently captured by soaking the rock specimens. It is possible to simulate the reservoir water immersion-air-drying cycle at the water-level-fluctuating zone, scrutinize different water immersion pressure, and simulate the air-drying process after the reservoir water level decreases. The whole processes were computerized, which controlled the water pressure, air drying temperature, mixing time; automatic collection of water pressure, temperature and other parameters.

### 3.3 Testing Procedure

The sandstone samples were socked in a rock dissolving immersion apparatus. After each immersion-air dry cycle, a group of rock samples were subjected to a triaxial compression creep test. The creep test at the saturated state of the rock sample was used as a basis. The employed confining pressure was 10MPa. Axial stress was applied in multistage till failure developed. The initial axial stress was about 60% of the ultimate compressive strength. The applied axial stress in a decreasing order is listed in Table 1. The triaxial compression creep test was conducted by using RLW-2000 rock triaxial creep testing machine, as shown in Figure 5.

**Fig. 4** YRK-2 rock pressure and soaking-air drying equipment

**Table 1** Stress loading scheme for the creep test

| Axial stress / MPa | Number of water-rock interaction cycles | | | | | | |
|---|---|---|---|---|---|---|---|
| | 0 | 1 | 2 | 3 | 6 | 10 | 14 |
| First step | 125 | 120 | 120 | 120 | 120 | 118 | 118 |
| Second step | 140 | 135 | 130 | 130 | 130 | 128 | 126 |
| Third step | 155 | 150 | 140 | 140 | 140 | 138 | 134 |
| Fourth step | 170 | 157.5 | 150 | 150 | 150 | 148 | 138 |
| Fifth step | 177.5 | 165 | 160 | 155 | | | 142 |
| Sixth step | | | | | | | 144 |
| Seventh step | | | | | | | 146 |

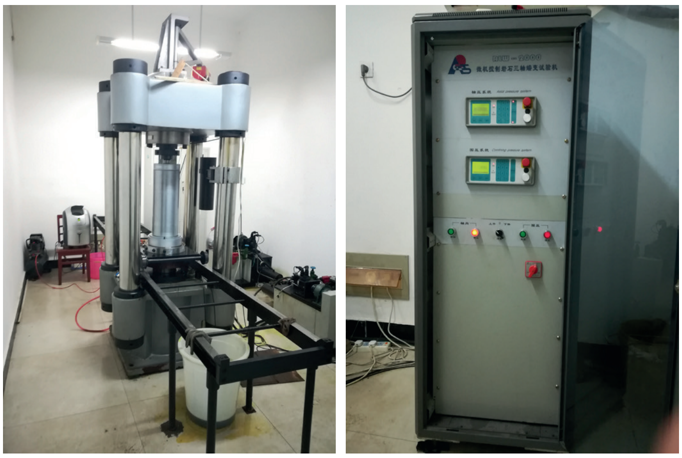
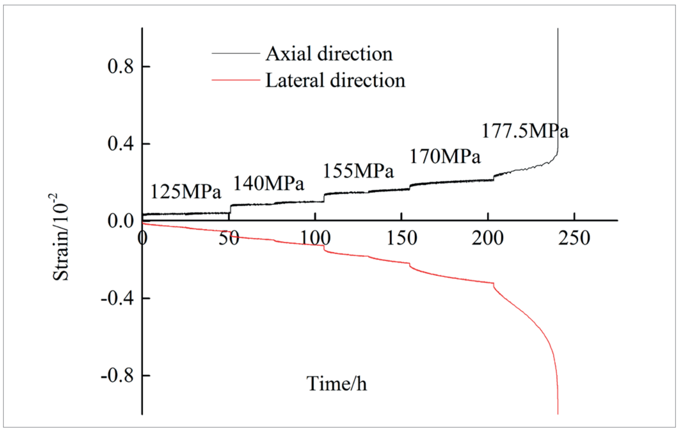


