A Study on the Law of Non-Uniformity of Rock Deformation under Quasi-Static Loading

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Abstract. Under internal and external factors, a series of slow deformation waves with different energy levels will occur in geological bodies. Slow deformation waves propagate in earth plates or along faults and may trigger earthquakes of different magnitudes. This wave is formed by the deformation and cracking of solid under external actions. The study of slow deformation waves showed that there are similarities in wave propagation at the earth’s plate scale and laboratory scale levels. A uniaxial compression test is conducted on a small-scale cuboid red sandstone sample under a certain loading speed to investigate the propagation law of the deformation wave. The digital image correlation technique is used to investigate the variation characteristics of the deformation wave of the sample. Furthermore, the variation characteristics of the three strain components of the slow deformation wave generated during the loading process are clarified. The deformation wave’s propagation speed is determined according to the motion of the localized maximum of the strain component in the loading direction. Simultaneously, semi-quantitative analysis is undertaken to reveal the temporal and space non-uniformity presented in the damaged sample surface.

1. Introduction

In the geological movement process, there is a kind of slow-propagating deformation wave along the seismic or structural zones. A wave phenomenon occurs because of strong earthquakes and other activities. This deformation wave is not an elastic wave because its wave velocity is lower than the elastic wave velocity represented by S-wave and P-wave in the earthquake. For the mechanism of this wave occurrence, Feng [1] pointed out that it is due to the combination of external triggering and the change in the nature of the medium in the focal area. For the formation of slow deformation waves, Bykov [2] suggested that the slow deformation wave in the fault is caused by the grain boundary slip of the medium in the fault. Additionally, Geng [3] suggested an interlayer consisting of a rheological medium in the earth’s interior. Thus, some slow deformation waves may be excited to propagate in this rheological medium under certain conditions, which are essential in preparing and generating earthquakes. For the transmission of slow deformation waves, the study on the plastic flow network and deformation wave of continental lithosphere shows that [4], the driving force of continental plate margin, mainly realizes its long-distance transmission through the network flow. The slow deformation wave of the lower lithosphere, including the lower crust and lithospheric mantle, controls the intraplate tectonic deformation and seismic activity. Moreover, some experts and scholars have

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presented the concept of the epicenter migration wave [5] for the propagation speed of deformation waves. They calculated the velocity of the epicenter migration waves in several seismic zones, with a magnitude of tens of kilometers per year [6].

Research on deformation and failure of solid under external factors is one of the basic topics in materials and engineering [7–11]. Recently, with the deepening of research, the scope of space and time scales for solid deformation and failure research has gradually expanded [12–14], from a global scale to the atomic scale and rapid loading deformation failure to the material deformation failure with creep speed [15–17], which significantly expands people’s vision. In theoretical research, a theoretical model of slow deformation waves in deep tunnel surrounding rock has been established based on the theory of continuous phase transformation and Lagrange analytical mechanics [18]. In large-scale research, the characteristics of slow deformation waves are determined by measuring the spatial and temporal characteristics of the geophysical field. Additionally, the study shows that directional migration of seismic sources is a common phenomenon. For example, it has been observed in Northwest China [19]. Zuev [20] studied the slow deformation waves in rock and alkali metal halide crystal specimens at the laboratory scale by compression and tension experiments and found that slow deformation waves in rock and alkali metal halide crystal specimens is similar to the slow deformation wave observed in metal materials previously.

In the past 50 years, the concept of deformation waves has been significantly developed. However, the quantitative understanding of such waves is insufficient, and the stress-strain state conditions, propagation, and evolution law in rock mass have not been thoroughly clarified. Although scholars have investigated the propagation law of slow deformation waves produced in small rock block samples during loading, most of the selected materials are mainly metal and halide; the studies of rock materials are not deep enough. For instance, the propagation and evolution law and velocity characteristics of deformation waves in longitudinal, transverse, and shear components of rock materials are not discussed. The deformation wave of the specimen in the creeping stage is also not discussed.

This paper processes and analyzes the change of longitudinal, transverse, and shear strains on the specimen surface through small-scale laboratory experiments based on DIC data processing technology. The evolution law of slow deformation waves on three strain components, i.e., longitudinal, transverse, and shear, are investigated. According to the characteristics of local strain maximum, the propagation velocity of slow deformation waves in the linear loading and creep stages is obtained, and the influence factors of deformation wave velocity are preliminarily discussed.

2. Experimental investigations

2.1. Sample preparation, test equipment

To investigate the characteristics of deformation waves on small-scale samples in the laboratory, we selected a large red sandstone. We took the standard cuboid test blocks of 50 mm × 50 mm × 100 mm as the research objects. The grain size in the samples varies in the range of 200–300 μm. The sample is divided into three groups. Mechanical compression tests at room temperature were conducted on the dynamic disturbed triaxial testing system DRTS-500, consisting of a loading system and a data acquisition system. Three control models could be applied, including stress, strain, and displacement controls. This experiment adopted displacement control. On the testing machine, the maximum axial load is 500 KN, and the external actuator generated the axial pressure. The red sandstone sample was made of stones of 600 mm × 300 mm × 110 mm polished and cut on a machine tool. Before the test, the test block needs to be treated; thus, facilitating the test block surface micro-vision shooting and point capture by the industrial camera. The sample treating process includes spraying a layer of ordinary white paint evenly on the surface of the test block, then drying it and spraying a layer of black granular paint properly.

2.2. Testing program

The specimen was loaded along the longitudinal axis with a moving clamping speed of 0.5 mm/min. In addition to recording conventional stress-strain curves, specimens were characterized by speckle
photography at all stages. Afterward, the image was processed using DIC software, which enables the evolution of the displacement vector $r(x, y)$ field at the point on the specimen face to be tracked and recorded. Under each test condition, three repeated tests were conducted.

