NUMERICAL STUDIES OF SEISMIC PATTERNS AND FAILURE PROCESS IN RELATION TO HETEROGENEITY OF ROCKS

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ABSTRACT:

Seismic pattern is one of the most promising subjects in earthquake prediction studies because it generates information about physical conditions such as the degree of heterogeneity in the source region of an impending large earthquake [1]. According to the statistical studies in nature, there exist three types of seismic patterns: (1) main shock-aftershock type, (2) foreshock-main shock-aftershock type, and (3) swarm type. The foreshock as a precursor can be used to predict a major earthquake. However, what makes the seismic patterns different? Many scientists investigate the seismic patterns through experimental or theoretical method [2]. However, the theoretical models are difficult to deal with the rocks with some discontinuities. Almost no convenient experimental method is available to obtain the stress field information and the progressive failure process image in heterogeneous rocks. Therefore, the physical mechanism of precursory occurrence is difficult to be fully understood. Numerical simulation can provide much information regarding the stress distribution and the failure-induced stress redistribution. In this work, a series of numerical model tests were performed to investigate the effects of the heterogeneity of rocks on the rock failure and induced seismic patterns using the Rock Failure Process Analysis code (RFPA2D). It suggested that rock failure with the different heterogeneity produces different seismic sequence types, similar to the above-mentioned statistical results in nature. That is, type (1) occurs in more homogeneous cases, (2) in moderately heterogeneous cases, and (3) in extremely heterogeneous cases. Besides, the numerical simulation displays that the non-linear behavior of rock deformation and failure mode are clearly influenced by the heterogeneity of rocks. With the increase of the degree of rock homogeneity, the macroscopic failure process presents obvious brittle behavior.

KEYWORDS: Numerical simulation, heterogeneity, seismic pattern, rock failure

1. INTRODUCTION

Seismicity pattern is one of the most promising subjects in earthquake prediction studies because it generates information about physical conditions such as the degree of heterogeneity or the state of stress in and around the source region of an impending large earthquake (MATSU’URA, 1986). Besides, the studies of earthquake patterns are also of help to understand the seismic geotectonics and to reduce earthquake hazard. According to the statistical studies in nature, there exist three types of seismic patterns: (1) main shock-aftershock type, (2) foreshock-main shock-aftershock type, and (3) swarm type. The foreshock as a precursor can be used to forecast a major earthquake. As stated above, much important information is included within seismic patterns. However, what makes the seismic patterns different? For this, many scientists investigate the seismic patterns through experimental or theoretical method. MOGI (1962) has taken up glass as the simplest example to track the precursory phenomena (such as foreshocks) experimentally prior to main shock, but failed because glass breaks suddenly without any advancing warnings. For this issue, a serious dispute about earthquake prediction has been provoked among the seismic peers. Extreme pessimism has predominated at times according to the view that earthquakes are a kind of sudden fractures on the basis of experimental observations of glass or glass-like fractures. Sometimes the optimism has prevailed from a few cases to be predicted successfully based on some precursors such as foreshocks prior to those earthquakes. We know that the possibility of earthquake prediction is decided by whether or not precursory phenomena occur and whether it is possible to observe them. However, the crustal medium is not, after all, the glass or glass-like materials. The possibility still exists of observing precursory phenomena prior to earthquakes. In fact, the observations have provided us many useful cases. For example, obvious foreshock activities are observed before Haicheng earthquake Ms.7.5 in 1975, Liaoning province, China, which is renowned as the first successful example of earthquake prediction in a practical sense.

Mogi (1963) carried out fracture experiments on various types of brittle materials with different degrees of heterogeneity. It shows that three types of acoustic emission sequences have been found: (1) Main shock-aftershock type, (2) Foreshock-main shock-aftershock type, and (3) Swarm type. It comes to the conclusion that these types are the result of differences in the structural heterogeneity of the medium. That is, type (1) occurs in homogeneous cases, (2) in moderately heterogeneous cases, and (3) in extremely heterogeneous cases. Based on the observational results, it was discovered that the types of natural earthquake sequences in China and in Japan indeed was classified into the three types (1), (2) and (3) and that these types do not occur randomly in spatial terms but show a distinct regionality (Mogi, 1985).

A special seminar is held on May 11-12, 1998 in Nikko, Japan, where systematical discussions on this topic are made and papers were published on the journal " Pure and applied geophysics" in Vol.155 of 1999. One discussion was conducted on the topics of ‘‘Foreshocks, their Recognition and Properties’’. Six papers discussed the topic of foreshocks based on observations.

