Damage stress and acoustic emission characteristics of the Beishan granite

X.G. Zhao, M. Cai, J. Wang, L.K. Ma

A R T I C L E   I N F O

Article history:
Received 12 October 2012
Received in revised form 8 June 2013
Accepted 1 September 2013
Available online 10 October 2013

1. Introduction

Safe disposal of high-level radioactive waste (HLW) is an important issue and also a challenging task for all countries utilizing nuclear energy. Due to long half-life and high toxicity, the HLW is required to be isolated from the biosphere until its hazard is reduced by radioactive decay so that there is no significant risk to human and the environment. In the international nuclear energy community, deep geological disposal has been considered as a suitable way to deal with HLW. An HLW repository can be constructed in a host rock at a depth of several hundred meters below the ground surface. Different rock types, such as granite, tuff, rock salt, and clay, are being considered as potential host rocks of HLW repositories and extensive laboratory and field studies have been conducted [1–5]. Beishan granite is a preferred candidate host rock for the construction of an HLW repository in the Beishan area, China [6,7]. A better understanding of the mechanical behaviors of the host rock is essential to long-term stability evaluation and engineering optimization of the radioactive waste disposal system in the rock.

Peak rock strength is required in rock mechanics design, and the International Society for Rock Mechanics (ISRM) suggests that uniaxial and triaxial compression tests can be used for its determination. Two peak strength criteria, i.e., the linear Mohr–Coulomb failure criterion and the nonlinear Hoek–Brown failure criterion [8], are widely used in rock engineering. Martin [9] indicated that the peak strength of granite was not a unique material property but was loading condition (such as the loading rate) dependent. The crack initiation stress (σc) and crack damage stress (i.e., long-term strength σcb) during uniaxial compression were found less dependent on loading conditions. The two stress thresholds have been considered as key parameters to describe rock mass responses around underground openings [10,11].

Based on a comparison of the crack initiation measured in laboratory uniaxial compression tests with the spalling strength of crystalline rocks in the field, Martin and Christiansson [12] suggested that the crack initiation stress could provide a lower bound limit for the spalling strength. Using the cracking initiation stress and peak strength, Cai [13] suggested a method to estimate the tensile strength and Hoek–Brown strength parameter m. Hence, it is important to know the characteristic and critical stress levels such as crack initiation stress during rock deformation for engineering design and application.

Description of rock failure process using only conventional stress and strain measurements is not sufficient. The rock failure process is associated with acoustic emission (AE). AE can be defined as the transient elastic wave generated by the rapid release of energy from a source within a material [14]. Due to its high sensitivity to crack initiation, propagation, and coalescence in rocks subjected to loading, AE monitoring provides a powerful tool for investigating brittle rock failure and this technique has been widely used in rock mechanics studies and engineering applications [15–18]. In general, AE event counts, AE count rates scaled with the stress–strain relationship, and source location of the events, are frequently used by researchers to study the rock failure characteristics under different loading conditions. In addition, some waveform parameters involved in the generation of an AE event such as ring-down count, energy, peak amplitude, rise-time and event duration also provide useful information to further investigate rock cracking mechanisms associated with macroscopic deformation and failure. For example, amplitude distributions of AE signals have been used to infer the relationship between variations of AE event magnitudes and failure processes.
of rocks [19]. Based on frequency-spectra analysis of the full-wave AE data, He et al. [20], and Zhao et al. [21] correlated the frequency–amplitude of AE signals with the characteristics of rockburst stages. A schematic illustration of these AE event waveform parameters is shown in Fig. 1, and definitions of the terminologies can be found in [22].