**Fig. 5** RLW-2000 rock creep testing apparatus

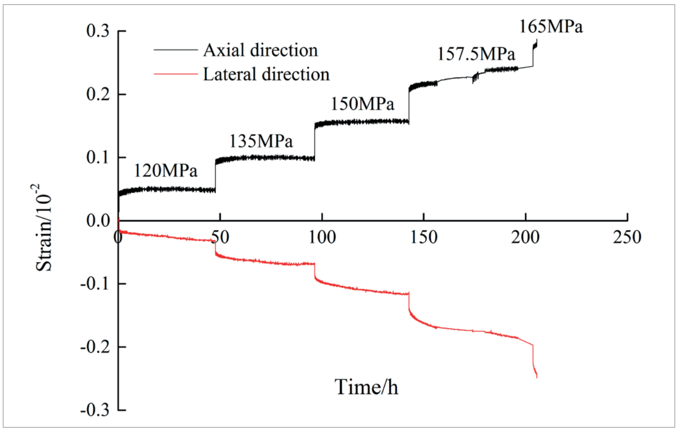
## 4 Results

### 4.1 Creep deformation characteristics

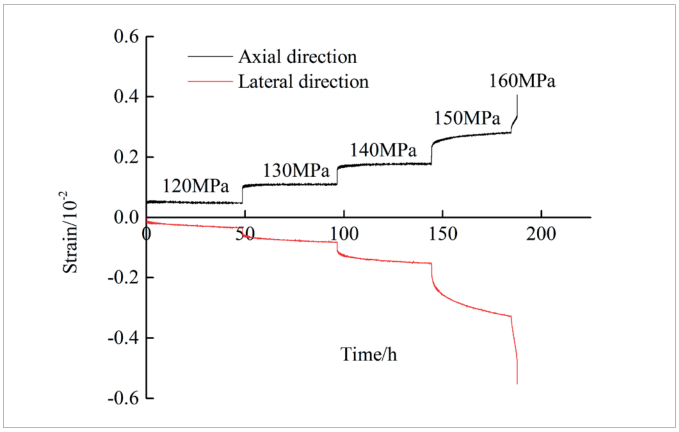
At the end of each soaking, a group of rock samples were subjected to triaxial compression creep tests. The creep curves of the specimens were obtained by using the superposition principle. The axial and lateral strain creep curves for different water-rock cycles are shown in Figure 6. The numbers indicated on the curves (Figure 6) are the axial stress values.



