Construction and Building Materials 162 (2018) 113–123

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Characterization of the deformation behavior of fine-grained sandstone by triaxial cyclic loading

Chaojun Jia [a,b], Weiya Xu [a,b], Rubin Wang [a,b,*], Wei Wang [a,b], Jiuchang Zhang [a,b], Jun Yu [a,b]

[a] Research Institute of Geotechnical Engineering, Hohai University, Nanjing 210098, PR China
[b] Key Laboratory of Ministry of Education for Geomechanics and Embankment Engineering, Hohai University, Nanjing 210098, PR China

HIGHLIGHTS

- Performed triaxial cyclic compression tests on fine-grained sandstone.
- Found the evolution of the elastic modulus and Poisson's ratio with cycles.
- Observed a three-stage process for axial and lateral irreversible strain.
- Conducted SEM tests to discuss the deformation mechanism of the fine-grained sandstone.

ARTICLE INFO

Article history:
Received 29 June 2017
Received in revised form 23 October 2017
Accepted 1 December 2017

Keywords:
Fine-grained sandstone
Cyclic loading
Confining pressure
Stress level
Cyclic number

ABSTRACT

In order to study the deformation behavior of fine-grained sandstone subjected to cyclic loading, a series of triaxial cyclic compression tests were performed under different confining pressures in the laboratory. Each of the tests combined constant-amplitude cyclic loading and increasing-amplitude cyclic loading. The experimental results showed that the evolutions of the elastic modulus and Poisson's ratio with cycles had 3 variation modes according to the applied deviatoric stress. Within a given stress level, the axial and lateral irreversible strain initially increased with a decreasing rate, followed by steady-state increases before failure. When the specimens approached failure, an accelerated increase in the irreversible strain occurred. Under lower stress levels, the volumetric strain was characterized by compaction-dominated behavior. However, it changed from compaction to dilation within each loading cycle under higher stress levels. SEM (scanning electron microscope) tests were conducted on unruptured specimens to study the deformation mechanism of the fine-grained sandstone during cyclic loading. This marks the beginning of a study that aims to provide a reference to the design, construction, and operation of hydropower stations in China.

1. Introduction

Rock serves as building material in many engineering applications, such as hydropower engineering, mining engineering, petroleum engineering, road engineering and other engineering applications [22,34]. It is inevitable that the surrounding or building materials will be subjected to cyclic loading due to the influence of strong blasting, drilling, excavation disturbances and repeated wheel loading. It is well established that the mechanical behavior of materials under cyclic loading is highly different from those under monotonic loading [1,8,27]. Cyclic loading involves large irreversible deformations that lead to premature failures at stress levels much less than the peak strength determined under monotonic loading. Therefore, it is significant to investigate the deformation behavior of rock subjected to cyclic loading for the design and construction of engineering projects.

In the past few decades, extensive work has been carried out to study the response of rock to cyclic loading. In general, 2 types of experiments are performed: the constant-amplitude cyclic loading experiment and the increasing-amplitude cyclic loading experiment. Research that leverages constant-amplitude cyclic loading experiments have shown that the fatigue strength and deformation behavior of rock typically depends on the amplitudes [2,3,7,32], frequencies [2,3,21], waveforms [32], and applied deviatoric stress and residual strain [35]. However, experimental results showed that the average Young's modulus and axial stiffness can decrease or increase with loading frequency and amplitude. Compared with that of sinusoidal and square waveforms, the triangular waveform is the least damaging. The applied deviatoric stress corresponding to the transition from volumetric compaction to volumetric

* Corresponding author at: Research Institute of Geotechnical Engineering, Hohai University, Nanjing 210098, PR China.
E-mail address: rbwang_hhu@foxmail.com (R. Wang).

https://doi.org/10.1016/j.conbuildmat.2017.12.001
0950-0618/

dilation can be considered the threshold for fatigue failure. The increasing-amplitude cyclic loading experiments conducted on rock demonstrated that the deformation behavior was significantly different from that of constant-amplitude cyclic loading experiments. For instance, Heap and Faulkner [11] carried out both aforementioned experiments, and showed that increasing-amplitude stress cycling caused a gradual reduction in sample stiffness, equating to a decrease in Young's modulus and an increase in Poisson's ratio measured at a constant stress level. Zhang et al. [40] conducted increasing-amplitude cyclic loading experiments on argillite with bedding structure. The results indicated that the stress-strain hysteresis of the triaxial cyclic loading tests describe the degradation effects of cumulative micro-cracking damage on the argillite's orientation-dependent elastic properties. Song et al. [30] performed cyclic loading and unloading tests on coal rocks and established a relationship between the electromagnetic radiation and dissipated energy in the failure process of the coal rock mass.

Sandstone is a clastic sedimentary rock that has been widely used in many engineering applications [27,38]. Numerous studies containing numerical modelling, laboratory experiments, and field observations have been used to investigate the mechanical behavior of sandstone subjected to cyclic loading [6,16,25,28]. Both the loading frequency and amplitude significantly influence the deformation behavior of sandstone in cyclic loading conditions [2,3]. Based on the experimental results with saturated sandstone, a relationship between the accumulation of axial strain and the fatigue life of the sandstone was established [33]. Moreover, intensive experimental tests on sandstone indicated that the rock with the most induced micro-cracks during loading cycles had the least fatigue life [26]. On the other hand, the influence of the confining pressure, as well as frequency, on the mechanical properties and fatigue damage evolution of sandstone subjected to cyclic loading were discussed [20]. Acoustic emission techniques [12] and micro-computed tomography observations [39] have been adopted to monitor the growth of the micro-cracks and the failure process of sandstone subjected to cyclic loading.