In the present study, experimental investigations into the engineering properties of the Beishan granite have been executed. The objectives of the experiments are to determine damage stress characteristics and to understand the failure process of the rocks using the AE monitoring technique in combination with strain measurement. Real-time spatial distributions of AE events in the rock during uniaxial compression and triaxial compression tests are captured. The identification methods of crack initiation and crack damage thresholds are discussed, and the relationships between confining stress and crack initiation stress and crack damage stress are analyzed. The obtained results will be used in establishing constitutive models for use in numerical codes for the rock response prediction around underground excavations in the site characterization and evaluation of a potential HLW repository in the Beishan area.

2. Description of rock specimens

Drill cores with a diameter of 63 mm were taken from borehole BS06 in the Xinchang rock block in the Beishan area. The sampling depth was from 450 to 460 m below the ground surface. The granite used in the laboratory test was fine-medium-grained (Fig. 2a), and was relatively isotropic in texture and composition with low porosity and water content. The rock density was 2.69 g/cm³, and the average P-wave velocity was 5239 m/s. Based on cross-polarized light observations, a typical photomicrograph of a thin section of the rock was obtained and it showed the microstructure and mineralogical composition of the rock (see Fig. 2b). The rock displayed granular mosaic texture, and was mainly composed of approximately 52% plagioclase, 17% quartz, 15% alkali feldspar, 12% biotite, 3% albite, and <1% myrmekite. Accessory minerals primarily consisted of sphene, apatite, zircon, and magnetite. A total of 42 core-based cylindrical rock specimens with a diameter of 50 mm were prepared. The specimen length was twice the diameter. The tolerance of perpendicularity and flatness of the specimens met the specifications of the ISRM Suggested Method [23]. In particular, the ends of all the specimens were carefully polished to minimize the end effect during loading.

3. AE characteristics of the Beishan granite

3.1. Testing facilities

Uniaxial and triaxial compression tests were carried out using a computer controlled servo-hydraulic compression system. The test system has a maximum load capacity of 2000 kN and can supply a maximum confining stress of 60 MPa. The axial and lateral strains of the sample during loading were acquired automatically by a pair of extensometers located in the middle height of the rock.
sample, and the measurement ranges for the axial and lateral extensometers were ± 2.5 mm and 6 mm, respectively.

In all tests, AE transducers (type Micro30, from American Physical Acoustics Corporation) and a six channel AE signal processing system (PCI-2) were used to record AE data. AE signals obtained from the AE transducers were amplified by a gain of 40 dB in order to filter out the background noise. The trigger threshold of AE was set to 40 dB for each test, and full waveform data were recorded with a data collection rate of 0.5 MHz. In the uniaxial compression test, AE transducers were in direct contact with the rock sample except that a thin layer of Vaseline was applied to provide a good acoustic coupling.

The minimum number of transducers forming an array is determined by the spatial dimension to be measured. In general, if the wave velocity of the rock is known and constant, a minimum of \( N \) sensors are required in the array for an \( N \)-dimensional problem [24]. For a cylindrical rock specimen, at least four transducers are required. Six transducers were used in the present study to increase AE source location accuracy. Three AE transducers were treated as a group and installed evenly in a plane 10 mm away from the end of the specimen as shown in Fig. 3. An unsymmetrical layout of the two groups of transducers was adopted to have a better coverage of the rock volume.

In the present experiment, the AE transducers could not withstand high pressure in the triaxial compression cell. Therefore, in the triaxial compression test, the AE transducers with a similar distribution as that in the uniaxial compression test were magnetically attached to the wall surface of the triaxial cell. It should be noted that the elastic waves generated from rock damage needed to pass the Teflon heat-shrink jacket wrapped tightly around the specimen first, and subsequently the hydraulic oil and the steel wall of the triaxial cell before reaching the transducers. Consequently, the strength of the recorded AE signals was reduced due to the existence of these three media. This meant that the measured AE hits might be less than those obtained from attaching the AE sensors directly to the rock sample, which was impractical for the triaxial test in our study. Fortunately, based on the acquired AE monitoring data, we found that the measurement method used in our experiment had a negligible impact on judging the characteristic stress thresholds and on capturing the AE distribution in the complete process of rock deformation. This meant that the measurement technique was able to provide a feasible means to study AE characteristics of rock failure under confined conditions.