TANG (1993) has given the analytical explanations based on a simple mechanical model for the testing of machine-specimen system. Firstly, the instability behavior of this system is approached by determining the deformation rate of the rock specimen. As the deformation rate is strongly related to the patterns of acoustic emissions, the relation between the counts of acoustic emissions and the statistical distribution of the local strength of rock can be established, in which the fact is considered that the acoustic emissions are transient elastic waves due to the local damage of rock. Then, the seismic events as a function of time can be derived with the help of the deformation rate of rock under certain loading conditions. The analytical results show a good agreement with the experimental and observational ones.

However, the theoretical study concerning the AE response (the law of AE) of geologic materials, especially acoustic emission sequences is quite a shortage in the existing literatures. We know the analytical models have to be simplified and inevitably ignore some key factors influencing the material behavior, such as the heterogeneity. In many cases, the analytical models cannot deal with the rocks with some discontinuities. Although many conclusions given here may be obtained by the laboratory tests, almost no convenient experimental method is available to obtain the stress field information and the progressive failure process image during the failure in heterogeneous rocks. Therefore, the physical mechanism of precursory occurrence is difficult to be fully understood. Numerical simulation can provide much information regarding the stress distribution and the failure induced stress redistribution. In this paper, we use the code of RFPA^{2D} (Rock Failure Process Analysis code), which can both consider the heterogeneity of the medium and generate the acoustic emission (AE) data during the rock failure process (Tang, 1997).

2.MODEL DESCRIPTIONS

2.1. Brief Introduction to RFPA^{2D}

Based on the linear finite element method, RFPA code is a two-dimensional package for the analysis of rock failure process. The program allows to simulating the progressive failure of brittle rock from initial micro-failure to collapse by virtue of a simple approximation that gets rid of the numerical complexities of non-linear and discontinuum codes. Besides, the code has also been developed by considering the deformation of an elastic material containing an initial randomly distributed fractures. When load is applied, the fractures will produce, grow, interact and coalesce. As a result, the behavior becomes non-linear and the macroscopic fractures will be formed (TANG, 1997; TANG 1998). For heterogeneity, the most important assumption is given by RFPA that the progressive failure of rock material is caused by the heterogeneity in rock strength. The consideration of heterogeneity for the elements is achieved by assigning the elements random strength and elastic modulus by assuming a Weibull's distribution as defined by the following equation:

$$\varphi(\alpha) = \frac{m}{\alpha_0} \cdot \left(\frac{\alpha}{\alpha_0}\right)^{m-1} \cdot e^{-\left(\frac{\alpha}{\alpha_0}\right)^m} \qquad (2.1)$$

where α is the parameter of element (such as strength or elastic modulus). α_0 is related to the mean value of the material parameters for the elements, such as strength and elastic modulus. m is defined as homogeneity index, which controls the shape of the distribution function relating to the degree of material heterogeneity. According to the above definition, the larger the m is, the more heterogeneous the material is, and vice versa. Φ is the probability density of the element strength (see Fig.1). By choosing a new Coulomb criterion with a tensile cut-off as the failure criterion or threshold, allowing the failure of an element in either shear or tension.

