Effect law of Damage Characteristics of Rock Similar Material with Pre-Existing Cracks

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Abstract. In order to further study the failure mechanism for rock similar materials, this study established the damage model based on accumulative AE events, investigated the damage characteristics for rock similar material samples with pre-existing cracks of varying width under uniaxial compression load. The equipment used in this study is the self-developed YYW-II strain controlled unconfined compression apparatus and the PCIE-8 acoustic emission (AE) monitoring system. The influences of the width of the pre-existing cracks to the damage characteristics of rock similar materials are analyzed. Results show that, (1) the damage model can better describe the damage characteristics of rock similar materials; (2) the tested samples have three stages during failure: initial damage stage, stable development of damage stage, and accelerated development of damage stage; (3) with the width of pre-existing cracks vary from 3mm to 5mm, the damage of rock similar materials increases gradually. The outcomes of this study provided additional values to the research of the failure mechanism for geotechnical similar material models.

1. Introduction

Rock is a common natural complicated geological body. Rock has defects such as cracks, beddings, and joins, which heavily influence its stability. The cracks’ geometrical parameters have crucial effects to damage characteristics of rock [1-3]. Therefore, the study of damage characteristics of rock with cracks has great importance and significance to the geotechnical research of the rock mass failure mechanism.

Many researchers have studied the damage characteristics of rock mass. Some of the typical researches are summarized here. Heiple and Carpenter [4] conducted a number of AE experiments and concluded that the AE ringing counts can reflect the material internal damage process. Jansen et al. [5] used the AE technology to investigate the damage accumulation and development during rock failure. Based on electromagnetic radiation characteristics, Jin et al. [6] studied the damage evolution of rock under uniaxial compression. Zhao et al. [7] established the damage-based constitutive model for rock under impacting load. Zong et al. [8] studied the mechanical and damage evolution properties of sandstone under triaxial compression. From a micro perspective and based on the AE technology, Liu et al. [9] obtained the failure development characteristics for coal and rock under uniaxial compression through the study of the acoustic emission. By analyzing the AE characteristics and failure development for salt rock under uniaxial compression, Zhou et al. [10] compared the damage model based on ringing counts and that based on energy parameters.

From the above literature review, one can see that the researches on the damage characteristics of rock have achieved abundant outcomes. However, there are still rooms for improvement. The most
objects of study are native rock, thus the research on rock similar materials is limited. However, similar material simulation experimental study is one of the important means in the research of geotechnical engineering, which have been widely used. Therefore, there is a need for the systematical study of the rock similar material. Most studies for rock damage characteristics are based on the AE ringing counts and established the damage model, and few researches have taken crack parameters into account. The AE ringing count is not a sufficient representation of rock damage, and crack parameters is one of the important factors that impact rock damage characteristics. For this reason, it is necessary to explore more appropriate factors that represent rock damage, and based on which establish new damage model for continued in-depth study.

In order to establish a more suitable damage model for rock similar material, and further study the damage characteristics of rock similar material with cracks. This study selected accumulative AE events as representation of damage, established the damage model, and selected crack width as one geometrical variable parameter, tested rock similar material samples with different pre-existing crack width. By using the self-developed compression apparatus and high precision acoustic emission monitoring system, the influence of crack width to the damage characteristics of rock similar materials are investigated. The outcomes of this research can be used for supplementation and improvement of the current deformation damage mechanism research for rock similar materials.

2. The damage model based on accumulative AE events

Among other AE characteristic parameters, the accumulative AE events represent local change to the material identified by the AE signal collision. This is directly related to material failure and is a good indicator for the damage to the material. Therefore, the damage model is established based on the accumulative AE events for rock similar material under uniaxial compression.

Kachanov [11] proposed the concept of damage variable ($D$), and defined it as:

$$ D = \frac{A_d}{A} $$

(1)

where $A_d$ is damage plane surface area, and $A$ is the initial cross sectional area of the material.

Due to the fact that it is challenging to determine the effective bearing area when the material is damaged, Lemaitre [12] proposed the equivalent strain hypothesis, which indirectly measures material damage based on the effective stress shown in the following equation.

$$ \sigma' = \frac{\sigma}{1 - D} $$

(2)

where $\sigma'$ is equivalent uniaxial stress, and $\sigma$ is the actual uniaxial stress.