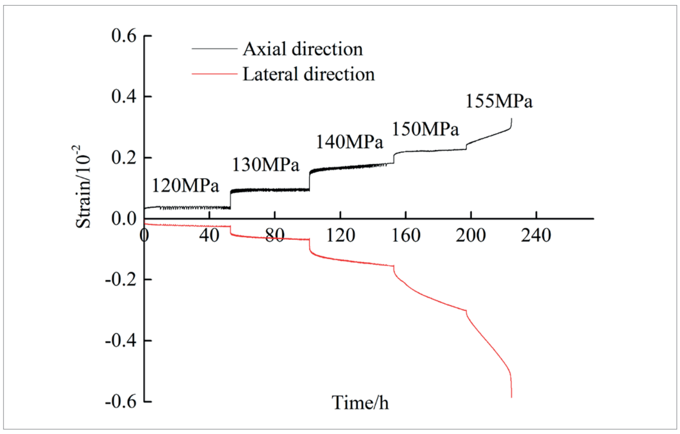

(a) 0th cycle



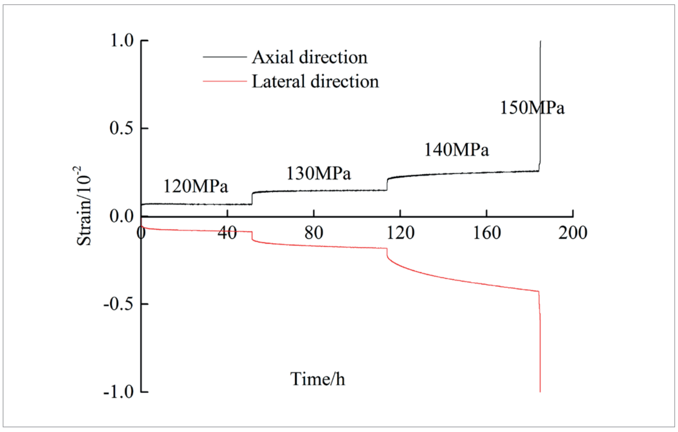

(b) 1st cycles



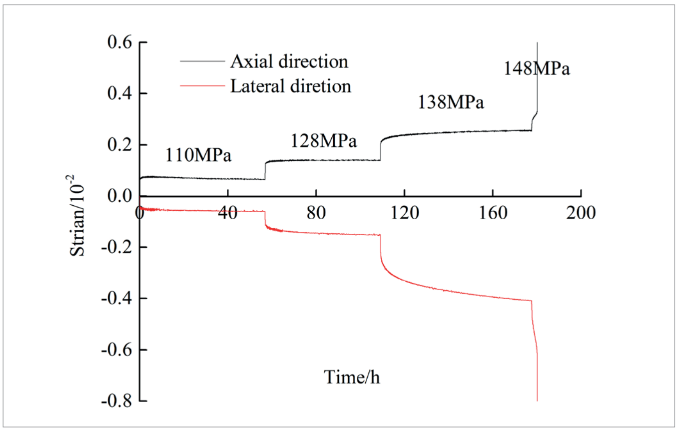

(c) 2nd cycles



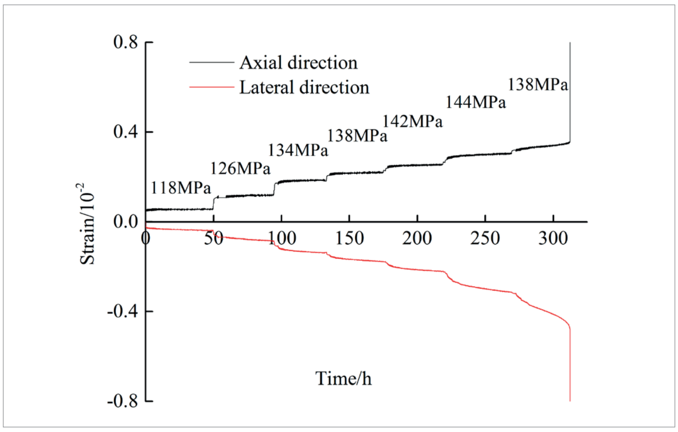

(d) 3rd cycles




(e) 6th cycles




(f) 10th cycles




(g) 14th cycles

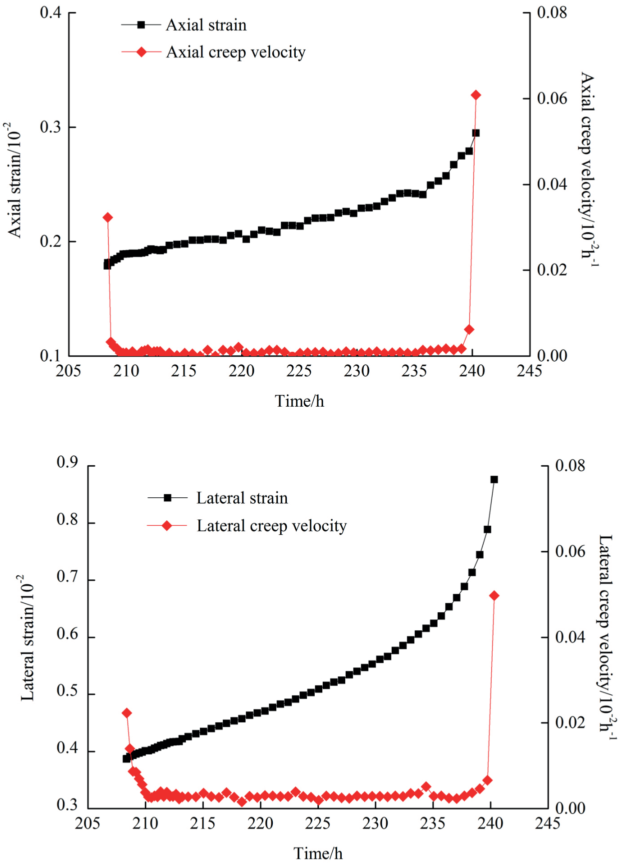
**Fig. 6** Typical creep curves obtained from the triaxial compression tests at different testing conditions

The specimens' deformation gradually reduced under low axial stress level, and mainly exhibited two creep stages (the attenuation and steady-state stages). However, at the failure stress level, the specimens' deformation exhibited different types of creep stages. Namely: attenuation creep stage, steady-state creep stage and nonlinear acceleration creep stage. Large creep deformation and rapid fractures were noticed when the duration was too short. It is important to address this practical problem. Therefore, an in-depth study is still important to capture the deformation characteristics of these rocks. The axial and lateral creep rate curves (Figure 7)

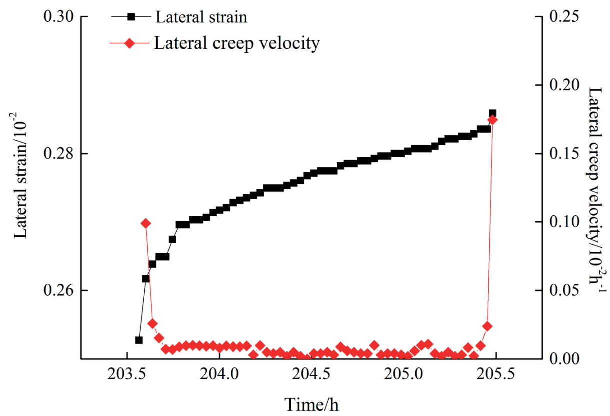
**Table 2** Tabulated results at the failure stress levels

| Experimental phases | | | Number of Water-rock interaction cycles | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | 0 | 1 | 2 | 3 | 6 | 10 | 14 |
| Secondary stage | Average creep velocity (10-2/h) | Axial direction | 0.00076 | 0.00193 | 0.00495 | 0.0054 | 0.0092 | 0.0117 | 0.0149 |
| | | Lateral direction | 0.0028 | 0.0069 | 0.0107 | 0.0142 | 0.0263 | 0.0278 | 0.0291 |
| | Total duration (%) | | 89.06 | 88.71 | 88.77 | 87.33 | 84.38 | 80.79 | 75.00 |
| | Ratio of Creep velocity between the lateral and the axial velocities | | 1.99 | 2.87 | 3.20 | 3.59 | 3.68 | 3.71 | 4.14 |
| Total duration (%) for the tertiary stage | | | 5.37 | 5.24 | 5.31 | 6.75 | 8.73 | 11.96 | 13.54 |

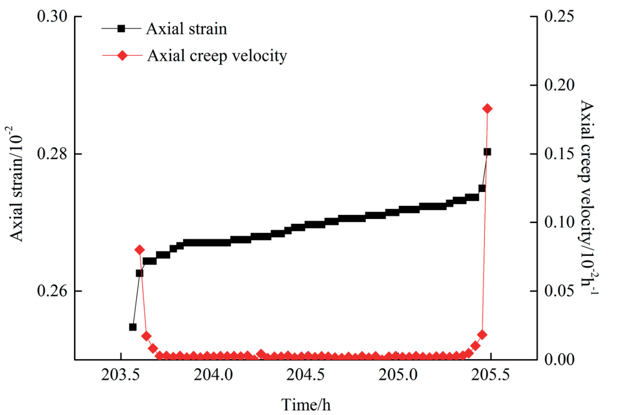
at the failure stress level were used to analyze the deformation characteristics of the sandstone at the accelerated creep stage. Moreover, Table 2 shows the creep duration at the failure stress level for different stages.

