Load-Unload Response Ratio (LURR), Accelerating Moment/Energy Release (AM/ER) and State Vector

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Abstract

A series of acoustic emission experiments under tri-axial compression with large rock specimen have been conducted. The experimental results supported the LURR (load/unload response ratio) and AER (accelerating energy release). A new measure called state vector has been proposed to describe the damage evolution of loaded rock specimens.

Introduction

The CPH (Critical Point Hypothesis) considers earthquake rupture as a critical point (Vere-Jones, 1977[15]; Sornette and Sornette, 1990[12]; Sornette and Sammis 1995[13]; Bowman et al, 1998[1]; Rundle et al, 1999[10]; Jaume and Sykes, 1999[5]). According to CPH the crust is not in a continuous state of criticality, but repeatedly approaches and retreats from a critical state. During the establishment of criticality the crust must be characterized by both susceptibility (Wei 2000[16]) to external factors and strong correlation between its different parts. The former will lead to triggering earthquakes significantly by tidal stress (Grasso and Sornette, 1998[4]) and consequently anomaly high value LURR (Yin and Yin, 1991[17]; Yin, 1993[18]; Yin et al., 1995[19]; Yin et al., 2000[20]) prior to large earthquakes. The later will lead to establishment of long-range correlations in the regional stress field (Sykes, and Jaume 1990[14]; Rundle et al, 1999[10] Sammis, and Smith, 1999[11]; Mora and Place, 2001[8]) and accelerating seismic activity of moderate-sized earthquakes (Ellsworth et al. 1981[3]; Keilis-Borok, 1990[6]; Sornette and Sammis; 1995[13]; Knopoff, et al. 1996[7] and Bowman et al., 1998[1]) and equivalently the accelerating seismic moment release (time-to-failure power law)--AMR/AER (Bufe and Varnes, 1993[2]; Bowman et al., 1998[1]: Jaume and Sykes, 1999[5]) prior to large earthquakes. LURR and AMR/AER have been tested with seismological observations by different research groups. In the present work we will test LURR and AMR/AER with the data of acoustic emission (AE) during the rock fracture experiments since there are striking resemblances between acoustic emission (AE) and earthquakes.

A series of experiments with rectangular prisms of three kinds of rocks (Dali marble, Wuding gneiss and Wuding sandstone) have been conducted. There are three large specimens for each kind of rock. The geometry of the large specimen is $105\times40\times10$ cm^3.

The specimen is loaded in two directions: the axial stress σ_1 and lateral stress σ_2. Another principal stress σ_3 is zero so that:

$$\sigma_1 \neq \sigma_2 \neq \sigma_3.$$

In other words, the stress state is really a tri-axial stress state. Under such stress state most of the specimens are broken in shear fracture way.

The loading history in our experiments has two kinds: monotonically loading and cycling loading which are shown in Figure 1 (top chart).

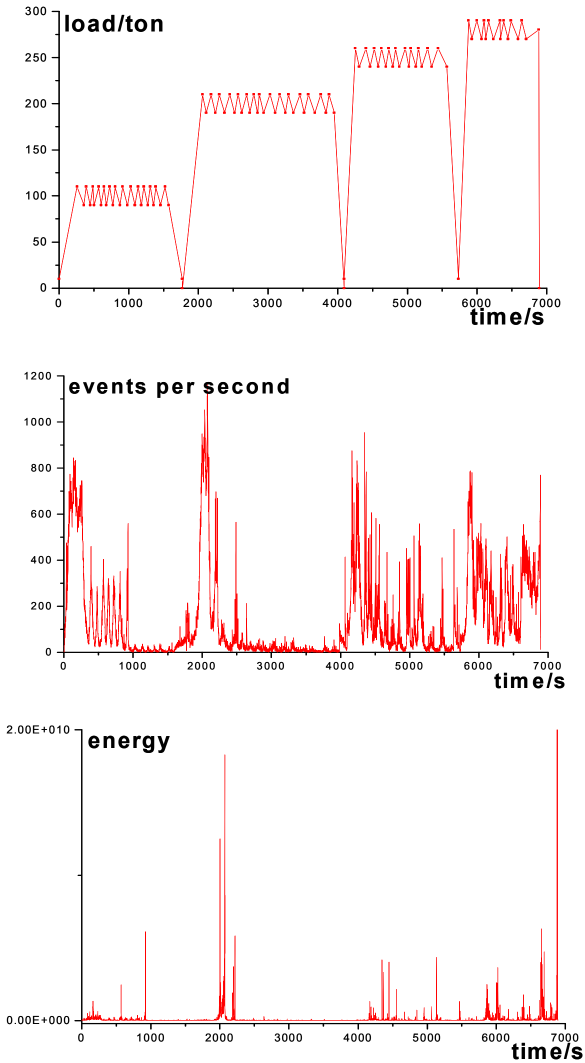

Figure 1: The cycling stress history in experiment and the responding experimental results (AE rate in middle chart and AE energy in bottom one) for Specimen G3

