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Experimental research on critical point hypothesis^{*}

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Abstract

According to the critical point hypothesis (CPH), energy release would accelerate in power law before occurrence of large earthquakes or failure of brittle materials. In the paper, CPH was studied by acoustic emission experiments of large-scale rock samples. Three kinds of rock samples were used in the experiments. The tri-axial loading condition was applied under different loading histories. The released elastic energy (Acoustic emission) was recorded with acoustic emission technique as microcracks emerged and developed inside the rock samples. The experimental results gave a further verification on the CPH. The elastic energy release of rock samples would accelerate before the failure even under different experimental conditions. Primary studies were also made on medium-term earthquake prediction by using accelerating energy release (AER) in the paper.

Key words: critical point hypothesis; accelerating energy release; acoustic emission; earthquake prediction
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Introduction

Earthquake is a kind of severe natural disaster. In order to predict earthquake effectively, the geoscientists at home and abroad have carried out a great deal of studies on seismicity. For example, Willis, (1924) and Tocher (1959) made some early investigations on seismicity before large earthquake. Chinese geoscientists performed even more studies in this field (CHEN, *et al*, 1981; HUANG, FENG, 1981; LIU, 1982; LU, 1985; LU, *et al*, 2001; MA, *et al*, 1982; MEI, 1960; MEI, *et al*, 1993; YIN, 1987; ZHANG, 1987; ZHANG, FU, 1985). However, the damage and failure of

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source media is usually a nonlinear process far from equilibrium along with random distribution of initial defects. All these make earthquake prediction extremely difficult. Up to the present, earthquake is hard to predict effectively. Therefore, People have to seek one or more physical parameters or methods, which may reflect the evolution of earthquake quantitatively. Then these parameters or methods can be used to predict earthquake.

Mogi (1969) had found that before great earthquakes, seismicity would increase remarkably, especially moderate earthquakes. Then Vere-Jones (1977) first put forward the concept of critical point. In recent years, more and more researchers accepted this idea with the deepening of research work in this field. Thus the critical point hypothesis (CPH) was founded (Sornette, Sornette, 1990; Sornette, Sammis, 1995; Sammis, Smith, 1999, Bowman, *et al*, 1998; Knopoff, *et al*, 1996; Rundle, *et al*, 1999; Jaume, Sykes, 1999; WU, 2000). According to the CPH, the crust does not always stay in a critical state. The occurrence of a great earthquake in a region will rescue the crust from the critical state. Then as tectonic stress increases, the crust will be driven back towards the critical state.

After proposing CPH, many researchers used their own mechanical models or computational methods to research it. Smith and Phoenix (1981), Curtin (1991) and Newman & Phoenix (2001) studied CPH by using the fiber model. They investigated the elastic energy release during the failure process of materials. Turcotte *et al*. (2002) and Ben-Zion and Lyakhovsky (2002) also performed analogous investigation on CPH. They got the analytical expression of energy release process under constant loading. The results indicated that prior to the failure of materials, energy release would accelerate in the form of power law. Whereas deeper research on CPH needs analyzing further the mechanism of entire damage process of solid medium in the earthquake region. With regard to rock materials, the emergence, progression, accumulation and clustering of microcracks lead to failure. Prior to the failure of materials, distinct critical phenomena will appear, which can be considered as precursors for the failure of rock materials and occurrence of large earthquakes (Sornette, 2000). According to the CPH, prior to the failure of rock materials or large earthquakes, there exist two kinds of precursors that comprise the growth of correlation length and increase of critical sensitivity. Load/unload response ratio (LURR) and accelerating energy release (AER) are two precursors easier to use. They reflect the changing critical sensitivity (Xia, *et al*, 2002; Yin, *et al*, 2002) and growing correlation length, respectively. The experimental research on LURR was discussed in another paper (YU, *et al*, 2003). In the paper, we will make an experimental research on AER.

With respect to the experimental research on AER, the forerunners in this field have done much work. Hirata, *et al* (1987) used acoustic emission (AE) to investigate the damage process of brittle materials. They found that at the beginning of loading process the microcracks were discrete. With the increase of load, the microcracks would increase in the form of power law prior to the failure of materials. Garcimartin, *et al* (1997) made experiments on the rupture of fiber-glass composites and also confirmed this critical scenario. Johansen & Sornette (1998) analyzed the AE recorded during the pressurization of spherical tanks. He also found there was a clear acceleration in the form of power law in the energy release of tanks prior to failure. However, these experiments were only performed to investigate the instances of engineering structural materials undergoing tensile rupture, rather than the situations of materials being pressed to rupture, especially the cases that tri-axial loading condition was applied to rock materials.