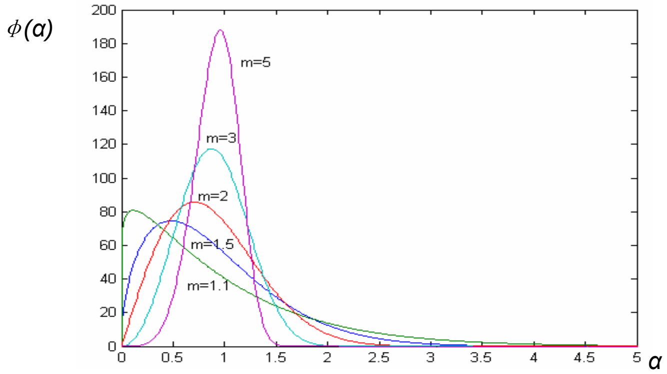


Figure1 Strength distribution for five different heterogeneous specimens

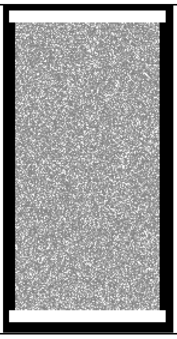
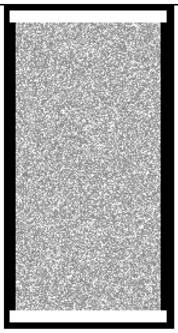
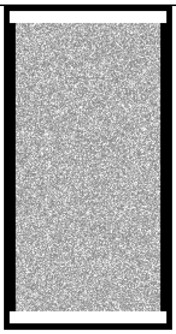
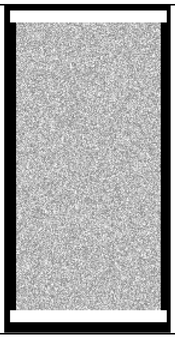
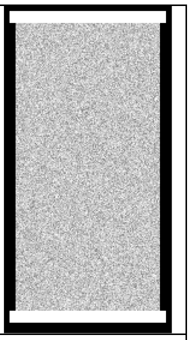
2.2. Model Description

Five specimens with different heterogeneity indices, m = 1.1, 1.5, 2, 3, 5, representing materials from relative heterogeneity to relative homogeneity were numerically studied under uniaxial compression. The mesh for the model is 260 x 130=33,800 elements representing a sample geometry of 26 centimeter's long and 13 centimeter's wide. The geometrical and mechanical properties for all the specimens are listed in Table 1 and Table 2. In the following simulations a plain strain condition is assumed. In this paper, smeared failure approach is used to predict the occurrence of microfracturing when the stress state of an element satisfies a strength criterion. The samples are loaded in a displacement manner at a constant rate of 0.002 mm/step, much like the displacement control in a servo-controlled laboratory test.

Table 1 Material parameters of specimens under uniaxial loading

Parameter	value
Homogeneity index(*m*)	1.1,1.5,2,3,5
Mean compressive strength(σ_0)	200(MPa)
Mean elastic modulus(E_0)	60,000(MPa)
Tension cutoff(λ)	10%
Friction angle(ϕ)	30^o

Table 2 Material properties for specimens in uniaxial loading condition

Specimens for testing influence of heterogeneity on failure mode and strength characterization					
Specimen name	s-h-1	s-h-2	s-h-3	s-h-4	s-h-5
Homogeneity index	m=1.1	m=1.5	m=2	m=3	m=5

3.NUMERICAL SIMULATION RESULTS

Fig.2 shows the b-value data for this simulation exhibit all of the features. During the early quasi-elastic phase of loading, where there is a low level of AE activity, the b-value remains essentially constant. A decreasing b-value associated with increasing stress lead to a lower value at peak stress and the minimum at failure, forming a short-term low b-value anomaly shown by parallel short dash lines in Fig. 2 prior to the main failure. Post-failure the b-value recovers as expected. The result is consistent with that in the real observational cases (Mogi, 1985).