### 3.2. Testing results

#### 3.2.1. Uniaxial compression test

Fig. 4 shows the complete stress–strain relationships and associated AE characteristics for a rock sample (i.e., B506MD-01) tested in uniaxial compression. Several characteristic stress levels could be identified using AE data in combination with the stress–strain curves. \( \sigma_{cc} \) was the crack closure stress level, which was indicated by the end of the initial concave part in the axial stress–strain curve. In this stage, there was often an initial flurry of acoustic emissions due to seating and loading adjustment, as well as crack closure. It is also likely that small cracks may form at a low stress level in areas already weakened prior to or during the sampling process [25]. As shown in Fig. 4b, the relationship between \( \sigma_{cc} \) and axial stress illustrates that the accumulative AE hit counts increased rapidly when load was applied, and the AE rate decreased subsequently to a constant level when linear elastic deformation took place (from \( \sigma_{cc} \) to \( \sigma_{ci} \)).

The crack initiation stress \( \sigma_{ci} \) was defined by the onset of stable crack growth or dilation. AE rate changed at \( \sigma_{ci} \) and it gradually increased as more new cracks were generated and the existing cracks extended their lengths (see Fig. 4b). \( \sigma_{ci} \) could be identified as the point where the AE curve departed from linearity. AE hits started to increase systematically when the applied stress was above \( \sigma_{cc} \). In the test result, a marked increase in AE rate occurred at a stress level of 0.5\( \sigma_{cc} \), where \( \sigma_{cc} \) was the uniaxial compressive strength of the rock. The important feature of stable crack growth is that cracks propagate parallel to the axial stress direction, leading to a decreased velocity of elastic waves in the direction perpendicular to the loading direction [9,13]. Subsequently in our test, AE hits increased drastically when \( \sigma_{cc} \) was reached, as presented in Fig. 4b. From this moment, the crack density was high enough so that cracks started to interact with the neighboring ones, leading to crack coalescence and formation of tensile spalls when loading continues. In addition, the volumetric strain reversal occurred and unstable crack growth began. For this rock sample, the onset of crack damage started at a stress level of 0.8\( \sigma_{cc} \).

When the stress was increased from \( \sigma_{ci} \) to \( \sigma_{ci} \), the volumetric strain change was not large, which meant that rock dilation before the peak stress was relatively small. The maximum AE hit rate was reached when the rock sample entered its post-peak deformation stage (see Fig. 4a). The accumulated AE hit counts in the post-peak deformation stage increased about 5 times compared with the AE hit counts at the peak stress. As the sample was further deformed, the volumetric dilation continued at a high rate because there was no confinement to limit the dilation process. As the specimen gradually disintegrated due to fracture propagation and coalescence, the AE hit rate decreased gradually.

It should be pointed out that the use of AE hits in combination with stress–strain measurements cannot exhibit damage evolution visually within the rock. To further reveal failure characteristics of the Beishan granite at different loading stages, real-time source locating technique was used to find the AE event locations as shown in Fig. 5. The spatial distributions of AE events revealed a good picture of microcrack evolution during the deformation process. It is seen that the local spalling failures in the rock served as sources of stress concentration. As the rock was further deformed, more cracks were generated and the AE event cloud expanded gradually and covered the right side and both ends of the sample, leading to densely distributed splitting fractures. In addition, the rock sample tended to present dispersive microcracking.

![Fig. 3. The designed positions of AE transducers in the uniaxial compression test.](image-url)
throughout each loading stage, indicating that certain amount of the rock’s cohesion strength was lost. Due to space limitation, AE distribution maps for other rock samples cannot be presented but the test results are very consistent.

