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Relaxation behavior of argillaceous sandstone under high confining pressure

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1. Introduction

To study the time-dependent behavior of rock, three cases are often considered: creep, which is increasing in strain when the stress is held constant; relaxation, which is decreasing in stress when the strain is held constant; a combination of both, when the rock unloads along a chosen unloading path.[1] The relaxation tests of rock are seldom carried out, because maintaining a constant displacement or strain on the sample for a long time is difficult.[2–4]

Creep tests show that the steady creep rate under same deviatoric stress decreased with increasing of confining pressure,[5] whereas, the effect of confining pressure on relaxation is rarely studied. Most reported relaxation tests concentrated on the characteristic of the relaxation curves under a specific confining pressure. Li and Xia[3] studied the uniaxial relaxation curves of four different rocks without drainage control and found that the relaxation curve of soft rock was smooth and continuous, whereas the relaxation curve of brittle hard rock was discontinuous. The uniaxial relaxation tests of rock salt showed that the relaxation of rock salt would terminate in a stress-free state.[2] However, a non-zero terminated stress of relaxation was observed during the triaxial relaxation tests of rock salt under a confining pressure of 5 MPa.[6] In addition, according to the results of triaxial relaxation tests of Opalinus Clay under drained and un-drained condition with a confining pressure of 10 MPa, the relaxation behavior after several loading cycles was independent of the loading geometry or draining.[7]

During the period of relaxation, the stored elastic strain energy in the sample will dissipate through plastic deformation,[8] which seems to be closely related to the initiation and propagation of cracks in the samples.[9] And the crack propagation in the samples may decrease the rock strength. However, no study has been reported regarding the strength reduction of rock during the relaxation period.

In this study, a series of triaxial relaxation tests under confining pressures 10–35 MPa were conducted on the argillaceous sandstone. A power law model was employed to analyze the effect of the confining pressure on relaxation behavior of rock. To study the strength reduction of the argillaceous sandstone after relaxation, the comparisons between the failure strength obtained from the relaxation tests and the conventional triaxial tests were carried out.

2. Testing equipment tested material

The triaxial relaxation tests were conducted using the TLW-2000 triaxial rheology system at the State Key Laboratory of Geomechanics and Geotechnical Engineering of the Chinese Academy of Sciences. For the relaxation test, a key technical parameter is the accuracy of the axial displacement control, which is less than ±0.001 mm for the used triaxial rheology system, and this accuracy is sufficient for the relaxation tests.[7]

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The relaxation tests were conducted on an argillaceous sandstone taken from Pakistan. The argillaceous sandstone are composed of quartz (31.2%), calcite (36.2%), clay mineral (25.9%; including kaolinite, illite and chlorite), hematite (3.3%), dolomite (2.1%) and albite (1.3%). According to the ISRM standard, the cylindrical samples for relaxation tests, with dimensions of $\Phi 50 \times 100$ mm, were carefully machined from large lump of rock mass. To minimize the initial differences between samples, only the samples with p wave velocity range of 3700–4700 m/s were selected for relaxation tests. Before the triaxial tests, all the samples were dried at 100 °C in the oven for 24 h.

A stepwise loading method was used in the relaxation tests. At the beginning of the relaxation test, the hydrostatic pressure was firstly applied on the sample with a rate of 0.2 MPa/s, and then the confining pressure was maintained constant during the whole relaxation test. Six levels of confining pressure including 10, 15, 20, 25, 30 and 35 MPa are chosen in this study.

For the TLW-2000 triaxial rheology system, the deviatoric stress can be applied by displacement control, or stress control, or a combination of both. In this study, the deviatoric stress was applied by the combination of displacement and stress control. The deviatoric stress was firstly applied by the axial displacement at a rate of 0.002 mm/s, when the deviatoric stress approached to its design value, the stress control will be used automatically. After the design deviatoric stress was attained, the axial displacement control was used again, and the relaxation test was carried out by maintaining the axial displacement constant for more than 72 h. The deviatoric stress increment of each step was about 12 MPa until the failure of sample.

