Research on tunnel damage process based on acoustic emission technology

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Abstract—For a long time, it is generally believed that the tunnel has excellent seismic performance and can resist earthquake damage, so it will not be damaged. However, according to the survey of tunnels after the Wenchuan earthquake in China, 110 tunnels were damaged to varying degrees. In this paper, a series of shaking table tests were carried out on the proportional tunnel model under seismic excitation. Acoustic emission technology is combined with seismic excitation to identify and describe the damage of tunnel lining. The tunnel lining strain and acoustic emission signals are collected in the test. In addition, this paper also introduces the use of acoustic emission technology to describe the damage of tunnel lining. Taking the crown as an example, through the correlation analysis of amplitude, counts and energy, it is preliminarily judged that the crown is damaged under working conditions 7 and 8; Then combined with strain analysis, it is proved that the correlation analysis is reasonable. Finally, the rationality of correlation analysis is further explained by the changes of counts, energy, and its cumulative parameters with time. At the same time, the damage process of tunnel lining under seismic excitation is described by defining damage variables, which can be divided into three stages: initial compression elastic stage, yield failure stage and residual stage.

1. Introduction

Tunnels are playing an increasingly important role in the world transportation infrastructure, so their safety and stability are of great importance. Tunnels located in areas with active seismic action are more vulnerable to the threat of earthquakes. Earthquake events such as the Chi-Chi earthquake in Taiwan (1999), Wenchuan earthquake (2008), Lushan earthquake (2013) and Jiuzhaigou earthquake (2017) show that the tunnel is easy to suffer immeasurable damage due to seismic vibration [1-2].

Many researchers have adopted a variety of methods to study the response of tunnel lining under earthquake, including field investigation, theoretical analysis, model test and numerical simulation. Model test is an advanced and complex method, which is often used to verify the results of numerical simulation and explore unknown phenomena [3-4]. However, most of the previous studies were used to validate tunnel seismic analysis methods and obtain data for the final stability analysis of tunnels. The damage process of tunnel lining under seismic excitation has not been extensively studied, and there is an increasing interest in identifying the damage process of tunnel lining under seismic action. Wang et al. (2009) [5] summarized the main failure patterns of mountain tunnels under earthquake action through the post-earthquake investigation in Wenchuan earthquake. Sun et al. (2011) [6] studied the dynamic response of the tunnel model under seismic excitation and the interaction between the...
surrounding rock and the lining by conducting model tests on two parallel tunnels, and analyzed the damage pattern of the tunnel cavity section. Wang et al. (2015)\textsuperscript{[7]} studied the dynamic response of tunnel lining under seismic action by shaking table test and identified the damage of tunnel lining by white noise scanning technique, focusing on the progressive damage state of tunnel lining. As an emerging non-destructive testing method, acoustic emission technology allows real-time, dynamic, and continuous monitoring of damage evolution processes in coal, rock, concrete, metal alloys and other materials, and locates the source of acoustic emission in three-dimensional space, which is a powerful tool for conducting research on internal cracking and damage evolution in materials\textsuperscript{[8-11]}. Based on acoustic emission technique, Wang et al. (2017)\textsuperscript{[12]} investigated the mechanical properties and damage evolution process of internal cracks in sand-paraffin specimens with different ratios, and evaluated the mechanical properties of materials from macroscopic morphology to microscopic mechanism by studying the mechanical parameters, main failure forms, acoustic emission response characteristics and their internal damage evolution law. Amedeo Manuello (2019)\textsuperscript{[13]} conducted a real-time study of the damage evolution of two precast concrete arch elements of a road tunnel in northwestern Italy using a multichannel acoustic emission acquisition system with in situ data processing and wireless transmission capabilities. Qiu (2019)\textsuperscript{[14]} studied the acoustic emission characteristics and mechanical behavior of asphalt mixture through four point bending test and acoustic emission test. The definition of damage variables based on acoustic emission energy was proved to be reasonable and reliable by numerical analysis. Tam Nguyen Tat (2018)\textsuperscript{[15]} studied the degradation mechanism of concrete beams under bending load by using acoustic emission technology, and proposed an empirical law between damage evolution and acoustic emission activity. Under axial compression loading, Wang (2018)\textsuperscript{[16]} selected the acoustic emission signals of steel fiber mortar specimens with different fiber contents throughout the damage process and analyzed the damage evolution process, failure mode and damage degree of steel fiber mortar with different fiber contents by using acoustic emission energy, RA value, AF value and b value.

In this paper, acoustic emission technology is used to monitor the response of tunnel model in shaking table test. The damage evolution process of tunnel lining is studied through the characteristic parameters of acoustic emission signal, which provides a new idea for real-time monitoring of tunnel quality and has certain practical significance.

2. Experimental Design

2.1. Tunnel prototype description

In this paper, the No. 2 tunnel in the third bid section of Nairobi-Malaba railway phase I is taken as the prototype structure, and the damage analysis of tunnel lining under seismic excitation is carried out through shaking table test. The tunnel section is a horseshoe shape with a height of 9.0m and a width of about 6.2m. The rock strata around the tunnel are mainly divided into two types: the upper surrounding rock is strongly weathered trachyte and the lower surrounding rock is weakly weathered trachyte.