3.2.2. Triaxial compression test

The triaxial compression tests were carried out under different confining pressures (i.e., 1.0, 2.0, 3.5, 5.0, 10.0, 15.0, 20.0, 30.0 and 40.0 MPa). Observation of the failed rock samples revealed that when the confining stress was increased, there was a gradual change of macroscopic failure modes from axial splitting at low confinements to shear localization at high confinements. At low confinements (0–2 MPa), the failure mode was dominated by splitting or spalling failure, accompanied by a large dilation as previously described in the results of uniaxial compression tests. When the confining stresses were further increased, a transition from axial splitting to shear failure occurred. Without loss of generality, the relationship between axial stress, strain, AE hit counts and AE source locations of a rock sample (BS06MD-24) at a confinement of 10 MPa was used to analyze the deformation process of shear failure, as presented in Figs. 6 and 7.

The development of AE hit counts during rock deformation was similar to that in the uniaxial compression test. The accumulated number of AE hits before the peak stress was small compared with that recorded at the post-peak stage where large rock dilation took place, especially during the process of strain localization. When the load reached the residual strength, the AE hit rate was more or less constant and the volumetric dilation rate eventually approached zero (see Fig. 6a). A zoomed-in plot was used to determine the crack initiation and crack damage stresses, as shown in Fig. 6b.

The 3D locations of accumulated AE events were used to visualize the gradual formation of the shear band (see Fig. 7). Before the peak strength, there were no clusters of AE events, and AE events were randomly distributed in the sample. The relatively uniform and diffuse distribution of AE events throughout the sample indicated that strain localization was a post-peak phenomenon. The number of AE events was high when the crack damage stress was reached; thus it was easier for adjacent cracks to interact with each other when the stress is higher than the crack damage stress. Once the peak stress was experienced, more events were generated and the cracks concentrated on or near a potential shear plane (Fig. 7d). Subsequently, the crack density in this region increased drastically, starting first at the lower right end and then expanding to the top left corner of the sample (Fig. 7e). As a consequence, a macroscopic shear fracture was formed (Fig. 7f–h). A detailed examination of the shear plane revealed that the shear fracture was formed due to the coalescence of many axially aligned microcracks (Fig. 7i), which were tensile in nature. This supports the notion that shear failure in brittle rocks is in fact caused by tensile damage accumulated in the rock during deformation.

It should be noted that the location accuracy of AE events in the confined test was not high due to the fact that the four different media (rock, Teflon, silicone oil, and steel) had different wave velocities. As a result, the AE signals were sensed from an “anisotropic” material. In addition, the used AE system only allowed the user to input the wave velocity parameter for a single medium. Hence, there existed a small error in the AE locations when compared with those in the unconfined test. Although the
Accumulative spatial distribution of AE events in the rock sample at different stress levels under uniaxial compression condition. (a)–(j) respectively correspond to points $\sigma_1$ to $\sigma_1$ in the complete stress–strain curve shown in Fig. 4a, and tested rock sample (k) indicates spalling failure (l) and splitting fractures approximately parallel to the direction of axial stress (m).
shear failure under confined conditions is captured reasonably well using the proposed method, further efforts are needed to produce innovative design for conducting direct AE measurements inside the triaxial cell.

4. Damage stress of the Beishan granite

4.1. Identification of crack initiation and crack damage stresses

In the experimental results presented in Section 3, the crack initiation, crack damage and peak stresses at different confinements were obtained. Among the three characteristic stress thresholds, the peak strength is the easiest to be determined and this task can be achieved even without strain measurement. The crack damage stress can be determined either from the reversal point on the volumetric strain–axial strain plot or from the intersection of the cumulative AE hit lines that clearly defines two constant AE rates before and after the crack damage threshold, as shown in Figs. 4 and 6. The crack damage stresses determined by the two methods for the uniaxial and triaxial compression tests are presented in Fig. 8a and b, respectively. It is seen that both methods produce consistent $\sigma_{cd}$ values with acceptable deviations. This conclusion is in agreement with that drawn from the triaxial compression test results of rock salt in which both methods were used to determine $\sigma_{cd}$ [26]. Compared with the AE technique, the volumetric strain method tends to be more objective because $\sigma_{cd}$ can be precisely registered from the maximum volumetric strain point whereas the AE method requires the user to define two lines that have constant AE rates before and after the crack damage threshold. Thus, the AE method is less objective compared with the volumetric strain method, and the error introduced might be high. When the stress–strain relationships are not available, the AE measurement can be employed to determine the crack damage stress threshold in compression tests. In the following discussion, the crack damage stresses obtained from the volumetric strain method are used.