According to elastic-plastic mechanics, the strain for an undamaged material can be expressed as:

$$ \varepsilon = \frac{\sigma'}{E} $$

(3)

where $E$ is modulus of elasticity, and $\varepsilon$ is the strain.

Combining equation (2) with (3), the uniaxial stress can be expressed as:

$$ \sigma = \sigma'(1 - D) = E\varepsilon(1 - D) $$

(4)

Assume the number of accumulative AE events is $N_m$ for complete damage of the surface (A) for the nondestructive material, the generated AE events per unit area $N_a$ can be calculated as:

$$ N_a = \frac{N_m}{A} $$

(5)

The accumulative AE events generated when the damage area is $A_d$ can be calculated as:


\[ N_d = N_a A_d = \frac{N_a}{A} A_d \]  

(6)

Combing equation (1) with equation (6), the damage variable can be expressed as a function of the accumulative AE events:

\[ D = \frac{A_d}{A} = \frac{N_d}{N_a} \]  

(7)

Rock material cannot be completely damaged when compressed, which means a residual strength exist and the damage variable cannot reach to 1. Thus the damage variable can be modified to:

\[ D = D_o \frac{N_d}{N_a} \]  

(8)

where \(D_o\) is damage critical value, \(N_a\) is the number of accumulative AE events when the damage variable is \(D_o\). Using the linear function transformation method, the damage critical value can be normalized as:

\[ D_o = 1 - \frac{\sigma_c}{\sigma_p} \]  

(9)

where \(\sigma_p\) is the peak stress, and \(\sigma_c\) is the residual strength.

When \(\sigma_c=\sigma_p\), \(D_o=0\), and thus \(D=0\) in equation (8). Such rock similar material can be treated as ideal elastoplastic material and compression cannot cause damage. When \(\sigma_c=0\), \(D_o=1\) in equation (8), which means the rock similar material can be completely damaged under compression. However, a certain level of damage will occur when compression is applied, and rock similar material has a residual strength. Therefore, in this study, \(D_o \in (0,1)\).

Combing Equation (4), (8), with (9), we achieve the following damage model for rock similar material under uniaxial compression, which is based on the accumulative AE events.

\[ \sigma = E \varepsilon \left(1 - D\right) = E \varepsilon \left(1 - \left(1 - \frac{\sigma_c}{\sigma_p}\right) \frac{N_d}{N_a}\right) \]  

(10)

3. Experimental designs

3.1. Specimen preparation

To prepare the rock similar material, sand is used as the aggregate, cement and starch are used as cementing agent, and water is the dissolvent. The sand to cement weight ratio is 10:1, and water amount is 1/9 of the total weight of the similar material. After uniformly mixing of the materials, it is put in a standard mould (Φ50mm × 100mm). The specimens are taken out of the mould after 1-2 minutes compaction, and cured in room temperature and condition for 5-7 days. The prepared specimens are shown in figure 1.

Several groups of tests were conducted. Due to limited space, only analyses of one group of specimens are presented in this paper. The results can represent the overall results for other test groups. The three specimens in this group are numbered W-1, W-2, and W-3. A hacksaw blade was used to make the cracks on each specimen. The length of the cracks is 40mm, and the angle is 45°. The crack width for specimen W-1, W-2, and W-3 are 3mm, 4mm, and 5mm, respectively. The completed specimens with different width of pre-existing cracks are shown in figure 2.
3.2. Loading equipment and conditions

The loading equipment used in this study is the self-developed YYW-II strain controlled unconfined compression apparatus, as shown in figure 3. Its major components include a loading ring, an electrical motor, a lifting board, an axial force meter, and an axial displacement meter. This apparatus is suitable for conducting the uniaxial compression test for similar materials, monitoring the stress-strain in the testing process. The deformation rate controlled method is used in this research, and the loading rate is 0.87mm/min.

3.3. AE monitoring system and monitoring design

The AE system used is the PCIE-8 system from the Physical Acoustics. The system achieves high maximum sustained processing speeds, better de-noising ability, reliability and stability. The threshold value is set to be 40dB, the transmission gain for the preamplifier is 40dB, the sampling frequency is 10MHz, and the resonant frequency for the sensor is 1-100kHz.

