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Fatigue properties of rock salt subjected to interval cyclic pressure

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ABSTRACT

Due to the influence of gas pressure operational modes, surrounding rock of salt carven underground gas storage always suffers combined stress composed of cyclic pressure and intervals of no stress (or small stress). We conducted comparisons between conventional fatigue tests and (six groups of) interval fatigue tests, which combine spaced stress cycles and normal stress cycles. Experimental measurements demonstrate that the combined cyclic stress has a strong impact on the fatigue activity of rock salt. In interval fatigue tests, the residual strain of a spaced stress cycle is notably larger than that of a normal stress cycle. As the conventional tests can be actually considered as a kind of fatigue tests with transitory intervals, the accumulative rate of residual deformation increases with the duration of the interval in all test groups. The testing results show the fatigue lives of samples from interval fatigue tests dramatically reduce in a certain range; when intervals extend beyond the value 120 s, fatigue lives perform with a slight rise. Based on the *S–N* curve and the *S–T* curve, an experiential model fitting the relationship between fatigue life and interval was established.

1. Introduction

Many natural and man-made rock structures can be weakened by cyclic loading, including faults, joints, bedding planes, tunnel walls, excavation roofs and ribs, bridge abutments and dams. Fatigue research is therefore a focus of much current interest in geology, geomorphology, engineering, and geophysics. Due to its excellent ductility [1] [2], good self-healing features when damaged [3], as well as extremely low permeability [4–6], as an ideal storage medium for oil gas, rock salt is receiving much attention, especially with respect to its fatigue characteristics [7–9]. Research into fatigue characteristics has significance for storage safety because of pressure changes that occur during gas injection and production or with the changing seasons. Factors that strongly influence the fatigue characteristics of rocks include stress [7,10,11], temperature [12,13], and loading frequency [14,15]. Typical theories for the effects of stress and temperature, based on continuum mechanics, thermodynamics, and damage mechanics, can be explained via the viscosity, plasticity of salt and halite crystals. Despite the lack of mature theories to explain the effect of loading frequency, sufficient experimental evidence can explain the empirical behavior to some degree and thereby guide the practical work. For salt gas storage, however, these researches into salt fatigue is not sufficient.

Fig. 1 shows the gas pressure exerted on the internal surface of the carven as a function of time, in Jintan salt mine, Jiangsu province, China, which served as a natural gas storage group since 2007. The injection pressure reaches the index value (max pressure), a pressure plateau results and lasts (approximately 3 months) until the gas production, during which the storage wall rocks are subjected to small (almost zero) and constant deviatoric stress [16–18]. This equivalently brings storage wall rocks combined stress composed of cyclic pressure and intervals of non/small deviatoric stress. In most cases, owing to the lack of a plausible theory and experimental data, intervals between pressure cycles have been neglected and are taken for granted that interval will not influence the fatigue characteristics of wall rocks. Therefore, it is necessary to investigate the fatigue characteristics for salt under combined stress. In light of experimental effort, the recent work has to be transiently concentrated upon the effect of time interval alone. This work will present the experimental evidence of the impact on the fatigue activity by time interval and establish a preliminary fatigue life model to formulate the relationship between fatigue life and time interval. The result could play a warning role in the safety of gas storage and provide beneficial reference in designing and estimating fatigue life of gas storage facilities to some degree (see Fig. 2).

2. Experiments

2.1. Samples and experimental conditions

The loading equipment used in the tests was a conventional mechanical rigid testing machine MTS 815. The rock salt samples

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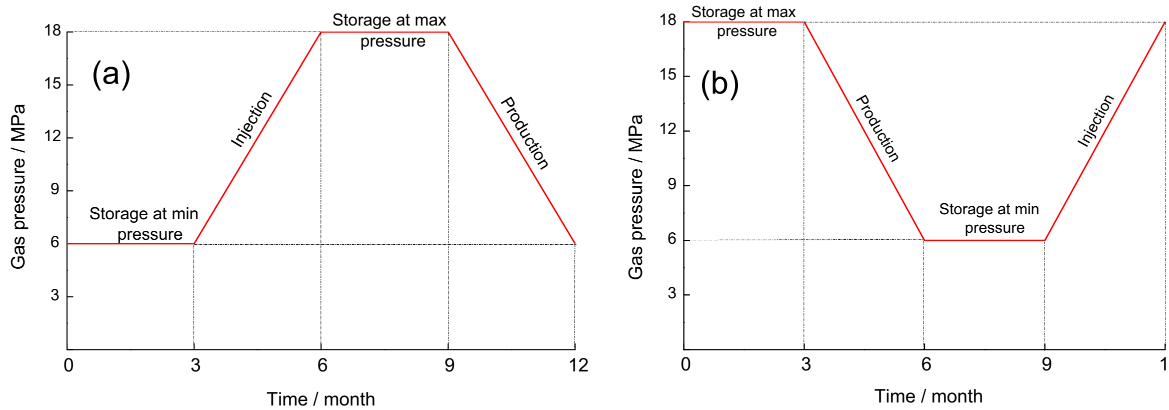

Fig. 1. Gas pressure curve of the salt cavern gas storages for (a) synchronized injection–production mode and (b) asynchronous injection–production mode in a cycle (one year).

