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A mechanism of fatigue in salt under discontinuous cycle loading

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1. Introduction

The fatigue properties and their relationship with material deformation, damage and failure is an important topic in geo-technical engineering field, including rock cutting, drilling and blasting, underground openings, supports and rock pillars.^{1–6} In recent years, the Chinese Government has constructed many underground oil gas storages in rock salt layer to ensure energy supplies and reserves. Owing to the influence of periodic injection-production action and seasonal temperature variation, understanding the fatigue behavior of rock salt becomes crucial for ensuring safety and stability of storage caverns.⁶ In recent years, much research has focused on the effects of various factors on fatigue in salt and other rocks. Song et al.⁶ and Fuenkajorn and Phueakphum⁷ studied the effects of cyclic loading on mechanical properties and acoustic emission for Pakistan salt and Maha Sarakham salt, respectively. Grgic and Giraud⁸ studied the influence of different fluids on the static fatigue of a porous rock and the mechanical-chemical coupling effect. Erarslan and Williams^{9,10} examined the damage mechanism of rock fatigue and its relationship to the fracture toughness of rocks using Brisbane tuff disc specimens. Le et al.¹¹ reported a comprehensive set of size effect on fatigue crack kinetics for Berea sandstone. Mellouli et al.¹² studied the impact of thermal fatigue damage on hardness effect for hot-working tool steel. These references provided a number of ways to interpret and characterize the fatigue

behaviors, such as residual strain, elastic module evolution and acoustic emission.

A salt mine in Jintan, Jiangsu province, China, composed of sixty-three underground salt caverns (USCs) serves as a gas storage group since 2007. Fig. 1 shows its periodical variation in gas pressure within one year.¹³ As the gas pressure maintains the maximal value for three months (from sixth month to ninth) until the gas production, the storage wall/pillar rock around USCs will be subjected to a relatively smaller deviatoric stress to ensure that USC capacity loss by creep action is slow^{14–17} This equivalently brings storage wall rocks combined stress composed of cyclic pressure and intervals of non/small deviatoric stress. However, the investigation into this essential factor (intervals) has rarely been made. This work experimentally explores the impact of non-stress interval on the fatigue in salt. The results would contribute to enriching the knowledge comprehensiveness of the factors that impact the safety of gas storage and the accuracy in designing and estimating fatigue life of gas-storage facilities.

2. Experimental conditions

2.1. Samples and experimental techniques

The loading equipment used in the tests was a conventional mechanical rigid testing machine, which was developed and manufactured in the State Key Laboratory for Coal Mine Disaster Dynamics and Controls. The rock salt samples were collected from the Khewra salt mine in Pakistan. The rock salt consists of a high purity of NaCl (greater than 96%), small amounts of K₂SO₃ (around

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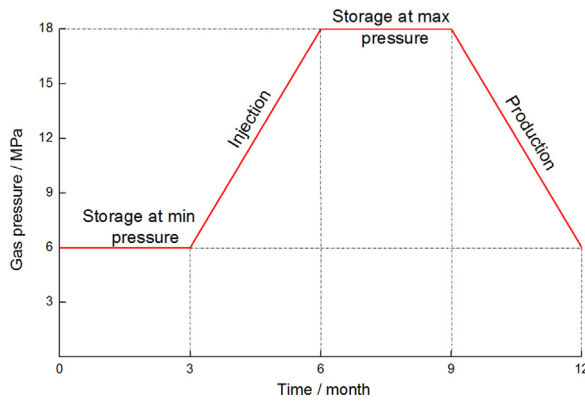


Fig. 1. Working path of gas pressure of underground salt cavern in one year.

3.1%), some mud and other undissolved substance (less than 0.9%). The samples were shaped into standard cylindrical blocks of 50 mm diameter and 100 mm length. Duplicate tests were conducted to enhance the reliability of the results.

2.2. Experimental methods

The loading path used in our experiments combined cyclic stress and intervals. The experiments were performed at a loading velocity of 2kN/s. The upper and lower stress are set at 34.8 MPa (85% of the compression strength 41 MPa)⁶ and nearly 0 MPa, respectively. The first loading and unloading period (or cycle) is marked as the *F* cycle, the normal stress cycle (immediately following a cycle) is the *N* cycle, and the spaced cycle (immediately following an interval) is the *S* cycle. The stress path in tests is: *F–N–interval–S–N–interval–S–N–interval–S...to failure*. Each fatigue test has a given interval duration; tests with durations of 5, 10, 15, and 20 min were run (Table 1). No significant effect of working order of the *S* and *N* cycles was observed via a confirmatory test (stress path: *F–interval–S–N–interval–S–N–interval–S–N...to failure*).