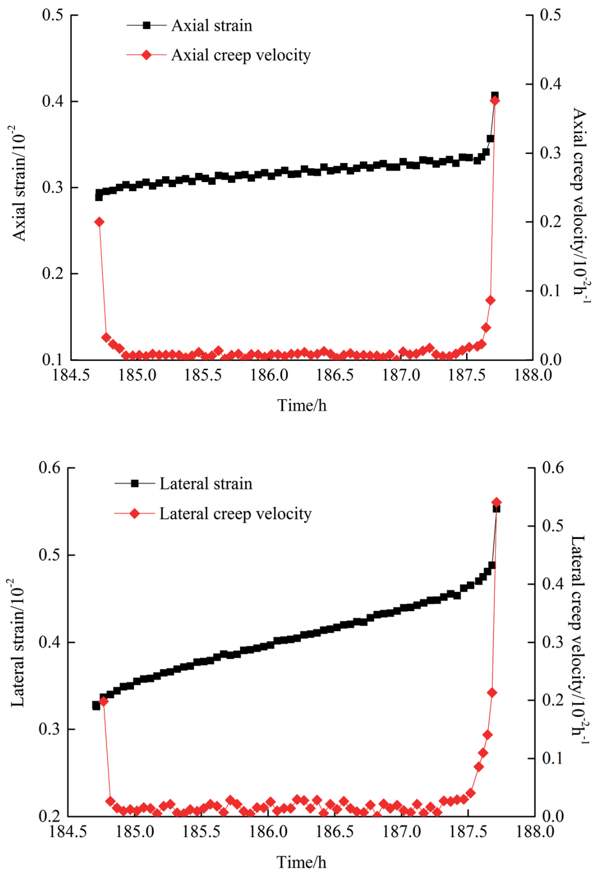


(a) 0th cycle

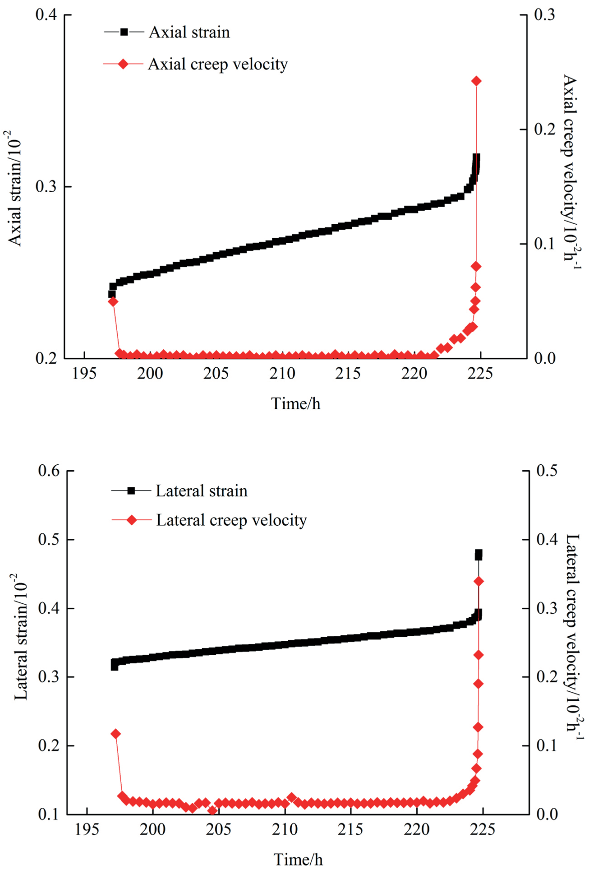


(b) 1st cycle

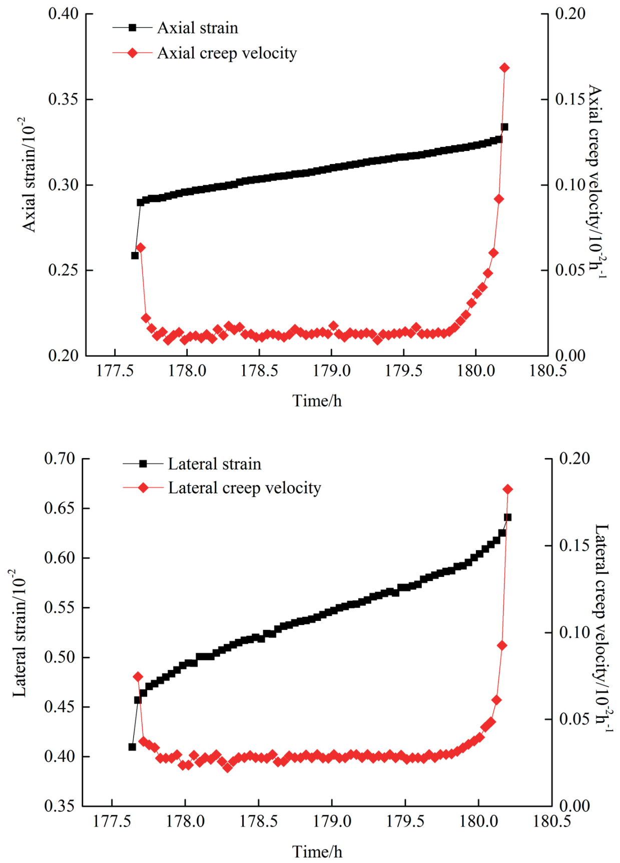


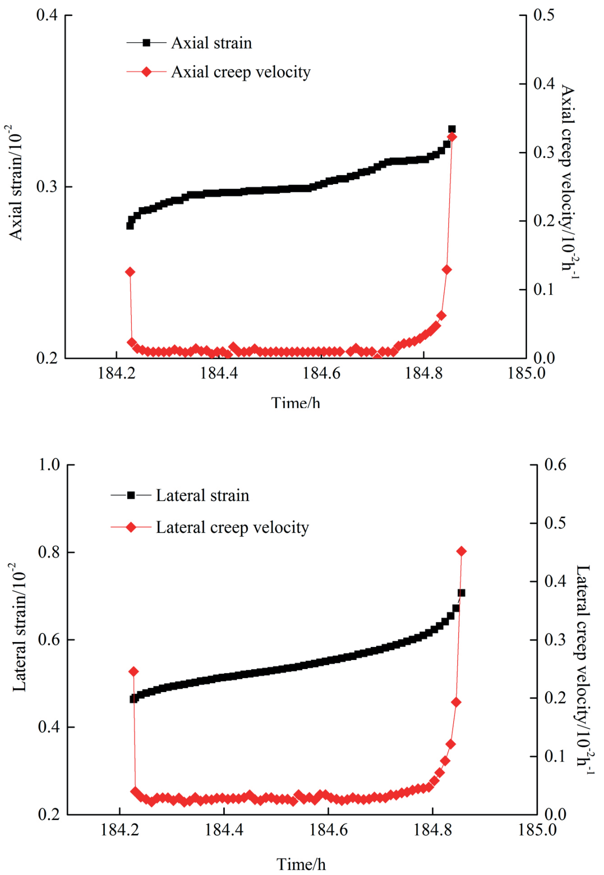
(c) 2nd cycles



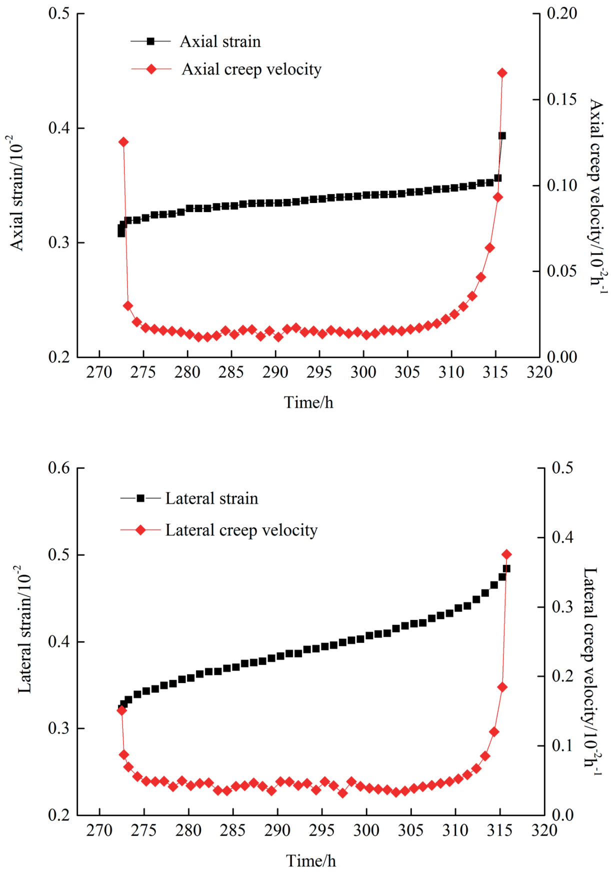

(d) 3rd cycles




(f) 10th cycles




(e) 6th cycles




(g) 14th cycles

**Fig. 7** Strain rate vs. time for the accelerated creep stage at different soaking condition

**Table 3** Creep failure strength and long-term strength for the sandstone specimens

| Parameters | Number of water-rock interaction cycles | | | | | | |
|---|---|---|---|---|---|---|---|
| | 0 | 1 | 2 | 3 | 6 | 10 | 14 |
| Failure stress/MPa | 177.5 | 165 | 160 | 155 | 150 | 148 | 146 |
| long-term strength/MPa | 165 | 151 | 143 | 137 | 131 | 127 | 125 |
| Long-term strength ratio (%) | 92.96 | 90.15 | 89.38 | 88.39 | 87.33 | 85.81 | 85.62 |