3. Test results and analysis
In this test, the sample was loaded at a loading speed of 0.5 mm/min; the loading value was set from 0 to 190 kN. The stress-strain curves are shown in Fig. 1. Compared with the transformation process of each stage under loading, the sample loading is in the compaction stage when the total strain of the red sandstone sample is about 0–0.005. The loading time interval at this stage was between 0 and 63 s. In the time interval between 63 and 263 s, the test loading entered the linear hardening stage, and the corresponding strain of the red sandstone sample is 0.0050–0.0084. This study focused on the loading stage of the specimen before point A, i.e., the compaction and linear hardening stages (Fig. 1).

![Fig. 1 Stress-strain and stress-time diagrams](image)

4. Distribution of deformation waves on different components of strain

4.1. Distribution of longitudinal strain deformation wave
The waveform of longitudinal strain $\varepsilon_{xx}$ wave at two time points, i.e., 8 and 16 s, is selected to compare and analyze the deformation wave motion characteristics at 0.5-mm/min loading speed, as shown in Fig. 2 (a) and (b).
The three-dimensional (3D) diagram in Fig. 2 (a) shows that each position is undulated, and the stress reaches about 1.0 MPa. Additionally, the strain fluctuations spread from the applied stress end to the entire sample surface plane, and waves along the X-axis covered the entire specimen surface. From the side view, along the direction of the sample X, the strain magnitude is the largest, and the magnitude decreases in the X range of 0–20 mm. Furthermore, the fluctuation in the range of 20–60 mm is minimal and uniform. From the position 60 to 100 mm, the fluctuation becomes larger, and the magnitude is slightly larger than in the X range of 0–20 mm.

Fig. 2 (b) shows that the stress reaches 1.8 MPa; the entire sample surface is also fluctuating. However, the strain magnitude tends to be the same over the sample surface from the side view. Simultaneously, the magnitude of the strain at the passive and applied ends are gradually equalized.

4.2. Distribution of transverse strain deformation wave

Similarly, we selected the waveform of the transverse strain $\epsilon_{xy}$ wave at two-time points, i.e., 8 and 16 s, as shown in Fig. 3 (a) and (b).

As shown in Fig. 3 (a), the stress reaches 1.0 MPa, and the 3D diagram shows an uneven distribution. From the side view, the distribution of the maximum strain value is relatively uniform, and there is no similar situation that the longitudinal strain in half of the length is larger than in the other half of the length of the specimen. The stress in Fig. 3 (b) reaches 1.8 MPa; the 3D profile distribution is similar to that in Fig. 3 (a), without obvious regularity. However, the maximum strain’s position in the profile changes.
4.3. Distribution of shear strain deformation waves

Similarly, we selected the waveform of the shear strain $\varepsilon_{xy}$ wave at two-time points, i.e., 8 and 16 s, as shown in Fig. 3 (a) and (b).

Overall, the shear strain distribution in the shear strain wave is more uniform, and the maximum strain fluctuation is not large. The regularity is not obvious.

![3D diagram](image1)

![Side view](image2)

(a) waveform at 8 s (b) waveform at 16 s

Fig. 4 Deformation wave of shear strain at different time moments

5. Wave velocity of the longitudinal strain deformation wave

Because of the uniform longitudinal loading of the sample, the longitudinal strain wave has a certain regularity. The propagation velocity of the slow deformation wave is investigated based on the propagation characteristics of the longitudinal strain wave.

In the study of metals and alloys, V. I. Danilov [21] found deformation waves in the linear hardening stage of pressurized or tensile specimens. Therefore, we focus on the longitudinal strain wave propagation in the linear hardening stage during the loading process of the experiment.

Three lines along the X-axis direction on the sample surface (Fig. 5) are taken as the detection lines after the microcharacterization images are processed. The following steps are employed to determine the moving speed of the deformation wave. Select the deformation wave diagram with the same time interval, record the maximum points of strain localization along the X direction of the sample in each diagram, mark the distribution of the maximum points in each diagram, draw a line (Fig. 6), and calculate its slope to determine the moving speed of the maximum point, i.e., the moving speed of the deformation wave. It is found that the fluctuation on the central line is the most significant, and the movement is more pronounced and regular. Therefore, the middle line, i.e., L2 data, is used for analysis.
After data processing, when the red sandstone sample is loaded at 0.5-mm/min uniaxial loading speed, the wave velocity of deformation wave of three groups of experimental data samples is $5.4 \times 10^{-5}$, $6.0 \times 10^{-5}$, and $6.3 \times 10^{-5}$ m/s. After averaging, the peak velocity of strain localization is $5.9 \times 10^{-5}$ m/s.

**6. Conclusion**

The surface of the red sandstone sample in the deformation process under uniaxial compression is characterized using DIC technology to study the propagation law of deformation waves. The evolution
charactersitics of the slow deformation wave generated by the red sandstone sample in the loading process are observed and analyzed. The characteristics of different components of deformation wave are as follows:

1) In the initial stage of loading, the longitudinal strain $\varepsilon_{xx}$ (Fig. 2), the transverse strain $\varepsilon_{yy}$ (Fig. 3), and the shear strain $\varepsilon_{xy}$ (Fig. 4) fluctuate significantly at the loading applied and passive ends. The strains fluctuate weakly, and they gradually became equalized with time. It shows the existence and propagation of deformation waves in a rock mass.

2) The deformation wave velocity in the linear hardening stage of the red sandstone sample during the loading process is obtained. Through comparative study, it is concluded that deformation wave velocity is not significantly affected by material.
3) This study is preliminary on the deformation of rock materials under compression; it provides a basis for the study of spatial and temporal heterogeneity of rock material deformation. Further detailed research and analysis are needed.

7. References

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