Experiment results

The AE signals are recorded continuously with 《A-line 32D---AE system》made by A.F Ioffe Physical Technical Institute, Russian Academy of Sciences and Interunis Ltd. The A-line 32D---AE system is a 32 channels AE system. Each channel consists of an AE sensor, a pre-amplifier and an AECB board (Acoustic Emission Channel Board).

AE sensor pick up the stress wave from the specimen and convert it into an electronic signal which is then amplified by a preamplifier and converted into a digital data stream in a AESB. AE features such as arrival time, rise-time, duration, pick amplitude, energy and counts are extracted by a FPGA (Field Programmable Gate Array). In parallel to the feature extraction, the complete waveform can also be stored and recorded.

In the mean time AE events can be located in real time and can be shown on the screen and recorded.

The experimental results of cycling loading are shown in Figure 1.

LURR

The Load-Unload Response Ratio (**LURR**) is defined as

$$Y = X^{+}/X^{-} \tag{1}$$

Where, X^{+} and X^{-} are the response rates during loading and unloading according to some measure. The idea that motivated the LURR earthquake prediction approach is that when a system is stable, its response to loading is nearly the same as its response to unloading so LURR ~ 1, whereas the response to loading and unloading becomes quite different and LURR >1 when the system is approaching an unstable state.

High LURR values indicate that a region is prepared for a strong earthquake. In previous years, a series of successful intermediate-term predictions have been made for strong earthquakes in China and other countries using the LURR parameter (Yin and Yin, 1991[17]; Yin, 1993[18]; Yin et al., 1994[19]; Yin et al., 1995[19]; Yin et al.， 2000[20]). Usually the released seismic energy is adopted as the “response” and then the LURR is defined as:

$$Y = \frac{\left(\sum_{i=1}^{N^{+}} E_i^{m}\right)_{+}}{\left(\sum_{i=1}^{N^{-}} E_i^{m}\right)_{-}} \tag{2}$$

where, E denotes released seismic energy, the sign “+” means loading and “–” means unloading, m=0 or 1/3 or1/2 or 2/3 or 1. When m=1, E^m is exactly the energy itself; m=1/2, E^m denotes the Benioff strain; m=1/3, 2/3, E^m represents the linear scale and area scale of the focal zone respectively; $m=0$, Y is equal to $N+/N–$, $N+$ and $N–$ denote the number of earthquake occurred during the loading and unloading duration respectively.

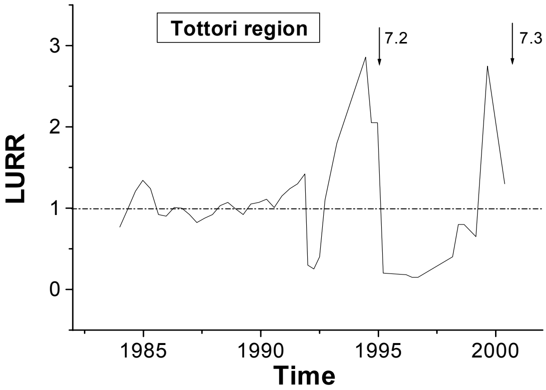

Figure 2: The LURR anomaly prior to the Kobe earthquake and the Tottori earthquake.

Typically the Y-t curve is like that of Figure 2. While the LURR reaches to a high value several months or years prior to the occurrence of strong earthquake, in the eve of large earthquake the LURR decrease to a low level and then the large event occurs.

The results of LURR in this experiment are shown below in Figure 3 for sample G3 (large specimen). Prior to the final fracture of the specimen the LURR reach to a high value, then the LURR decreases and followed by the occurrence of macro-fracture. The experimental results coincide with the seismological observation very well. It suggests that both the Macro-fracture and the earthquake have the CP (Critical Point) behavior.