## 4.2 Long-term strength of sandstone

The long-term strength of the rock mass can be defined when its strength decreased and converged [27]. The most reasonable way to determine the long-term strength is to define it, and to take a single-stage dead load test and to determine the relationship between the rock breaking strength and time. The failure duration corresponds to infinite load for the long-term strength. However, this method requires multiple testing machines, and it utilizes both time and money. Hence, it is rarely used in practice. In this paper, the long-term strength of the sandstone rock was determined by using the commonly used stress-strain isochronal curve [28]. After plotting the stress-strain isochronal curve cluster, the long-term strength was determined from the inflection point on the curve cluster (Table 3). Figure 8 shows the creep failure strength and the long-term strength degradation curves for the sandstone rock specimens.

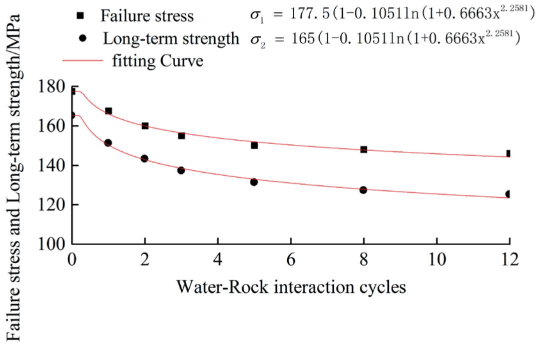



**Fig. 8** Failure stress vs. long-term strength for the sandstone at different water-rock interaction cycles

## 4.3 Creep failure patterns

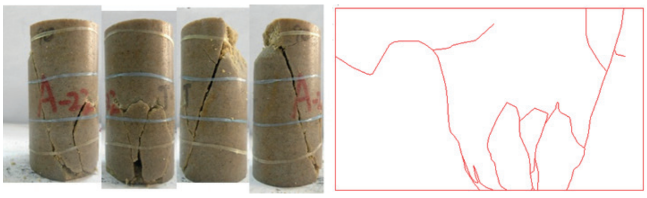
The triaxial compression failure modes were not similar at different testing conditions, and the corresponding failure mechanisms have not been exactly the same. Therefore, a series of photographs were used to study the deformation law of the sandstone specimens as shown in Figure 9.

## 4.4 Micro-structure characteristics

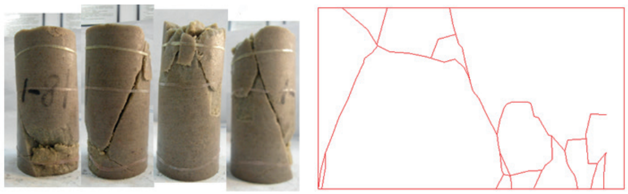
The microscopic morphology of the sandstone samples were gradually changed at different immersion cycles. SEM scanning is one of the most important devices used to study the microstructure and morphology of the geomorphology. One can get a number of physical and chemical properties of the sample, such as morphology, composition, crystal structure, electronic structure, and etc. SEM micrographs were used to study the micro-structural changes at different water-rock interaction cycles. Typical results of SEM are shown in Figure 10 with 1200× magnification.