As shown in figure 4, six sensor arrays were used to collect the AE signals. To improve contact between the sensors and the specimen and reduce signal loss, Vaseline is applied in between the sensors and the specimen, and the sensors are fixed to the specimen by sticky tapes. Lead-break tests were conducted close to each sensor to calibrate the sensors before the actual experiments.
4. Damage characteristics analysis

Based on the experimental results and the damage model derived in the above section, the parameters for specimen W-1 are $\sigma_p=518$ KPa, $\sigma_c=129$ KPa, $E=51944$ KPa, $N_m=323$, for W-2 are $\sigma_p=479$ KPa, $\sigma_c=119$ KPa, $E=30357$ KPa, $N_m=252$, and for W-3 are $\sigma_p=411$ KPa, $\sigma_c=102$ KPa, $E=46846$ KPa, $N_m=134$. The damage-strain curve can be plotted according to equation (8) and equation (9), as shown in figure 5. The theoretical stress-strain curves are derived according to equation (10), and plotted together with the actual experimental stress-strain curve in figure 6. As can be seen, the curves have very similar trends, and the theoretical curves are generally below the actual measured curves. This is due to the stress loss in the actual experiments. The close match of the two curves has proved the validity of the normalized damage variable based on the accumulative AE events in equation (8).

As can be seen in figure 5, the damage development processes for the three tested specimens are similar, and they are closely related to their load and deformation, and AE development. The damage development process can be divided into three stages.

The first stage is the initial damage stage (OA). In this stage, only minimum damage has occurred and the level is relatively low. This phase is in correspondence to the initial compression stage, and the slow accumulation of AE events stage. The original micro cracks and micro pores are compacted to close, and only few AE events are generated. The damages are due to the internal particle friction and grain sliding.

The second stage is the damage stable development stage (AB), in which the damage variables increase steadily. It is in correspondence to the elastic deformation stage, and the steady growth of AE events stage. New micro cracks are generated, and they are gradually extended and connected. The number of AE events increases steadily, which indicates stable damage.

The last phase is the damage rapid development stage (BC) and the damage variable rapidly increases to the maximum value. It is in correspondence to the plastic deformation stage, and the rapid increase of AE events stage. In this stage, micro cracks are rapidly generated, extended, and connected. The number of AE events accelerates at a growing rate until eventually causes specimen failure. The damages development is also non stable. The above analysis supports the conclusion that the width of
the pre-existing cracks does not have influence to the characteristics of specimen damage in different phases.

Further look at figure 5, we can see that the maximum damage variables for W-1, W-2, and W-3 are 0.791, 0.856, and 0.913, respectively. This means a larger pre-existing crack width increases the damage of specimen.

As can be seen from the three damage development stages, the damage evolution is a nonlinear process and it is not possible to use a continuous function to represent the damage mechanism. Based on polynomial curves fitting of the curves in figure 5, the damage evolution equations are obtained as equations (11) to (13). The degree of fitting is between 0.98263-0.9967, indicating a preferable fitting result.

\[
\begin{align*}
W-1: D & = \begin{cases} 
2.45182 \times 10^{-4} \varepsilon^2 - 0.00542 \varepsilon + 0.00645 & (0 \leq \varepsilon \leq 0.0037) \\
-7.17421 \times 10^{-6} \varepsilon^2 + 0.00541 \varepsilon - 0.08407 & (0.0037 \leq \varepsilon \leq 0.0075) \\
-6.54744 \times 10^{-4} \varepsilon^2 + 0.15742 \varepsilon - 18.15782 & (0.0075 \leq \varepsilon \leq 0.0088)
\end{cases} \\
W-2: D & = \begin{cases} 
5.56461 \times 10^{-5} \varepsilon^2 - 3.21685 \times 10^{-4} \varepsilon + 0.00675 & (0 \leq \varepsilon \leq 0.0063) \\
-8.24851 \times 10^{-6} \varepsilon^2 + 0.00356 \varepsilon - 0.45212 & (0.0063 \leq \varepsilon \leq 0.0113) \\
5.17245 \times 10^{-4} \varepsilon^2 - 0.45218 \varepsilon + 18.54782 & (0.0113 \leq \varepsilon \leq 0.0138)
\end{cases} \\
W-3: D & = \begin{cases} 
4.42056 \times 10^{-5} \varepsilon^2 - 2.14824 \varepsilon - 0.00517 & (0 \leq \varepsilon \leq 0.0101) \\
9.01485 \times 10^{-6} \varepsilon^2 + 0.00145 \varepsilon - 0.25634 & (0.0101 \leq \varepsilon \leq 0.0137) \\
-3.14245 \times 10^{-4} \varepsilon^2 + 0.05485 \varepsilon - 12.14521 & (0.0137 \leq \varepsilon \leq 0.0163)
\end{cases}
\end{align*}
\]