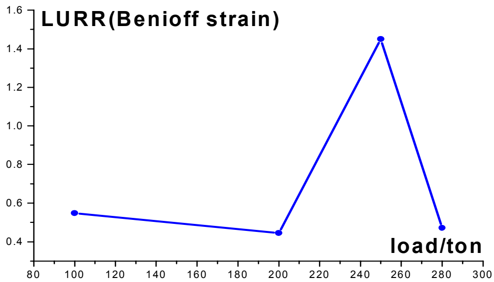

Figure 3: The LURR in rock fracture experiment (specimen G3)

AER (Accelerating Energy Release)

Prior to the occurrence of a large or great earthquake the seismic energy release accelerates. In many cases this acceleration can be modeled using a modified power-law time-to-failure with log periodic oscillation. The function has a form:

$$\sqrt{E} = A + B(t_c - t)^z (1 + C\cos(2\pi \frac{\log(t_c - t)}{\log \lambda} + \psi)) \qquad (3)$$

where E is the cumulative seismic energy, t_c is the time of large earthquake, t is the time of the last measurement of E and A, B ,C, ψ , λ and z are constants.

Figure 4 is the experimental results of specimen G1 that indicate the experimental energy release curves fit the pattern of ARE very well. Therefore our experiment results support the CPH once again.

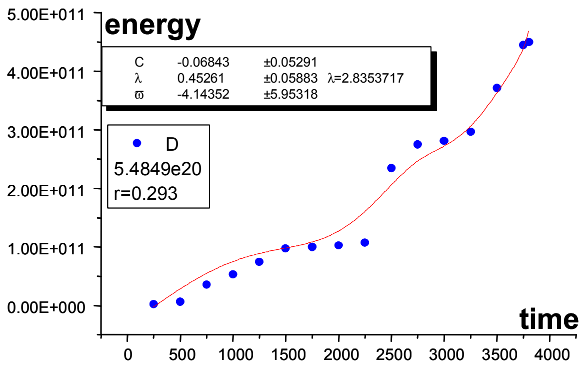

Figure 4: The curve of AER in rock fracture experiment.

State Vector

State vector is an idea stemming from statistical physics (Reichl, 1980[9]). Here it is used to describe the evolution of damage in rock specimen. The whole specimen can be divided into n regions. A specified physical parameter concerned the micro-damage (say AE energy or AE rate etc) in region i at time t_k denotes the i-th component of an n-dimension state vector $\boldsymbol{V_k}$. State vector $\boldsymbol{V_k}$ at time t_k is a point in the n-dimension phase space. Different State vectors $\boldsymbol{V_k}$ at different times form a track in the phase space. The track could be a tool to describe the damage evolution in experiment. For example, the included angle φ_{ij} between $\boldsymbol{V_i}(t = t_i)$ and $\boldsymbol{V_j}$ $(t = t_j)$ mirrors the change of damage pattern of the specimen from t_i to t t_j.

In the experimental course of the specimen M1 the angle $\varphi_{ij}(t)$ against time is plotted as Figure 5. At the first stage no interaction occurs among the microcracks in the specimen so that $\varphi_{ij}(t)$ just fluctuates at a low level. As long as the microcracks begin to interact, the damage states of different regions change severely so that the curve appears a peak. Then the final fracture occurs.

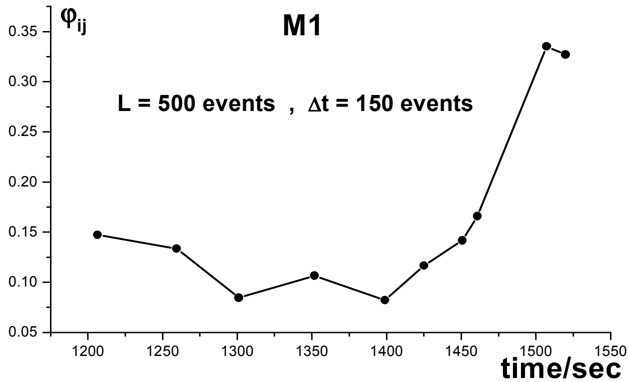

Figure 5: φij (t) as a function of time for marble specimen (M1)

Summary

The LURR theory and the AER (hence the critical point hypotheses) are confirmed with our experimental results and the state vector could be a novel measurement to describe the damage evolution or the seismogenic process for a specified region.

Acknowledgments

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