In view of the above-mentioned facts, we performed large-scale AE experiments in order to further investigate the energy release process of rock materials that were pressed to rupture. In the

experiment, large-scale rock specimens (105 cm in length) were subjected to the tri-axial loading condition. The experiment was conducted by international cooperation. The participants included Laboratory of Nonlinear Mechanics LNM, Institute of Mechanics, Chinese Academy of Sciences; Center for Analysis and Prediction, China Earthquake Administration; Ioffe Physical Technique Institute, Russian Academy of Sciences; Ibaraki University, Japan; Peking University; Earthquake Administration of Yunnan Province and so on. The AE system from Ioffe Physical Technique Institute, Russian Academy of Sciences was used to record the time, location and intensity of micro-cracks within the rock samples. The parameters of AE signals were output in digital form. The AE signals recorded in this way were far more than those recorded in the traditional waveform way. The large-scale rock samples used in the experiment could enhance relative accuracy of locations evidently, thus it would be easier to analyze the recorded information quantitatively.

Furthermore, according to the experiment, the damage rheology model proposed by Lyakhovsky, *et al* (1997a, b) was used to give numerical simulation on the important critical phenomenon that elastic energy release would accelerate prior to the failure of brittle homogeneous materials. The relating results will be discussed in another paper.

1 Experimental system

In our experiments, three kinds of rock materials were used and each had two specimens with a total number of 6. The dimensions were 105 cm×40 cm×15 cm for sandstone, 105 cm×40 cm×10 cm for gneiss and 105 cm×40 cm×10 cm for marble. The physical parameters of three kinds of rock materials are shown in Table 1.

Table 1 Essential physical parameters of rock specimens

Type of samples	Elastic modulus $E_0/10^4$ MPa	Lamé constant 1 $m/10^4$ MPa	Lamé constant 2 $l_0/10^4$ MPa	Poisson ratio ν	Density $\rho/10^3$ kg·m ⁻³	Wave speed c/m·s ⁻¹
Sandstone	11	4.36	4.73	0.26	2.2	2150
Gneiss	5	1.92	2.88	0.3	2.6	3200
Marble	4.5	1.35	1.86	0.21	2.1	3500

The pressure was subjected by tri-axial loading equipment (Changjiang 500 omnipotence experimental equipment). The rock specimens were subjected to both axial load S_1 and lateral load S_2 simultaneously (Figure 1). The lateral load S_2 was symmetrically applied to sample with steel plates on two smaller sides and retained at a constant of 60 t (the maximum lateral load capacity was 100 t). The other lateral load S_3 equaled to 0. Thus the three principle stresses were not equal ($S_1 \neq S_2 \neq S_3$).

The axial loads were subjected in two manners, one was monotonous ($S=b \times t$) and the other was cyclic. In this way, the critical phenomenon of accelerating energy release could be investigated. Figure 2 shows the cyclic load manner. The whole loading process can be divided into several stages. In each stage, the load is cycled by triangular oscillations with the amplitude of

Figure 1 Dimension of specimens, loading condition and distribution of AE sensors
O represents the location of sensors

Figure 2 Cyclic loading of rock specimens

10 t. Shearing fracture occurs in the last stage for all specimens.

The AE equipment (12 digits, 16 channels) of Ioffe Physical Technique Institute, Russian Academy of Science was used to investigate the time, location and intensity of microcracks within rock samples. 10 piezoelectric transducers resonance from 50 to 250 kHz were attached directly onto the rock sample surface ('o' represents the location of transducer in Figure 1), 5 on each side. They were used to

monitor the high-frequency AE generated in the sample as it was stressed. The nucleation and growth of microcracks were represented by AE events. Thus we were able to investigate the nucleation and growth of fracture by acquiring and analyzing AE signals (Lockner, *et al*, 1991; Lockner, 1993; Tomilin, *et al*, 1994).