Over the last 40 years, various methods have been proposed to establish crack initiation threshold in laboratory compression tests involving stress and strain measurements [22,27–31]. Compared with the methods for crack damage threshold identification, the methods for identifying the crack initiation threshold for hard rocks are less accurate and continued research is on-going to address the problem. At present, the ISRM has established a commission on rock spalling, and one of the important objectives of the commission is to develop suggested guidelines for determining the crack initiation threshold of rocks. Recently, Nicksiar and Martin [32] proposed a new method, which is called Lateral Strain Response (LSR) method, for the determination of crack initiation stress. Meanwhile, they also utilized different strain based methods to evaluate the crack initiation threshold of Åspö diorite in uniaxial compression, and showed that any of the strain-based methods provided statistically accurate results.

It should be noted that the volumetric strain [27], the lateral strain [28,29] and the instantaneous Poisson’s ratio [31] methods depend strongly on user’s judgment because the curves associated with the strains are often strongly nonlinear (see Fig. 9b, c, d and f). Some errors due to subjectivity can occur when picking the crack initiation stress from the drawn tangential lines, especially when the quality of the stress–strain relationship is poor and the

---

**Fig. 6.** Complete stress–strain curve associated with AE hit characteristics showing different deformation stages of the Beishan granite at a confinement of 10 MPa (a), and a zoomed-in relationship between AE hit count and axial compression stress for identifying crack initiation stress and crack damage stress thresholds (b).
The nonlinearity of the curve is strong. The less subjective crack volumetric strain method [30] attempts to find $\sigma_{ci}$ by plotting the crack volumetric strain versus the axial strain (see Fig. 9e). The crack volumetric strain is calculated by subtracting the elastic volumetric strain from the total volumetric strain. A shortcoming of this method is that the determination of $\sigma_{ci}$ relies on the elastic constants (i.e., Young’s modulus $E$ and Poisson’s ratio $\nu$), and this method is especially sensitivity to the Poisson’s ratio [25].

Fig. 7. Spatial distribution of accumulated AE events in the rock sample at different stress levels under a confining stress of $\sigma_3 = 10$ MPa. (a)–(j) respectively correspond to points $\sigma_{ci}$ to $\sigma_{sh}$ in the complete stress–strain curve shown in Fig. 6a, and the sample fails in shear (i).

Fig. 8. Estimation of the crack damage stress from cumulative AE hit number and volumetric strain in an uniaxial (a) and a triaxial ($\sigma_3 = 10$ MPa) compression tests (b) based on Figs. 4 and 6, respectively.
Fig. 9. Determinations of crack initiation stress threshold based on various methods respectively proposed by different researchers. (a) Stress–strain curve of the Beishan granite (BS06MD-21) in triaxial compression at a confinement of 5 MPa. (b) Volumetric strain method [27], (c) lateral strain method [28], (d) extensional strain method [29], (e) crack volumetric strain method [30], (f) instantaneous Poisson’s ratio method [31], (g) lateral strain response (LSR) method [32] and (h) AE hit line method.
Compared with other strain methods, an advantage of the newly proposed LSR method [32] is that it removes the user’s subjective judgment (see Fig. 9g). However, the use of the LSR method depends on accurate determination of the crack damage stress and on having a fitting equation to find the maximum LSR stress value and the associated $\sigma_{ci}$.