(a) 0th cycle

(b) 1st cycle



(c) 2nd cycles



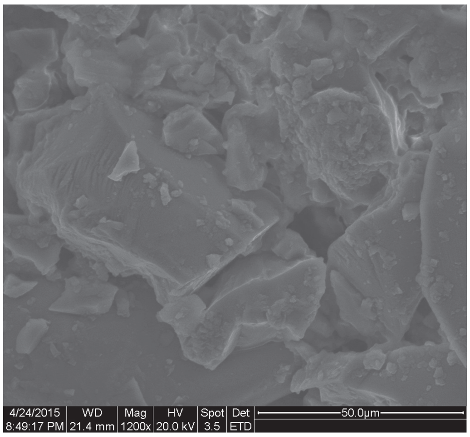
(d) 3rd cycles

(e) 6th cycles

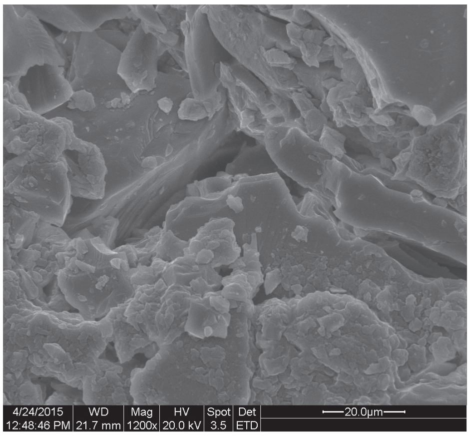
(f) 10th cycles

(g) 14th cycles

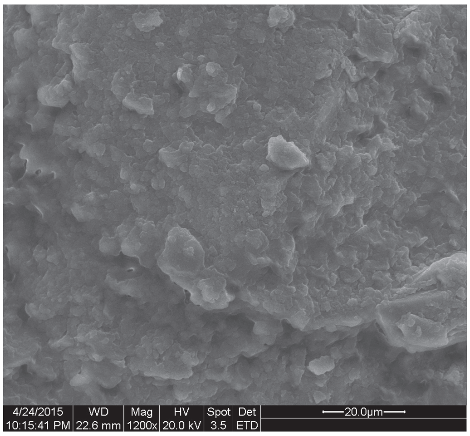
**Fig. 9** Crack patterns of sandstone



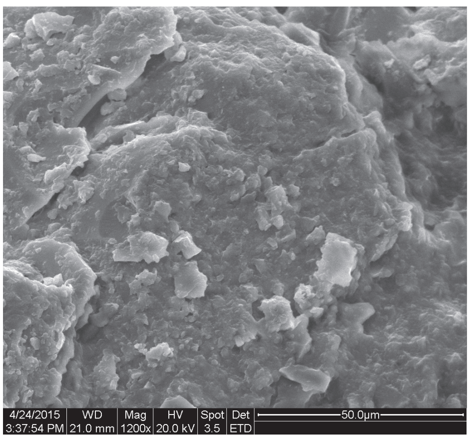

(a) 0th cycle



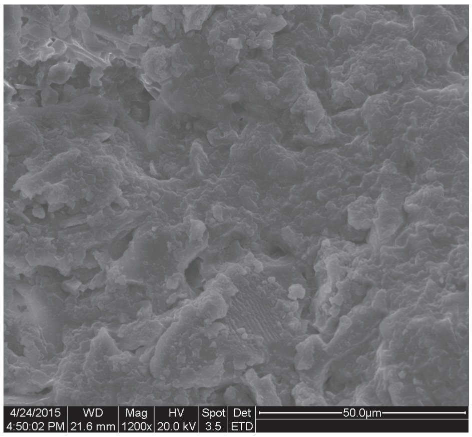

(b) 1st cycle



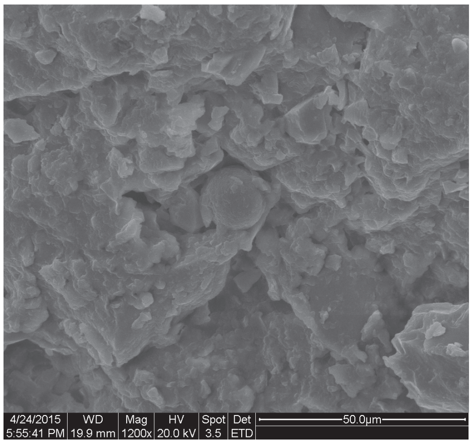

(c) 2nd cycles



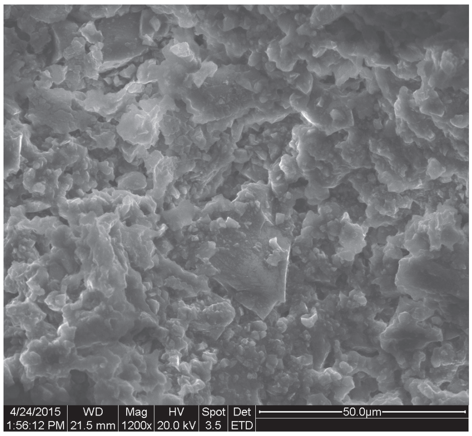

(d) 3rd cycles




(e) 6th cycles




(f) 10th cycles




(g) 14th cycles

**Fig. 10** Micro-structural changes on the rock specimens due to the water-rock interaction (1200×)

## 5 Discussions

### 5.1 Effect of water - rock interaction on the axial and lateral creep deformation of the sandstone rock

The following conclusions were pointed out based on Fig. 6:

Under different loading stress conditions, the creep characteristics of the rock specimen were axial and lateral. The creep process was getting stability when the applied axial stress was less than (or closed to) the long-term strength, which includes the initial and the stable creep stage. The axial and lateral strains were attaining stability and gradually decreasing to zero. However, the creep process showed instability when the axial stress exceeded the long-term strength that underwent the initial creep stage, stabilized creep stage, and accelerated creep stage. Rock specimens showed instantaneous deformation due to the transient stress. The instantaneous deformation was decreasing when the axial load increased by a unit stress. Similarly, the sandstone creep rate reached a steady state and then gradually increased, while the axial stress was increasing. Moreover, the instantaneous deformation, the axial and the lateral creep deformation, and the proportion of total deformation were gradually increasing when the number of cycles and the axial stress increased. This phenomenon indicated that the water-rock interaction affected the physical and mechanical properties of the sandstone rock, which in turn affected its creep characteristics. The lateral creep deformation was increasing more rapidly than the axial creep deformation when the number of cycles increased. The lateral deformation was very noticeable at the failure stress level.