After amplification and filtration, AE signals were sent to processor to be analyzed and disposed. Then the correlative parameters of AE signals, such as arriving time, energy, amplitudes, 3D coordinates of hypocenter and so on, were output in digital form. This method made AE-signal to be monitored much more efficient. In our experiment, more than 10^5 AE signals were recorded for a specimen. 3D locations were determined by correlative parameters of the recorded AE signals. The absolute error of AE event locations was less than 10 mm. The usage of large-scale rock samples in the experiment could obviously enhance the relative accuracy of location. As the statements above, AE signal locations could reflect the fracture process of specimen.

2 Data analysis

The energy of AE events recorded in the experiment represented the elastic energy released by rock specimen. Thus we can investigate the evolution of elastic energy release of brittle materials by analyzing the energy of AE events.

The energy accumulated at time t_k can be written as

$$E(t_k) = \sum_{t < t_k} E(t) \quad (1)$$

where $k=1, 2, 3, \dots, n$; $t_k \leq t_c$, t_c is the critical time, $E(t)$ represents the energy of AE events at time t .

The energy release process $E(t_k)$ can usually be fitted by equation (power law) as (Bowman, *et al*, 1998; Sammis, Smith, 1999)

$$w_p(t) = A + B(t_c - t)^z \quad (2)$$

where A, B, z are parameters to be fitted, t_c is the critical time. The optimum for A, B, z can be determined by minimizing the variance (Press, *et al*, 1986).

During the damage evolution process, since the solid materials are highly heterogeneous, the timescales of local damage evolution are various. With respect to the whole system, the damage process evolves according to a period, but this period will be influenced by the variety of timescales of local damage evolution. Consequently, the energy release process would display some

oscillations around the theoretical power-law fit (Figure 5b) rather than evolve according to a single period. However, using equation (2) to fit the energy release process is hard to meet these oscillations. In order to reflect the energy release process of the whole system more clearly, Sornette and Sammis (1995) and HUANG, *et al* (2000) suggested to allow exponent z to be taken as a complex values $z+iw$. Thus they can introduce a log-periodic correction to a simple power law and derive a log-periodicity fitting expression as equation (3). If equation (3) instead of the power-law expression is used to fit the energy release process, the evolution of energy release would be better fitted as

$$w_{lp}(t) = A + B(t_c - t)^z \left\{ 1 + C \cos \left[2p \frac{\lg(t_c - t)}{\lg I} + y \right] \right\} \quad (3)$$

where the meaning of parameters A , B , z is the same as that in equation (2). The amplitude of oscillation is bounded by C , which is significantly less than 1 (if $C=0$, equation (3) will simplify to equation. (2)). I describes the wavelength of oscillations in log space. y is a phase shift that depends on the units of time measurement. Among all these parameters, exponent z is of the most importance, which is less than 1. The smaller the exponent z is, the more evidently the energy accelerating release. Therefore, the research on the range of exponent z is one of the key problems to investigate CPH.

In order to test the result of log-periodicity fitting, the same energy release process is fitted using a simple linear relationship. Then we compare the results of linear fitting with that of log-periodicity fitting. Introducing a parameter r

$$r = \frac{D_p}{D_l} \quad (4)$$

where D_p represents the variance of log-periodicity fitting, which can be written as:

$$D_p = \sqrt{\frac{\sum_{i=1}^n [E(t_i) - w_{lp}(t_i)]^2}{n}} \quad (5)$$

D_l denotes the variance of linear fitting. The expression of D_l is similar to that of D_p .

If r is close to 1, a linear fitting explains the energy release process, which makes it difficult to argue for an accelerating energy release. On the other hand, if r is significantly less than 1, then the use of log-periodicity fitting is a significant improvement in describing the energy release process. This implies that the energy release obviously accelerates in the form of a power law.

The energy release processes of specimens ($E(t_k)$, $k=1, 2, 3, \dots, n$) and their log-periodicity fitting in the experiments are shown as follows (Figures 3 and 4).