In the present study, $\sigma_{ci}$ can be determined easily by using the linear AE hit line method to identify the inflection point in the AE hit-axial stress plot, as presented in Fig. 4b, Fig. 6b, and Fig. 9h. As mentioned above, when the stress–strain relationships are not available, AE monitoring is an alternative approach for identifying the crack initiation stress. It is observed from Fig. 9 that the $\sigma_{ci}$ values obtained from seven different methods are reasonably close to each other. This supports the conclusion arrived by Nicksiar and Martin [32], although they used only data from uniaxial compression tests without AE measurement. Presently, the ISRM has not provided a suggestion for the determination of $\sigma_{ci}$ during rock deformation in both unconfined and confined compression tests. According to the suggestion in [13], strain in combination with AE should be used to evaluate crack initiation stress whenever available.

Table 1

<table>
<thead>
<tr>
<th>Sample no.</th>
<th>$\sigma_3$ (MPa)</th>
<th>E (GPa)</th>
<th>$\nu$</th>
<th>$\sigma_c$ (MPa)</th>
<th>Crack initiation stress $\sigma_{ci}$ (MPa)</th>
<th>VS</th>
<th>AE</th>
<th>LSR</th>
<th>Mean</th>
<th>SD</th>
<th>Cov (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BS06MD-01</td>
<td>0</td>
<td>62.45</td>
<td>0.18</td>
<td>129.61</td>
<td>60.22</td>
<td>64.57</td>
<td>64.97</td>
<td>63.25</td>
<td>2.63</td>
<td>4.17</td>
<td>103.75</td>
</tr>
<tr>
<td>BS06MD-02</td>
<td>0</td>
<td>62.12</td>
<td>0.12</td>
<td>127.25</td>
<td>77.34</td>
<td>78.99</td>
<td>80.18</td>
<td>78.84</td>
<td>1.43</td>
<td>1.81</td>
<td>119.81</td>
</tr>
<tr>
<td>BS06MD-03</td>
<td>0</td>
<td>65.76</td>
<td>0.14</td>
<td>156.63</td>
<td>77.00</td>
<td>84.73</td>
<td>83.84</td>
<td>83.36</td>
<td>5.79</td>
<td>6.95</td>
<td>134.55</td>
</tr>
<tr>
<td>BS06MD-04</td>
<td>0</td>
<td>64.05</td>
<td>0.15</td>
<td>152.50</td>
<td>70.95</td>
<td>82.50</td>
<td>86.36</td>
<td>84.30</td>
<td>1.94</td>
<td>3.02</td>
<td>105.44</td>
</tr>
<tr>
<td>BS06MD-05</td>
<td>0</td>
<td>65.08</td>
<td>0.15</td>
<td>155.29</td>
<td>81.84</td>
<td>91.48</td>
<td>86.81</td>
<td>85.08</td>
<td>2.80</td>
<td>3.87</td>
<td>178.91</td>
</tr>
<tr>
<td>BS06MD-06</td>
<td>0</td>
<td>61.48</td>
<td>0.12</td>
<td>154.66</td>
<td>65.93</td>
<td>69.57</td>
<td>67.49</td>
<td>67.66</td>
<td>2.50</td>
<td>3.74</td>
<td>99.93</td>
</tr>
</tbody>
</table>

Mean: 63.49 ± 0.14 × 145.99 ± 0.32 × 74.19 ± 0.32 × 74.41 ± 0.32 × 72.67 ± 0.32 × 2.84 ± 0.32 × 3.91 ± 0.32 × 113.73 ± 0.10 ± 0.50 ± 0.78 ± 0.64

Mean: 64.48 ± 0.15 × 163.83 ± 0.33 × 73.76 ± 0.33 × 74.61 ± 0.33 × 77.81 ± 0.33 × 75.39 ± 0.33 × 2.13 ± 0.33 × 2.83 ± 0.33 × 121.13 ± 0.46 ± 0.74 ± 0.60

Table 1: Determinations of characteristic parameters of the Beishan granite in unconfined and confined compression tests.