### 5.2 Analysis of sandstone deformation characteristics for the accelerated creep stage

The sandstone rock showed the following deformation characteristics (Table 2 and Figure 7) at the nonlinear accelerated creep phase:

The proportion of the total cessation at the steady creep stage was more than 75%, the ratio of the initial creep stage and the nonlinear accelerating creep stage to the total diachronic phase were small. The rate of steady creep was decreasing from 89.06% to 75.00% when the duration of the water-rock interaction increased. However, the proportion of non-linearly accelerated creep has been increasing from 5.37% to 13.54%. Similarly, the brittleness of the rock specimens was decreasing while its plasticity gradually increased. The rate of lateral deformation was larger than the axial deformation at different water-rock interaction cycles. The ratios of lateral deformation toaxial deformation were 1.99, 3.59, 3.71, and 4.14 corresponded to the $0^{th}$, $3^{th}$, $10^{th}$ and $14^{th}$ of water-rock interaction cycles. The rates of lateral and axial deformations were increasing while the duration of the water-rock interaction increased. Since the softening of the specimen increased with the duration of the water-rock interactions, the creep stage enhanced lateral expansion. The axial and lateral creep rates (at the steady creep stage) of the sandstone were increasing and the nonlinearly accelerated creep stage was decreasing while the number of water-rock interaction cycles increased. The ductility of the sandstone rock has been increasing at a higher water-rock interaction cycles.

### 5.3 Analysis of Failure and long-term strength

The following points were noticed from Table 3 and Figure 8: the failure stress at the saturated state was 177MPa, and the strength of the rock specimens were decreasing by 5.63%, 12.68% , 15.49%, 16.62% and 17.75% (at the $1^{st}$, $3^{rd}$, $6^{th}$, $10^{th}$, and $14^{th}$ cycles respectively.) For the first three successive water-rock interaction cycles, the long-term strength of the rock was dramatically reduced. In contrast, the rate of reduction on the long-term strength of the rock was getting a steady state after six successive water rock interactions. The initial long-term strength of the rock samples was 165MPa, and the strength of the rock samples decreased by 8.48%, 16.97% , 20.61% ,23.03% and 25.45% (at the $1^{st}$, $3^{rd}$, $6^{th}$, $10^{th}$, and $14^{th}$ cycles respectively). For the first three successive water-rock interaction cycles, the long-term strength of the rock was dramatically reduced. In contrast, the rate of reduction on the long-term strength of the rock was attaining a steady state after six successive water rock interactions. During constant water-rock interaction, the long-term strength of rock samples has been decreasing. Besides, the long-term and failure strength ratios were decreasing. This is because the rock specimens were softened due to the water-rock interaction.

### 5.4 Creep failure characteristics of the sandstone rock

The rock specimens exhibited different destructive characteristics under the triaxial compression test, as shown in Figure 9. Shear failure was the predominant failure type, and it was noticed throughout the specimens. Specially, for the first three cycles, the sandstones specimens were failure primarily due to shear failure. Therefore, the crack patterns were irregularly distributed (similar to “X” type). Interestingly, the failure surface yielded powder. In the latter cycles, the failures of the sandstone specimens were also due to the shear failure, and the cracks were developed throughout the body of the specimens.

### 5.5 Micro-structure characteristics of sandstone under water-rock interaction

The following discussions can be made based upon the SEM results as shown in Fig 10:

Initially, the surface of the sandstone was clear, straight and smooth. Its shape was obviously irregular and densely compacted. There were no visible cracks inside the rock specimens except for a few primary fissures. After the first and second stages, the edge of the sandstone was gradually becoming smooth. Very small local pores were developed. Gradually, the edges and the corners of the sandstone specimens became spherical. The dissolution of the particles was noticeable. The bond between the particles became very loose, and the developments of micro and macro cracks were significant. After the $10^{th}$ and $14^{th}$ cycles, the surface of the sandstone became very smooth, and lost its cementation property. Hence, many large particles were gradually decomposed into small particles.

There was a change in the microstructures of the sandstone at different water-rock interaction cycles.

## 6 Conclusions

1.) For the first three successive water-rock interaction cycles, the long-term strength of the rock was dramatically reduced. In contrast, the rate of reduction on the long-term strength of the rock was getting a steady state after five successive water rock interactions.

2.) At the failure stress level, the rock specimens exhibited similar characteristics at different water-rock interaction cycles. All of the creep curves showed three typical stages: primary (damped), secondary (steady-state) and tertiary (non-linearly accelerated) stage. In addition, the deformation was significant at each stage. Generally, both primary and tertiary stages had short duration. In contrast, the secondary stage had relatively long duration.

3.) At the early stage of the water-rock interaction, the failure of the sandstone specimens was primarily attributed to the shear failure. Therefore, the crack patterns were irregularly distributed (similar to “X” type). In the latter cycles, the failures of the sandstone specimens were also due to the shear failures, and the cracks were developed entirely.

4.) The densely compacted micro structures of the sandstone rock were transformed into loose and porous state.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