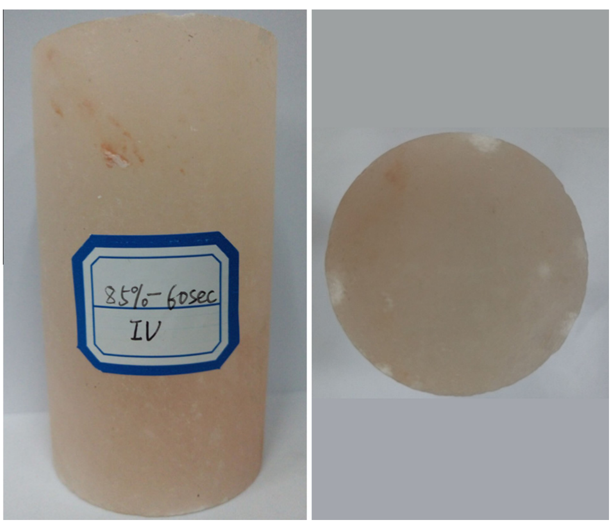

Fig. 2. Photograph of the processed samples.

were collected from the Khewra salt mine, Pakistan. The samples were cut into standard cylindrical blocks with 50 mm diameter and 100 mm length. The components of salt are listed in Table 1. The experiments were conducted at room temperate 18–23 °C and relative humidity 56–68%, 0.5–2 h for one test. During test the samples were encased by a tied thin fresh-protection package to keep a relatively constant humidity and prevent the falling salt-fragments from rusting the testing machine.

2.2. Experimental methods

The experiments were performed using a cyclic loading path with a velocity of 2 kN/s. The stress paths are shown in Fig. 3. Every time interval (ΔT) followed two loading periods. To facilitate the presentation and analysis, the first loading and unloading period is labeled as the *O* path, the following normal stress period interval is the *B* path, and the spaced stress period (following the interval immediately) is the *A* path. For a single fatigue test, the duration of the interval was held constant at values of 3, 5, 30, 60, 120 and 900 s. Replicated tests were conducted to ensure the lithology of the samples stable and enhance the reliability of the results. Each test was carried out at least two times (i.e. one or more replicates).

Table 1
Components of salt in the tests.

Components	NaCl	K_2SO_3	Mud and others
Percentage composition (%)	96	3.1	0.9

3. Results and discussion

3.1. Evolution of the irreversible deformation

Firstly, a simple comparison between conventional tests (in which the sample is subjected to consistent upper and lower stresses) and interval fatigue tests was made. Many researchers usually divided the deformation curves of samples into three stages [10,14,19]: decelerated deformation, uniform deformation, and accelerated deformation. During the uniform deformation stage, the increments of irreversible deformation (also known as residual deformation) of each stress period are almost constant. The sum of the residual deformations is the deformation accumulation. Fig. 4 shows the stress–strain curves of the rock salt samples in the fatigue tests. Two types of tests curves are similar: all show the stage features, varying only in the degree of closeness of the curves. We can hardly identify any impact of interval time using these data.

To explore the differences, the residual axial strain of conventional fatigue tests and part of interval fatigue tests are plotted in Fig. 5. The minimal residual strain of odd cycle and even cycle are read from the dataset and labeled in the figures. In conventional fatigue tests, the axial residual strain of pressure cycle progresses as usual with some fluctuations in a narrow rang and two minimal value are identical. While in interval fatigue tests, the axial residual strain of *A* path stress period is always larger

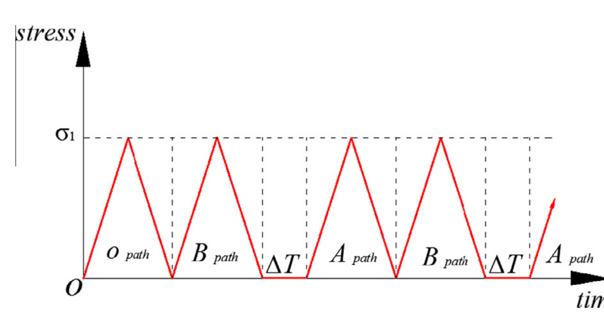

Fig. 3. Stress path as a function of time. The upper stress σ_1 is 34.8 MPa (85% of the compression strength, 41 MPa), while the lower stress is nearly zero. The samples are subjected to cyclic stress until failure.