Further derive the above equations according to equation (10), we can get the damage constitutive equations for the three tested specimens.

\[
\begin{align*}
W-1: \sigma & = 51944 \varepsilon + \begin{cases} 
2.45182 \times 10^{-4} \varepsilon^2 - 0.00542 \varepsilon + 0.00645 & (0 \leq \varepsilon \leq 0.0037) \\
-7.17421 \times 10^{-6} \varepsilon^2 + 0.00541 \varepsilon - 0.08407 & (0.0037 \leq \varepsilon \leq 0.0075) \\
-6.54744 \times 10^{-4} \varepsilon^2 + 0.15742 \varepsilon - 18.15782 & (0.0075 \leq \varepsilon \leq 0.0088)
\end{cases} \\
W-2: \sigma & = 30357 \varepsilon + \begin{cases} 
5.56461 \times 10^{-5} \varepsilon^2 - 3.21685 \times 10^{-4} \varepsilon + 0.00675 & (0 \leq \varepsilon \leq 0.0063) \\
-8.24851 \times 10^{-6} \varepsilon^2 + 0.00356 \varepsilon - 0.45212 & (0.0063 \leq \varepsilon \leq 0.0113) \\
5.17245 \times 10^{-4} \varepsilon^2 - 0.45218 \varepsilon + 18.54782 & (0.0113 \leq \varepsilon \leq 0.0138)
\end{cases} \\
W-3: \sigma & = 46846 \varepsilon + \begin{cases} 
4.42056 \times 10^{-5} \varepsilon^2 - 2.14824 \varepsilon - 0.00517 & (0 \leq \varepsilon \leq 0.0101) \\
9.01485 \times 10^{-6} \varepsilon^2 + 0.00145 \varepsilon - 0.25634 & (0.0101 \leq \varepsilon \leq 0.0137) \\
-3.14245 \times 10^{-4} \varepsilon^2 + 0.05485 \varepsilon - 12.14521 & (0.0137 \leq \varepsilon \leq 0.0163)
\end{cases}
\end{align*}
\]

5. Conclusions
(1) The damage model based on accumulative AE events for rock similar material under uniaxial compression has been established, and the damage model can better describe the damage characteristics of rock similar material.

(2) The pre-existing cracks do not have influence to the characteristics of specimen damage in different phases. All specimens have three stages during failure: initial damage stage, stable development of damage stage, and accelerated development of damage stage.
(3) With the width of pre-existing cracks vary from 3mm to 5mm, the influence of pre-existing cracks to damage variables increases, the damage of rock similar material increases gradually. The damage evolution equations and the damage constitutive equations for rock similar material have been established.

References
[1] Bahaaddini M, Sharrock G and Hebblewhite B K 2013 Comput. Geotech. 49 206–25.
[2] Camones L A M, do Amaral Vargas Jr E and de Figueiredo R P 2013 Eng. Geol. 153 80–94.
[3] Manouchehrian A, Sharifzadeh M, Marji M F and Gholamnejad J 2014 Arch. Civ. Mech. Eng. 14 40–52.
[4] Heiple C R and Carpenter S H 1983 Acoustic emission from dislocation motion (New York: Gordon and Breach Science Publishers).
[5] Jansen D P, Carlson S R and Young R P 1993 J. Geophy. Res. B12 22231–43.
[6] Jin P J, Wang E Y, Liu X F, Huang N and Wang S H 2013 Int. J. Min. Sci. Tech. 23 213–9.
[7] Zhao G M, Xie L X and Meng X R 2014 Int. J. Min. Sci. Tech. 24 505–11.
[8] Zong Y J, Han L J, Wei J J and Wen S Y 2016 Int. J. Min. Sci. Tech. 26 601–7.
[9] Liu B X, Huang J L and Wang Z Y 2009 Chin. J. Rock Mech. Eng. 28 3234–8.
[10] Zhou Z W, Liu J F and Zou H 2016 J. Yangtze Riv. Sci. Res. Inst. 33 63-8.
[11] Kachanov L M 1958 Izv. AN SSSR Otd. Tekhn. Nauk. 8 26–31.
[12] Lemaiture J 1972 Proc. ICM-1 (Kyoto) pp 540–9.