3. Experimental results

3.1. The accumulation of the irreversible deformation

Under normal/conventional conditions, the spacing closeness of every cycle's strain-stress curve will undergo three phases, sparse-dense-sparse.^{6,13,14} Three phases correspond to three phases of deformation-evolution, respectively. Fig. 2 shows the axial stress-axial strain curve and the typical phase feature. The width of the ovals among the curves represents the distance between

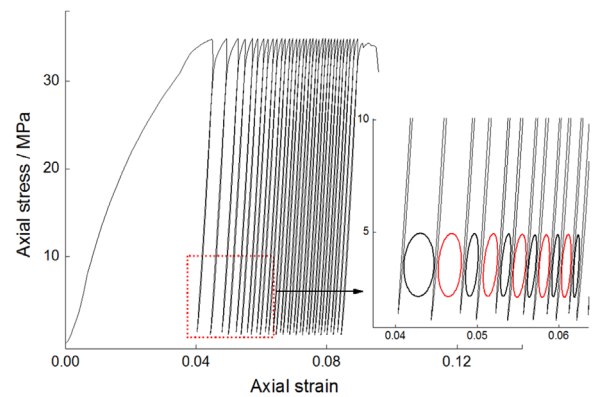


Fig. 2. Entire strain–stress curve of interval fatigue test with 5 min intervals. The red ovals represent the strain increments from the *S* cycles; the black ovals represent the strain increments from the *N* cycles.(For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

loading lines and unloading lines, namely, the strain increment in each cycle. The black ovals are obviously narrower than the red, which implies a difference in deformation characteristics compared to normal/conventional fatigue stress-strain curves.

Sample deformation can be decomposed into reversible and irreversible components. The reversible component is induced by the elasticity of rock, while the irreversible component can be induced by plasticity or fatigue behavior of rock. In this study, the irreversible component is termed residual strain, which is calculated by subtracting each strain value that corresponds to lowest stress. Fig. 3 shows the residual strain accumulation with the stress cycle number. The compressive strain is defined to be positive, whereas the extension strain (expansion) is negative. As shown by the enlarged local region, in *S* cycles, the speed of accumulation is faster. This phenomenon indicates that a distinct difference in deformation evolution exists between *S* and *N* cycles. For a clear presentation of the difference, the residual strains from *S* and *N* cycles are summed separately (Fig. 4), excluding *F* cycle. The accumulation of residual strain from *S* cycles is notably faster than that from *N* cycles. From Table 1, it can be found that the total residual strains keep constant with a negligible float; the average residual strain from *S* cycle is larger 18–60% than *N* cycle.

3.2. Variation of residual strain ratio

The development of residual strain can reflect the damage progress inside the rock salt. We define the ratio of residual strain and total strain to track the dynamic development of irreversible deformation, based on the axial deformation. The calculated

Table 1
Residual strain and fatigue life of samples from tests carried out with intervals of different duration. Numerical values in some blanks are axial deformation, radial deformation, and volumetric deformation. For the test that combines different intervals, parameters of the first six cycles are excluded from the average of the residual strain. The last cycle is not concluded in the fatigue life.

Tests	Interval duration	Total irreversible deformation/ × 10 ⁻²	<i>N</i> cycle/ × 10 ⁻³	<i>S</i> cycle/ × 10 ⁻³	Ratio of <i>S/N</i>	Fatigue life
Test with constant intervals	0	8.08/-/-	1.37/-/-	-	-/-/-	58
	5 min	8.31/-8.39/-8.35	1.14/-1.60/-2.06	1.49/-1.98/-2.50	1.31/1.24/1.21	34
	10 min	8.18/-7.76/-7.35	1.48/-1.88/-2.28	1.74/-2.26/-2.78	1.18/1.20/1.22	24
	15 min	7.16/-7.69/-8.22	2.33/-3.47/-4.61	2.84/-4.82/-6.58	1.22/1.39/1.43	13
	20 min	8.44/-8.35/-8.26	1.70/-2.48/-3.26	2.52/-3.86/-5.21	1.48/1.56/1.60	20
Test combining with different intervals	0	8.19/-/-	0.86/-/-	-	-	39
	5 min	-	-	0.93/-/-	1.08/-/-	-
	10 min	-	-	1.00/-/-	1.16/-/-	-
	15 min	-	-	1.03/-/-	1.20/-/-	-
	20 min	-	-	1.15/-/-	1.34/-/-	-

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