The previous works cited above primarily focused on the deformation properties of sandstone subjected to uniaxial cyclic loading. Rock materials encountered in applied engineering are typically in a triaxial cyclic loading state. Moreover, sandstones can be divided into coarse sandstone 2–0.5 mm), medium sandstone 0.5–0.25 mm) and fine-grained sandstone 0.25–0.0625 mm) according to the grain size, and could have different of sand size sediments. The grain size of sandstone has been proven to affect the mechanical properties significantly [36]. The mechanical properties of sandstone with coarse and medium grains have been studied sufficiently. However, the studies about the mechanical properties of fine-grained sandstone subjected to cyclic loading are rare. Previous studies mainly focused on the mechanical behavior of rock materials subjected to constant-amplitude cyclic loading or increasing-amplitude cyclic loading. Considering the hydropower station, the rock mass undergoes complex cyclic loading states because of the different operation scenarios of the reservoir.

Therefore, in this paper, we reported the results of a series of triaxial cyclic compression tests on fine-grained sandstone. The triaxial cyclic loading and unloading path is a combination of constant-amplitude cyclic loading and increasing-amplitude cyclic loading. Before the cyclic loading tests, monotonic loading tests were performed to obtain the static mechanical properties of sandstone. Finally, SEM tests were conducted on the specimens from the cyclic loading tests in order to discuss the mechanism of irreversible deformation. The overall goal of this study was to determine the deformation evolution process of fine-grained sandstone. The experimental results could provide important reference for the design, construction and operation of hydropower stations.

2. Experimental materials and procedures

2.1. Specimens and experimental system

The specimens used in this test included compact sandstone collected from a dam site in the Yunnan province of China. The sandstone was an off-white fine-grained (average grain size was 0.23 mm) rock material with an average connected porosity of 2.21% and a bulk density of 2608 kg/m^3. Thin sections of specimens were prepared for petrographic analysis, and the results are shown in Fig. 1. The sandstone was composed largely of quartz and feldspar, with a small amount of white mica. Partial angular rock debris could be observed locally. Calcium cement was completely cleavable, filling the voids in the quartz cement matrix.

The joint surface of the sandstone was quite clear and the angle between the horizontal planes was approximately 25°–30°. The sandstone was drilled from an ancient river covering layer which was located 50 m underground. After polishing and cutting, the cylindrical specimens with 50 mm in diameters and 100 mm in lengths were prepared according to the International Society for Rock Mechanics (ISRM).

A servo-controlled rock mechanics experimental system was used to complete all the experiments. Both the deviatoric stress and confining pressure were loaded by 2 separated servo-controlled pumps, which had maximum loading capacities of 375 MPa and 60 MPa, respectively. Axial strain ε_1 was monitored continuously throughout each experiment using 2 linear variable displacement transducers (LVDT) with a resolution of ±1 μm, while the radial deformation ε_3 was obtained through a ring radial displacement transducer chain wrapped tightly around the central part of the samples. All the stress and strain data were recorded by a computer directly. A more detailed description about this test system is shown in the literature [34].

2.2. Test method and procedure

In order to investigate the deformation behavior of sandstone, 2 types of triaxial tests were carried out. The first was the monotonic loading test which is the conventional triaxial compression test, and the second was a cyclic loading test. These tests were performed under the confining pressures of 1, 3, and 5 MPa.

To perform the monotonic triaxial tests, the confining pressure was loaded to the desired value at a rate of 0.5 MPa/s. After that, deviatoric stress was applied to the top end of the specimen with a constant loading rate of 7.5 MPa/min until failure was reached in order to obtain the critical stress points of the sandstone under different confining pressures.

The specific cyclic loading path, shown in Fig. 2, was a combination of constant-amplitude cyclic loading and increasing-amplitude cyclic loading, and the test procedure was as follows.

1. The confining pressure was loaded to the desired value at a controlled rate of 0.5 MPa/s.
2. The specimens were loaded to the first level of deviatoric stress at a rate of 7.5 MPa/min, and then the deviatoric stress was unloaded to approximately 10% of the peak stress at the same strain rate. In each subsequent loading-unloading cycle, the maximum and minimum stresses were the same as the previous cycle. Each stress level was repeated thirty times.

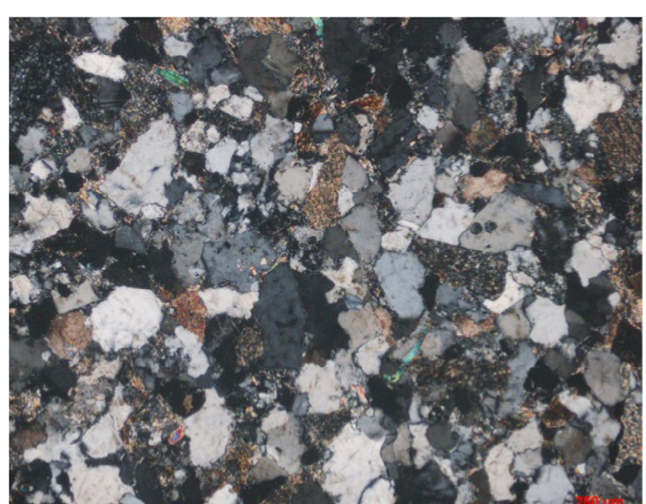

Fig. 1. Photomicrographs of thin sections showing representative microstructures of the fine-grained sandstone.