Evaluation of Brittle Failure Characteristics around an Opening Using Acoustic Emission and X-ray CT

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1. INTRODUCTION

The failure of underground structures depend on the magnitude of initial stress, the strength of intact rock, and the condition of discontinuities in rock mass. Underground structures which are constructed in deep depths usually experience squeezing and brittle failure caused by high induced-stress. While squeezing occurs in weak rock masses, brittle failure such as rockbursts, spalling and slabbing is prevalent in hard rock masses [1]. In particular, brittle failure is absolutely influenced by the stress condition and rock strength of in situ rock [2,3]. This brittle failure could be a particular severe problem during underground excavation, as it involves the detachment of rock fragments at a high velocity. Therefore, for safe construction of underground structures in hard rock masses, the characteristics of brittle failure should be evaluated.

As the brittle failure usually happen as a high velocity and small displacement, it is not easy to determine the precursor and initiation stress level of failure in displacement detection method. To overcome this problem, new techniques for analysis and detection of failure characteristics of rock and underground structures have recently tried to adopt the non-destructive method such as acoustic emission (AE) and computer tomography in rock engineering and civil engineering. However, there are a few researches [4, 5] for the fusion of non-destructive technique and rock engineering technique.

Accordingly, this study conducted physical model experiments to figure out the characteristics of brittle failure using non-destructive method. In order to do this, we performed physical model experiments and attempted to quantitatively represent the brittle failure characteristics with stress conditions using an AE and X-ray CT. We could evaluate the severit of brittle failure and failure initiation stress through AE parameters and figure out where the brittle failure occurs through AE source locations. We could also visualize and quantify the angular extent and depth of the failure around openings through CT image.

2. EXPERIMENTAL SYSTEM

2.1 Polyaxial experimental system

The model experiments were performed using a polyaxial experiment system, which consist of polyaxial pressure chamber, loading system and data acquisition system [3]. It could be examined under three independent stress conditions. The loading system used in the experiments was manufactured by Interlaken corp., which could apply the load as high as 500 ton.

The model material used as a substitute rock was cement mortar. It is a prismatic cube of 290 mm × 290 mm × 290 mm and had a half-excavated circular opening of 60 mm in diameter which corresponds to a tunnel in real scale.
2.2 Acoustic emission measuring system

A Physical Acoustic Corporation (PAC) PCI/Disp system was used to measure the acoustic emission from the experiments. This comprises acoustic sensors (pzt crystals), pre-amplifiers and a recorder. The acoustic emission sensors are Hagisonic's AE-SC model with the diameter of 3.6 mm and the thickness of 2.4 mm, the resonant frequency of 150 kHz, and the frequency band of 100 kHz to 1,000 kHz. These are attached to the sample with an electronic wax couplant. The acoustic emission signals are amplified by a PAC model 1220A pre-amplifier with a gain of 40 dB. The measurement and processing of acoustic emission signals used the AEwin program supplied from PAC. Measured signals are processed using a AEwin program supplied by PAC.

2.3 X-ray computer tomography scanner

The experimental specimens were scanned by X-ray CT post-experiments using a medical scanner (Fig. 1). The Siemens SOMATOM Sensation 16 scanner allows spiral scanning to a maximum resolution of 0.16 mm. The CT scanner consists of a gantry that performs both transmission and reception while rotating the X-ray tube in a high speed and a scanning table that passes the sample through the beam and receiver. The SOMATOM Sensation 16 uses the multi-slice method and can perform volume scan with the slice thickness of 0.5 mm. Volume scan offers the advantage of scanning all images without loss of data while the table is moving at a constant speed. The maximum resolution is 30 LP/cm (about 0.16 mm) and the maximum rotation speed of the X-ray tube is 0.75 cycle/sec. The CT scanner generates X-rays from the X-ray tube using the differences of X-ray absorption, and obtains the attenuation profile of X-rays that penetrate the object while rotating. The strength and weakness of the X-rays are converted to the strength and weakness of current by the detector, and the measured analog signals are transformed to digital signals before the images are reconstructed to visual images (Fig. 2).

3. EXPERIMENTAL METHOD

3.1 Physical model experiment

Physical model experiments were conducted to investigate the relationship between the characteristics of brittle failure and stress conditions. In these model experiments, the vertical applied stress ($S_V$), which is perpendicular to the opening axis, was applied by load control method. The horizontal applied stress ($S_{H1}$), which is parallel to the opening axis, was hydraulically applied by pressure control method and the other horizontal applied stress ($S_{H2}$), which is perpendicular to the opening axis, was implemented with the hydraulic system of SBEL. The two independent stresses ($S_V$ and $S_{H2}$) are applied initially at low level.
(about 1 MPa). Then $S_{H1}$ is increased to a constant value. After reaching the predetermined magnitude of $S_{H1}$ and $S_{H2}$, $S_{V}$ is incremented to a desired magnitude. The magnitude of stresses in this study always maintain the relationship $S_{V} > S_{H2} > S_{H1}$.