3. Results of the relaxation tests

Eight triaxial relaxation tests were carried out. To describe the relaxation test results, the relaxation stress after t hours of relaxation is defined as

$$\sigma_r(\mathrm{t}) = \sigma_0 - \sigma_l(\mathrm{t}) \tag{1}$$

where σ_0 is the initial deviatoric stress at the beginning of each relaxation step, and $\sigma_l(\mathrm{t})$ is the remaining deviatoric stress after t hours of relaxation. The details for each relaxation tests are shown in the Table 1, and the triaxial relaxation curves of all samples are shown in Fig. 1. For all samples under different confining pressure, obvious stress relaxation was observed since the first relaxation step, and Schulze[7] reported similar results during the triaxial relaxation tests of Opalinus Clay under drained and un-drained condition.

To identify the accuracy of axial displacement control during relaxation tests, a typical relaxation curve was redrawn in Fig. 2. Fig. 2(a) shows that the variations of axial displacement were controlled less than ±0.001 mm (between 0.566 mm and 0.568 mm) during the relaxation period. The "deviatoric stress noise" induced by axial displacement control should be less than ±0.29 MPa (the modulus of the sample is about 29 GPa), which is much less than the fluctuation of deviatoric stress measured by axial stress sensor installed outside the triaxial cell. In fact, the measured deviatoric stresses are an addition of the deviatoric stress applied on the sample and the friction stress between the piston and the triaxial cell. And, the friction effect can be easily removed using a mathematical method (Fig. 2(a)). According to Fig. 2(a), the triaxial relaxation curves without friction effect was smooth and continuous, which is similar with the relaxation curves of soft rock claystone obtained from axial relaxation tests.[3]

Table 1
Details of each relaxation tests of the argillaceous sandstone.

Samples	Confining pressure/Mpa	Deviatoric stress of first step/MPa	Stepwise increment of deviatoric stress/MPa	Deviatoric stress at failure/MPa
2-9-2	10	72	12	118
2-6	15	84	12	110
2-31-1	15	72	12	144
2-19	20	84	12	121
2-1	25	84	12	170
2-11	30	96	12	122
2-5	30	96	12	171
2-8-1	35	108	12	190

Note: For the name of samples, the first number indicates the rock type of the sample, and the second and third number indicates the location where the samples are taken from.

To perform further analysis on the characteristic of relaxation curves of argillaceous sandstone, the relaxation stress of samples were calculated according to Eq. (1). A typical curve of variations of relaxation stress is shown in the Fig. 2(b). The variations of relaxation stress can be divided into two stages. At the beginning few hours of the relaxation, the relaxation stress rapidly increases with time, and the rate of relaxation sharply decreases with time; this stage can be named the fast relaxation stage. Then, the rate of relaxation decreases to a notably low level, and this stage can be named the steady relaxation stage. Because no external energy is introduced during the period of relaxation,[9] the rate of relaxation will approach zero at the end of the steady relaxation stage.

3.1. The effect of confining pressure on relaxation stress

To analyze the effect of confining pressure on relaxation stress, a power law model is employed to describe the variation of the relaxation stress with time for different relaxation steps:

$$\sigma_r(\mathrm{t}) = At^n \tag{2}$$

where A and n are the model parameters. The fitting results show that the power law model can describe the variation of the relaxation stress well (Fig. 3), and the fitting results of parameters A and n for all samples are given in the Table 2. According to the fitting results, the value of parameter A varies from 3.0 to 14.0, and the value of parameter n varies from 0.10 to 0.30. In such parameters ranges, the value of A is closely related to the relaxation stress σ_r at the fast relaxation stage, and the value of n is mainly dependent on the relaxation rate at the steady relaxation stage (Fig. 4).

The variations of the parameter A with the initial deviatoric stress of the relaxation steps for different samples are shown in the Fig. 5(a). The parameter A of each sample increases with the initial deviatoric stress, and the effect of confining pressure on parameter A was not obvious. Disregarding different confining pressure of samples, the mean value of A at the same initial deviatoric stress is calculated and presented in the Fig. 5(b). An index relationship between the mean value of A and initial deviatoric stress is fitted with a correlation coefficient of 0.90 to the following equation:

$$A = 2.40e^{0.0080\sigma_0} \tag{3}$$

The fitting results indicate that the relaxation stress of fast relaxation stage, is mainly dependent on the magnitude of initial deviatoric stress σ_0, and this results is similar with the creep behavior of rock. Besides, according to the fitting results, the relaxation stress of fast relaxation stage is hardly affected by the confining pressures, however, according to the creep tests of strongly weathered sandstone under low confining pressure (the confining pressure less than 2 MPa), the creep behavior of rock is decreased clearly by the confining pressure. The differences