Figure 3 Energy release and its log-periodicity fitting of sample 1
(Sample1: sandstone, monotonons loading, $z=0.21$, $r=0.316$)

Figure 4 Energy release and its log-periodicity fitting of samples 2~5

(a) Sample 2: sandstone, cyclic loading. $z=0.49$, $r=0.58$; (b) Sample 3: gneiss, monotonous loading. $z=0.38$ and $r=0.40$; (c) Sample 4: gneiss, cyclic loading. $z=0.38$, $r=0.39$; (d) Sample 5: marble, monotonous loading. $z=0.32$, $r=0.28$

Sample 6: The loading history is more complex as shown in Figure 5a. The material is marble. The energy release process and its log-periodicity fitting are shown in Figure 5b. Exponent $z=0.35$, $r=0.43$.

Figure 5 Axial load of sample 6 (a); Energy release and its log-periodicity fitting of sample 6 (b)

3 Discussion

According to CPH, prior to the failure of brittle heterogeneous materials, the energy release would accelerate. Based on this theory, many scientists have performed their studies. Turcotte, *et al* (2002) used the fiber model to investigate the energy release process of materials. They found that under the constant load, the exponent $z=1/3$. Ben-Zion and Lyakhovsky (2002) used earth-

quake cases to research the exponent z and found it in the range of 0.1 to 0.55. Rundle, *et al* (2000), Bowman, *et al* (1998) and Sornette (2000) also studied exponent z and got the analogous results. Using different kinds of rock materials with different load histories, our experimentally measured z -values were 0.21, 0.49, 0.38, 0.38, 0.32 and 0.35 (the average was 0.35 that is close to $1/3$). These values fluctuated around $1/3$. Our results were consistent with the results mentioned above. YU, *et al* (2004) also got the analogous conclusions by analyzing the exponent z of $M \geq 7.0$ earthquakes in Chinese mainland. Then minimum and maximum exponent z in the experiments were 0.21 and 0.49, respectively. The range of exponent z was consistent with that of earthquake cases.

On the other hand, Bowman, *et al* (1998) found the r -values are usually within 0.4~0.6 by investigating several earthquake cases. The r -values of our experiments were 0.32, 0.58, 0.40, 0.39, 0.28 and 0.43. All these r -values are much less than 1, which indicate that the energy release process is better fitted by the log-periodicity expression. The values of exponent z were also much less than 1. Therefore, all the experimental results have shown a distinct precursory acceleration of energy release.

In a word, from the range of exponent z we can get the conclusions that prior to the failure of materials or the occurrence of large earthquakes, energy release will accelerate. The range of exponent z usually fluctuates around $1/3$, depending on the material or geological makeup. The range of exponent z in our experiments can be used for reference to that of earthquake events.

4 Attempt of applying AER to mid-term earthquake prediction

If exponent z is determined, we can make a prediction on the time and magnitude of macrofracture or the occurrence of large earthquakes using equation (2). Here is our primary research on the seismicity in some districts using this method.

As a retrospective study, we studied the Kunlun Mountain $M=8.1$ earthquake (with epicenter on 35.93°N ; 90.53°E). We chose the $M \geq 5.0$ earthquakes with the distance of 8° from the epicenter to research the Benioff strain release process. We got $z=0.48$ from the fitted results based on the data within that district. Then, using the data from 1989 to 2000 we could "predict" the coming earthquakes in this district (Figure 6a, b). We "predicted" that from August 2000 to May 2003, there would be an earthquake of $M=8.0\sim 8.7$. On November 14, 2001, Kunlun Mountain earthquake actually occurred in this district with the magnitude of 8.1. Furthermore, the method was used to investigate the seismic activity in some district of Chinese mainland and Sendai district, Japan (YU, 2004).

The results obtained are tentative. As a new method of earthquake prediction, although AER can relatively quantitatively predict whether an earthquake might occur or not in a district, its validity requires more practice to test. If AER is integrated with other earthquake precursors, such as LURR (YIN, YIN, 1991; YIN, *et al*, 1995; 2002; 2003) and so on, the reliability of earthquake prediction could be increased. Hence, earthquakes may be more accurately predicted.

5 Conclusions

Here we investigate CPH by experiments. Although the physical parameters of rock materials and loading history were divergent, prior to the failure of every specimen, the elastic energy release did accelerate in the form of power law. These evolution processes of AER indicate that it could serve as a precursor to predict the fracture of heterogeneous brittle media and the occurrence

of earthquakes.

Figure 6 Power-law fitting of Kunlun Mountain (a); Predicted results before Kunlun Mountain $M=8.1$ earthquake (b)

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