Note: E—Young’s modulus, $\nu$—Poisson’s ratio.
possible. Hence, three different methods, i.e., volumetric strain (VS) method [27], LSR method [32], and AE hit line method, were used to establish the crack initiation stress in the following analysis.

Using the three selected methods described above, the crack initiation stresses at different confinements were determined and the interpreted results for all tested samples are listed in Table 1. To reveal the dispersion degree among the crack initiation stresses obtained from the three methods and their means, we calculated the standard deviation (SD) and coefficient of variation (CoV) for the dataset. It is observed from Table 1 that the cases with SD values less than 10 MPa and 10% account for 70% and 85% of the all tested rocks over a confinement range of 0–40 MPa; hence, the slope of the crack initiation surface is of subordinate importance [10]. To estimate the depth of brittle failure around tunnels excavated in moderately jointed to massive hard rocks, Martin et al. [34], based on the Hoek-Brown failure criterion, proposed a $m$-zero damage initiation criterion:

$$\sigma_1 - \sigma_3 = \frac{1}{3} \sigma_c.$$  

The fundamental assumption in using the $m$-zero damage initiation criterion is that the failure process around the tunnel is dominated by cohesion loss associated with rock mass fracturing. It must be pointed out that this approach is only valid when used with an elastic analysis utilizing the strength factor concept to estimate the maximum depth of failure at low confinement conditions. When using the laboratory crack initiation stress to establish in situ spalling strength, caution should be taken when using Eq. (3) to predict the brittle failure of hard rocks. This is due to the fact that when those researchers tried to link the crack initiation stress to in situ rock strength, some important factors such as gradual failure process due to tunnel face advance and complex excavation boundary conditions were not properly considered. As argued in Cai et al. [10], the in situ strength could be significantly higher if the actual tunnel excavation geometrical condition were honored. This was further explained using the Mine-by tunnel case history in Canada [35].

Compared with the crack initiation stress, the crack damage stress is more sensitive to confinement as a high slope of the envelope can be seen (Fig. 11a). Similar to the crack initiation stress thresholds, two crack damage thresholds, one for the splitting confinement zone and the other for the whole confinement zone, can be expressed as

$$\sigma_1 = 0.78 \sigma_c + 3.70 \sigma_3.$$  

$$\sigma_1 = 0.84 \sigma_c + 5.54 \sigma_3$$

respectively. It is seen that the slope of crack damage envelope in the high confinement zone is steeper than that in the splitting

4.2. Confinement-dependent crack initiation and crack damage stresses

Fig. 11a presents the crack initiation and crack damage thresholds at different confining stresses. It is seen that the crack initiation and crack damage stresses increase with increasing confining stress. The best-fit crack initiation threshold for all the tested rocks over a confinement range of 0–40 MPa can be written in the form of

$$\sigma_1 = 0.51 \sigma_c + 3.21 \sigma_3.$$  

In the splitting zone ($\sigma_3 = 0–2$ MPa), an envelope that better represents the crack initiation stress threshold can be expressed by

$$\sigma_1 = 0.50 \sigma_c + 1.36 \sigma_3$$

The major difference between Eqs. (1) and (2) is that the envelope represented by the later has a smaller slope in the principal stress space, indicating that crack initiation stress is less sensitive to confinement under low confinement conditions. It is seen that the slopes of the two crack initiation thresholds have a negligible impact on the threshold levels in the splitting zone. However, with the increase of confining stresses, the crack initiation threshold becomes more sensitive to confinement. For example, when $\sigma_3$ is equal to 1 MPa, the crack initiation stresses obtained from Eqs. (1) and (2) are 77 and 74 MPa, respectively. Whereas when $\sigma_3$ is increased to 20 MPa, the crack initiation stresses obtained from Eqs. (1) and (2) are 138 and 100 MPa, respectively.