The severity of failure is classified as three grades based on Bae et al. [6]. The magnitude of $S_{V}$ is determined based on the information gathered from the pre-experiments, accumulative AE hits curve and AE sources (Table 1). The AE signals and AE parameter are measured during the experiments, and CT scanning is performed post-experiment.

Table 1. Determination of the maximum stress from accumulative AE hits curve and AE sources

<table>
<thead>
<tr>
<th>Severity of failure</th>
<th>AE sources</th>
<th>Accumulative AE hits curve</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grade A (No failure)</td>
<td>Sources just start to be detected.</td>
<td>Accumulative AE hits curve gradually increases. Stress level corresponds to secondary cracking stress level or below.</td>
</tr>
<tr>
<td>Grade B (Visible cracks)</td>
<td>Detected sources and rate of detected sources start to increase.</td>
<td>Accumulative AE hits curve starts to increase significantly for the first time. Stress belongs to between secondary cracking stress and crack coalescence stress.</td>
</tr>
<tr>
<td>Grade C (Heavy spalling)</td>
<td>Rate of detected sources start to significantly increase</td>
<td>Accumulative AE hits curve increases abruptly. Stress level corresponds to crack damage stress or above.</td>
</tr>
<tr>
<td>Model failure</td>
<td>Rate of detected sources start to significantly increase and ram rapidly move and stress abruptly decrease.</td>
<td>Accumulative AE hits curve increases abruptly.</td>
</tr>
</tbody>
</table>

3.2 AE setting parameter

To detect efficiently AE signals, AE channel-setting parameters should be properly set. The important setting parameters are AE threshold, peak definition time (PDT), hit definition time (HDT), and hit locking time (HLT) etc.. The AE threshold is a basic parameter that controls the channel sensitivity. For a noise level, $m \pm 3\sigma$, where $m$ and $\sigma$ are the average and standard deviation of noise signals respectively, is applied as the standard background noise, which is proposed by Maji and Shah [7]. Only those AE hits that have amplitude equal to or greater than the set threshold (40 dB) are measured. The AE arrival time is defined as the time at the point where the amplitude equal to or greater than the background noise is generated. The time parameters PDT, HDT and HLT used in the process of measuring AE's waveform are set to 200 $\mu$s, 800 $\mu$s, 1000 $\mu$s, respectively, so that sufficiently long waveforms could be included.

The sampling rate is set to 10 MHz and frequency band is from 100 kHz to 2000 kHz. Individual trigger is used so that measurement will begin when a waveform over the threshold was measured for each sensor. The pre-trigger is set to 40 seconds. To determine AE propagation velocity, pencil break test was performed. However, the AE propagation velocity obtained from the pencil break test was similar to the P-wave velocity in laboratory test, so the P-wave velocity in laboratory test is used as the propagation velocity of AE.

For AE source location in the experiments, a total of eight AE sensors are attached to the experimental sample. Fig. 3 shows the arrangement and locations of the sensors used in this study. The sensor arrangement was determined in consideration of a symmetry of the sample and a part where the generation of AE is expected, also consideration of the limitation of attachment locations due to the loading method of the used polyaxial pressure chamber.

Settings for three-dimensional source location of AE consist of the AE propagation velocity, sensor locations, lockout time, and iteration time so on. The lockout time is the time that takes for a source location program to restart another AE source locating. It defines the distance between two sensors which are the farthest away from each other divided by the AE propagation velocity.
3.3 CT scanning

On completion of the model experiments, the samples are removed and sectioned into pieces approximately 120 mm x 200 mm x 80 mm. These smaller samples improve the precision of the resulting CT images. Any loose materials in the failure zone is removed before scanning. Scans are at a transmission energy of 140, a transmittance of 110 and with a rotations speed 0.75 cycle/sec. The slice thickness is 1 mm. Scanning at high transmission energy produces improved penetration and contrast within object, and using high transmittance decreases noise. The CT images are reconstructed in three dimensions by the DICOM program enabling the extraction of desired sections.

4. EXPERIMENTAL RESULTS

4.1 Location of failure zone

V-shaped spalling (Fig. 4) was observed in the wall of parallel to the \( S_V \) as seen in previous researches [6, 8]. The AE sources were located in the same region where the V-shaped spalling was observed (Fig. 5). Little damage occurred around the opening face due to 3D arching effects. As the distance from the opening face increased, the failure zone became wider and deeper [3].

![Fig. 3. AE sensor locations](image1)

![Fig. 4. V-shaped spalling observed around the opening.](image2)

4.2 Determination of the severity of failure and failure initiation stress using AE technique

We investigated the severity of failure and failure initiation stress with stress conditions through the accumulative AE hits curve and quantities of generated AE sources during the experiments and the visual observation post-experiments. The severity of failure means the degree of failure occurred around the opening and the failure initiation stress means the stress level at which brittle failure begins to be detected.