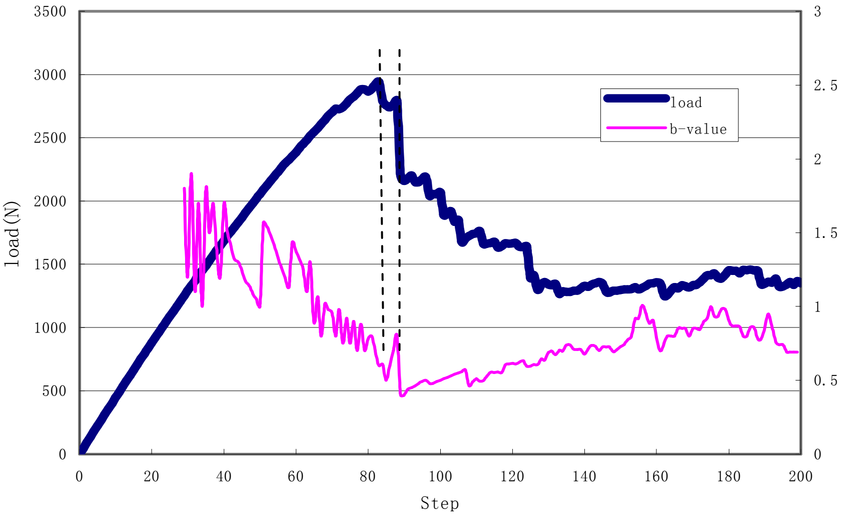
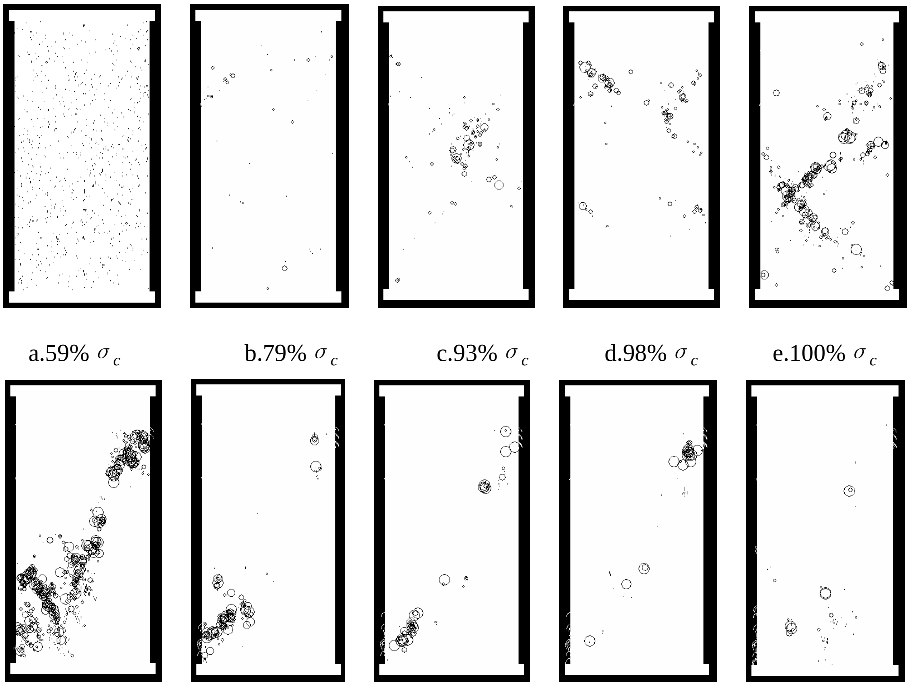


Figure 2 b-value and loading changes vs step for specimen s-h-2

Fig.3 shows the locations of AE events for specimen s-h-2 at different stages of compression. Each circle is one AE event and the size of the circle represents the relative magnitude of the AE released energy. When the applied loading increase up to 59% peak stress, the AE locations for events occurred as shown in Fig.3a, where the AE events are rondomly distributed throughout the specimen, reflecting the statistically uniform deformation during the initial linear elastic phase. At this phase, it is difficult to predict where the macro-fracture will appear. When the loading reaches to its 98% peak strength, more and more AE events tend to cluster around a newly formed zone that seems to become the potential macroscopic faults in the coming failure process (stage d). However, what is more interesting is to find that another newly-formed zone to be more active for AE events is not in the expected site shown in stage d but in a zone nearly perpendicular to the fracture zone produced in stage d as shown in Fig. 3e, suggesting that not all clustering zones of AE events become finally large faults. Conversely only a few major large faults develop in the failure process of the specimen. Consequently, it is difficult to predict the place of a large fracture at this stage. It is believed to be the result of stress redistribution or stress transference from the stress-released area to its adjacent stress-accumulated area, where a higher stress will be built up. Finally, a micro-seismic fault developed along the diagonal line from the upper right corner to the bottom left corner (Fig. 3f). The RFPA code simulated the whole failure process of the rock specimen.



a.59% σ_c b.79% σ_c c.93% σ_c d.98% σ_c e.100% σ_c

f.95% σ_c g.70% σ_c h.63% σ_c i.56% σ_c j.49% σ_c

Figure 3 Plots of simulated AE locations for the specimen s-h-2.

4.DISCUSSION

4.1 Complete Stress-strain Curve in Relation to Heterogeneity

The dependence of the characteristics of stress-strain curves on the heterogeneity of specimens was studied using five specimens with different homogeneity indices as given in Table 2. The simulative complete stress-strain curves for the specimens are shown in Fig.4. Obviously, the stress-strain relation and the strength characterization depend strongly on the heterogeneity of the specimens. It can be seen that the shape of the relatively heterogeneous rock (e.g. m=1.1) has a gentler post-peak behavior. However, for more and more homogeneous rocks, the shape tends to become sharper and sharper. Besides, the maximal strength of the specimens is closely related to the homogeneity index m. The higher the value of the homogeneity index m, the higher the strength of the specimen is. As a result, the curve becomes more linear and the strength loss is also sharper in the homogeneity case.