Field observations demonstrate that brittle failure around underground openings in hard rocks often occurs in the form of spalling or slabbing. Some researchers [12,32,33] suggested that crack initiation stress from laboratory uniaxial compressive tests could be used as a lower-bound value for evaluating the onset of in situ spalling strength. Near the underground excavation boundary, the confining stress is low, generally in a range of 0 to a few MPa; hence, the slope of the crack initiation surface is of subordinate importance [10]. To estimate the depth of brittle failure around tunnels excavated in moderately jointed to massive hard rock masses, Martin et al. [34], based on the Hoek-Brown failure criterion, proposed a $m$-zero damage initiation criterion:
zone. When the load reaches the crack initiation stress level, microcracks are easy to propagate and coalesce under low confinement conditions. As damage accumulates, the frictional strength is hard to be mobilized when the confinement is low. However, with increasing confining stress, the frictional strength component can be mobilized easily, resulting in an increase of resistance against crack propagation. Hence, a higher stress is required to further propagate the cracks.

The influence of confinement on some stress ratios (i.e., $\sigma_{cl}/\sigma_c$, $\sigma_{sh}/\sigma_{cd}$, and $\sigma_{cd}/\sigma_c$) is presented in Fig. 11b. It is seen that the variation of confinement has no impact on the $\sigma_{cd}/\sigma_c$ ratio, and this ratio is approximately 0.76. However, the $\sigma_{cl}/\sigma_c$ and $\sigma_{sh}/\sigma_c$ ratios show a large confinement dependency in the splitting zone. At the low confinement zone, the $\sigma_{cl}/\sigma_{cd}$ and $\sigma_{sh}/\sigma_c$ ratios decrease rapidly as confinement increases. However, at the high confinement zone, the two stress ratios are not affected by the confining pressure.

5. Conclusions

Failure process of crystalline rocks is closely associated with crack initiation, crack propagation, crack damage, and strain or damage localization. In this paper, the deformation, peak and post-peak strength characteristics of the Beishan granite were studied systematically using laboratory uniaxial and triaxial compression tests. Experimental results showed that the complete evolution of crack damage in the rock during rock deformation can be successfully characterized using the real-time spatial AE locations in combination with the stress–strain relationships. Typical failure modes such as splitting in uniaxial compression and shear failure in triaxial compression were observed. The macroscopic failure modes were in good agreement with the ones reckoned from 3D AE event distribution data.

Crack initiation and crack damage stresses at different confinements were identified effectively using the linear AE hit line methods. The interpreted results were consistent with those obtained from the conventional stress–strain methods, indicating that the AE method can be used effectively for the determination of crack initiation and crack damage stresses in both unconfined and confined compression tests. Unlike the crack damage stress which is associated with a volumetric strain reversal, the crack initiation stress is difficult to be obtained directly from the stress–strain curves. A statistical evaluation of the results using three different methods illustrates that each approach determines the crack initiation stress reasonably well, and the use of either method for determining crack initiation stress is not confinement dependent. However, due to a lack of clear guidelines for determining the crack initiation stress, it is suggested that whenever possible the strain method should be used in combination with the AE method to determine the crack initiation stress.

For the tested rocks, the crack initiation and crack damage stresses increase with increasing confinement. Compared with the crack damage stress, the crack initiation stress is less dependent on confinement, especially in the low confinement zone (splitting zone). Work is being conducted to implement the obtained thresholds in numerical modeling to predict excavation responses in the Beishan granite. It is planned to carry out more triaxial tests on other Beishan granitic rocks to further study the influence of grain size and confining stress on their rock mechanical properties.

Acknowledgments

This work has been supported by the National Natural Science Foundation of China (Grant no. 11102061) and the China Atomic Energy Authority through the Geological Disposal Program.

References