This study identified three grades of failure severity-these refer to the criteria presented in the visual observation results by Bae et al.[6]: In Grade A, it is not possible to detect cracks visually. This is called the ‘no failure grade’. Cracks can be detected by visual observation in Grade B as fragments begin to isolate, known as ‘visible macro cracks’. In Grade C, heavy spalling is detected. Fig. 6 shows the resulting failure grades in the experiments and Fig. 7 shows relation between the failure grade and quantities of generated AE source. As shown in Fig. 7, they have a positive trend. However, this is not always the case. In some case even though high failure grade, numbers of AE source are very small. If the failure grade is determined only by the quantities of the AE source, there could be incorrect prediction of failure grade.
Therefore in determining the failure grade, we should adopt other parameters such as accumulative AE hits curve, strain, degree of cracks occurred etc, with quantities of AE sources.

A visual observation and AE measurements were used to determine the brittle failure initiation stress. In the visual observation, the brittle failure initiation stress was set at no failure grade (Grade A) in a conservative aspect. In the AE measurements, the method proposed by Lee and Haimson [9] was used. They determined the brittle failure initiation stress as the point at which the points of accumulative AE hits curve and AE hits curve increase rapidly (Fig. 8).
4.3 CT image and determination of extent and depth using CT.

The images extracted from a CT scanner are expressed in black and white as shown in Fig. 9. The damaged and failed zones can be identified by density. In other words, white parts represent high density and black parts low density. The damaged zones have lower density than surrounding parts due to cracks, and are displayed darker than surrounding parts in a CT image. Fig. 9 (b) is an image of opening cross section with failed zones which were separated from the opening sidewall. Fig. 9 (c) is the image of an axially cross section of the opening which shows that no failure is occurring near the opening face. Fig. 9 (d) is an image scanned from top which clearly shows the separated parts by failure and cracks near the opening face.

![Fig. 9. Cross-section CT image and reconstructed 3D CT image](image)

The damage level of brittle failure was classified as three grades as mentioned in the 4.2 section. Fig. 10 presents the 3D and cross section images of an experimental sample which is classified as Grade A and Grade C. As shown in Fig. 10 (a) the occurrence of failure could not be observed even in CT images, which is identical to almost no occurrence of AE source. However, the sample belonging to Grade C in Fig. 10 (b) clearly shows split in opening sidewall.

![Fig. 7. Number of AE sources with failure grade](image)

![Fig. 8. Failure initiation based on accumulative AE hits curve and AE hits](image)
The angular extent of failure ($\theta$) and depth of failure ($d_f$) for samples classified as a Grade C, were measured using CT images. The angular extent of failure was measured by both visual observation using calipers and CT images. Fig. 11 shows the results measured by visual observation and CT images, which indicate similar trends. From this comparison, we can see that CT images show the results more precisely than by visual observation. However, the depth of failure used only the results measured in CT images because to measure depth using calipers is both difficult and inaccurate.

Observations in CT images indicate that the average angular extent of failure was 28° to 42°, and up to 55°. The depth of failure was 1.009 to 1.143 times the opening radius. According to the field results of Kaiser et al [10], the extent of failure of a breakout was in the range of 30° to 60° to the direction of minimum principal stress and independent of the borehole size. Furthermore, from the results of a biaxial model experiment, Bae et al.[6] also reported that a brittle failure like the spalling in a circular opening occurred within 60°.

5. CONCLUSION

This study investigated the characteristics of brittle failure which may occur in underground structures constructed in great depths. For this, the AE technique and X-ray CT was used to determine the failure characteristics through physical model experiments. The main results obtained from this study are summarized below.

1) This study showed that AE detection method and X-ray CT could be usefully applied to determine the characteristics of brittle failure.
2) The severity of brittle failure was classified into three groups through the acoustic emission, especially accumulative AE hits and quantities of AE source. Brittle failure initiation stress also can be determined using accumulative AE hits.

3) The severity could be verified through CT image. CT images show their results more precisely than by a visual observation. Furthermore, the depth of failure used only the results measured in CT images because measuring a depth using calipers is both difficult and inaccurate.

4) The severity of failure and quantities of generated AE source have a positive trend. However, this is not always the case. In some cases even though in a high failure grade, numbers of AE source are very small. If the failure grade is determined only by the quantities of the AE source, there could be incorrect prediction of failure grade. Therefore in determining the failure grade, we should adopt other parameters such as accumulative AE hits curve, strain, degree of cracks occurred etc, with quantities of AE sources.

5) The V-shaped spalling was observed in the wall of parallel to the $S_v$, which is maximum principle stress, and the shape of spalling could be evaluated through the black and white in the CT image. The location of spalling was also evaluated using AE source location.

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REFERENCES