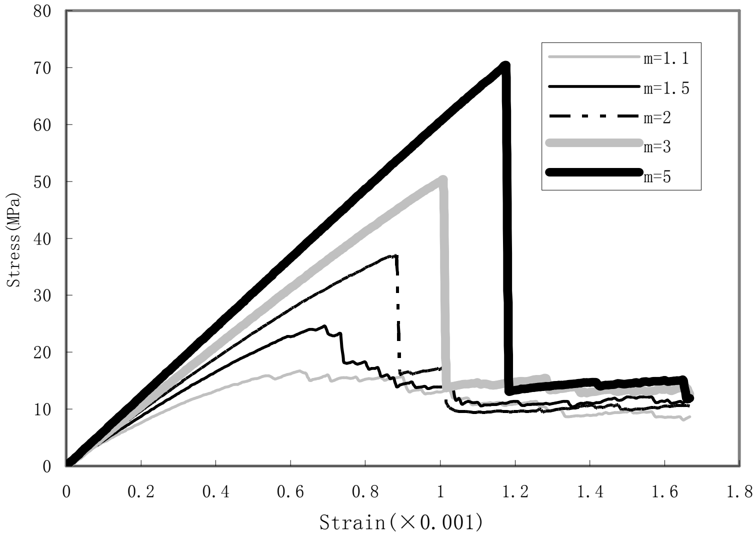


Figure 4 Influence of material heterogeneity on the stress-strain curves

4.2 Temporal Variations of AE Event rate And Their Relation to the Heterogeneity

The AE seismic patterns for specimens with different homogeneity index m are shown in Fig.5. When force is

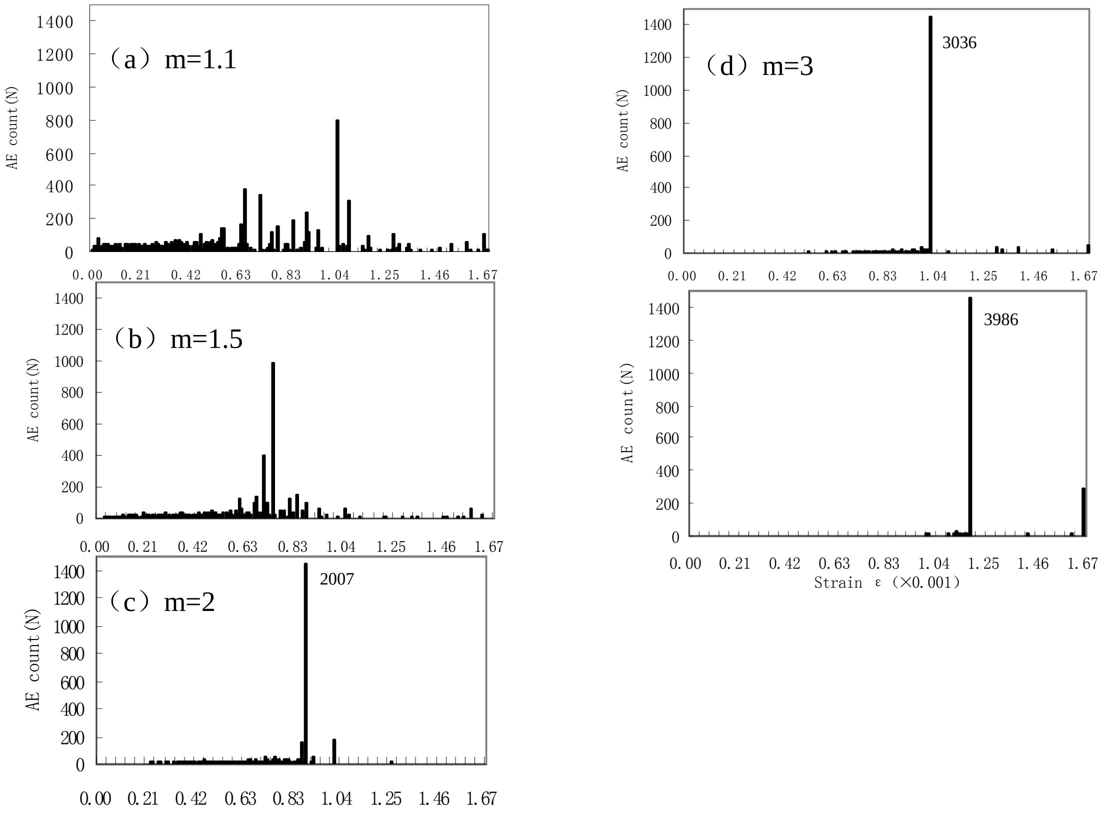


Figure 5 AE seismic patterns for 5 specimens with different homogeneity index m

applied to a heterogeneous rock until it fractures, micro-fractures occur prior to the principal fracture, and these are accompanied by the following various precursory phenomena, such as the AE activity prior to the main fracture, which in greater or lesser degree can also be expected in natural earthquakes and in actual fact have frequently been observed as precursory phenomena of large earthquakes, such as foreshocks as stated previously. Inversely, when force is applied to a homogeneous rock material until it fractures, micro-fractures seldom occur prior to the principal fracture, and these are accompanied by few or no precursory phenomena, such as foreshocks. Besides, the numerical results produced the three types of AE event sequence patterns: (1) main-shock-aftershock type, (2) foreshock-main shock-aftershock type, and (3) swarm type, which has a good coincidence with the natural observations according to the research based on the data of China, Japan or other regions, and these types do not occur randomly in spatial terms but show a obvious regionality. Consequently, it can be concluded that these types are the results of differences in the structural heterogeneity of the medium. Correspondingly the different earthquake prediction strategy is taken according to the different seismic patterns.

4.3 b-value And Their Variations with the Heterogeneity

Seismicity statistics are notoriously unreliable in terms of the accurate prediction of earthquakes because their statistical significance is severely limited by the number and quality of the data. However, in some cases it is possible to establish a numerical model to produce the AE events, further analyzing the relation of AE event rate and magnitude distribution of smaller earthquakes leading up to a main shock and giving the b-value. Besides, It is very significant to study the characteristic of b-value variation versus the heterogeneity for 5 specimens with different heterogeneity index.

For a micro seismic sequence, the b-value is determined by the least multiply method fit. Fig.6 shows the variation of b-value for 5 specimens with the heterogeneity index. It can be seen that the b-value is becoming smaller with the decreasing of heterogeneity index, which is coincident with that of experimental observations. Since b-value is related to failure strength distribution, the stress adjustment of one single element failure easily results in chain response when the difference of strength for each element is smaller, leading to the increase of larger events and decrease of smaller events, and making the b-value decreasing correspondingly. According to the b-value, we can judge the earth crust structure characteristics. It can be concluded that the heterogeneity of rock is the important factor affecting the b-value.

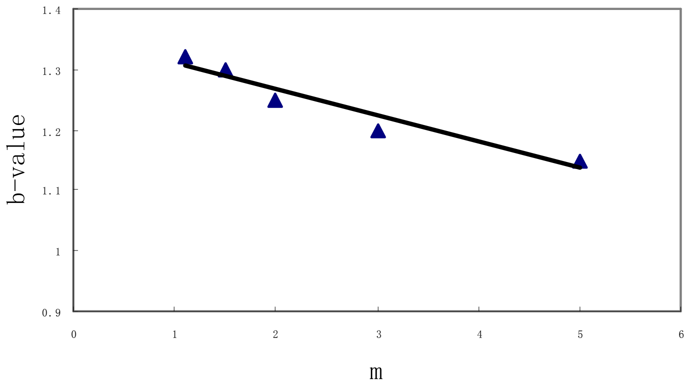


Figure 6 Heterogeneities m versus *b* value

5.CONCLUSIONS

The progressive failure of rock specimens and seismic patterns was investigated by damage-controlled testing of

5 samples under uniaxial condition. The testing was carried out to investigate the influence of mesoscopic heterogeneity on the progressive failure and seismic patterns. The results can be summarized as follows:

1. Heterogeneity plays an important role in determining deformation and strength characterization of specimens under uniaxial loading conditions. More homogeneous specimen shows a higher strength than the more heterogeneous one.
2. The numerical results demonstrate that the AE event patterns are influenced greatly by the degree of heterogeneity of the materials. There are three types of seismic consequence patterns: (1) main-shock-aftershock type, (2) foreshock-main shock-aftershock type, and (3) swarm type, accordingly corresponding to type (1) occurs in homogeneous cases, (2) in moderately heterogeneous cases, and (3) in extremely heterogeneous cases.
3. Heterogeneity of rock is the important factor affecting the b-value. The b-value is becoming smaller with the decreasing of heterogeneity index. Besides, for a specimen with the progressive loading, b-value will increase slowly, reach to the bottom at main fracture and recover posterior to the main fracture. This characteristic of b-value is of help to earthquake prediction.

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