2.2. Test equipment

A series of shaking table tests were carried out through the "High-speed Railway Multifunctional Shaking Table Test System" of Central South University. The test system consists of a 4m×4m six-degree-of-freedom fixed platform and three 4m×4m six-degree-of-freedom mobile platforms. The fixed platform and the mobile platform are located on the same straight line. They can be used independently or in conjunction with each other. Electric actuator (suitable for high-frequency vibration) and hydraulic actuator (suitable for low-frequency vibration) can be used. Due to the test requirements, electric actuator is used for research. The tunnel model is shown in Fig.1. Fig.1(a) shows the model box and Fig.1(b) shows the tunnel structure model. In this test, IMC data acquisition system and acoustic emission test system are used for data acquisition, as shown in Fig.2. Fig.2(a) shows the IMC data acquisition instrument, and Fig.2(b) shows the acoustic emission acquisition system.
2.3. Acoustic emission and strain sensor arrangement

The acoustic emission instrument from PAC was used in this test. Fig.3 shows the arrangement of acoustic emission sensors. Fig.3(a) shows the acoustic emission monitoring sections, which are divided into 4 sections, and the monitoring sections are arranged along the tunnel axis direction. Fig.3(b) shows the distribution of acoustic emission sensors in the 4 sections, and 3 acoustic emission sensors are arranged on each section, numbered Pi or Ai (i=1,2,3,4,5,6). Fig.4 shows the strain sensor arrangement, Fig.4(a) shows the strain sensor arrangement on the outside of the tunnel model, Fig.4(b) shows the strain sensor arrangement on the inside of the tunnel model, and Fig.4(c) shows the location distribution of the main observation points on the tunnel cross-section, the plotting ratio is 1:20 in mm.
### 2.4. Design of test conditions

Since the longitudinal wave arrives first, followed by the transverse wave, both of which are less destructive, and the surface wave arrives last during an earthquake, and the surface wave is a hybrid wave that is the main factor in the strong damage to the ground building, this paper focuses on the response of the tunnel lining after the arrival of the surface wave, while the peak acceleration of the site is about 0.4g. The seismic waves selected for the test are El-Centro and Kobe waves. The El-Centro wave is the first seismic wave recorded by human beings, with a duration of 26s for the main strong part, 54s for the whole waveform, and 0.02s for the discrete acceleration interval of the original record, which is widely used in structural tests and seismic response analysis. Kobe wave is a typical urban direct-down seismic wave with a duration of 7s, a recorded waveform length of 40s, and an original discrete acceleration interval of 0.02s, which has the characteristics of short duration and high energy compared with El-Centro wave. In the test, El-Centro or Kobe waves were input from X, Y and Z direction in one direction and X and Y in both directions simultaneously, where X direction is along the tunnel axis direction, Y direction is horizontal vertical tunnel axis direction and Z direction is vertical direction, and the test conditions are shown in Table 1.
3. Results and Analysis

In the crown acoustic emission source localization, its wave speed is 3000m/s. The event group that is continuously collected by P2 and P4 and the time difference between the two events is less than 400μs (the distance between P2 and P4 is 1221.48mm, the maximum time difference between the events received by P2 and P4 is the distance between P2 and P4 divided by the P-wave speed) is selected from the acoustic emission events collected by P2 and P4 sensors. There are two such event groups selected in working condition 7, and their time difference is 64.75μs earlier for P2 than P4 and 34.25μs earlier for P4 than P2. According to the time difference as well as the P-wave speed by linear positioning, the position of the acoustic emission source is in the tunnel crown within the error allowance.

In this paper, the tunnel damage analysis is mainly carried out by acoustic emission characteristic parameters, and the representative acoustic emission parameters are amplitude, counts, energy, etc. Taking the damage analysis of the crown of the cavern section as an example, the damage is mainly described by amplitude, count and energy.

3.1. Acoustic emission signal analysis and strain analysis of tunnel crown

The correlation analysis method is the most used method in the analysis of acoustic emission signals. Any two acoustic emission signal characteristics can be analyzed as a correlation diagram, which can play a role in identifying the source of acoustic emission. Therefore, we can judge whether there are cracks in the tunnel through correlation analysis of relevant parameters.

Fig.5 is the correlation analysis diagram of amplitude, counts and energy under various working conditions. According to the parameter distribution characteristics of the correlation diagram, most signals are relatively concentrated in low amplitude state, and their corresponding counts and energy are relatively low, while some signals are in high amplitude state, and their corresponding counts and energy are relatively high. It shows that the acoustic emission signal activity of the crown is strong under this working condition, which indicates that the number of acoustic emission events is increasing, and the occurrence and development of tunnel lining cracks are closely related to the acoustic emission activity and the number of events. Therefore, it can be initially judged that many high amplitude, high counts, and high energy signals appear in the arch of the working condition with cracks, i.e., the arch of working condition 7 and 8 appears to be damaged. In some cases, there are a few local abrupt changes, i.e., there are a few points with higher values of count and energy in some cases. The reason for these cases may be that the tunnel model has minor defects in some locations during the casting process or the concrete is not mixed evenly.

Because the tunnel lining concrete is a brittle material, its tensile strength is far lower than the compressive strength, so the failure of tunnel concrete under earthquake is mainly tensile failure. The tensile strain dominates the damage state of the lining model. The tensile strain is recorded and applied to analyze the seismic response of the monitoring location. Fig.6 is the loading history diagram, and Fig.7 is the variation diagram of crown strain with time under various working conditions.
In this paper, it is considered that the tensile strain exceeds 100με to produce damage, and the tensile strain is positive and the compressive strain is negative. According to Fig.7, the maximum strains of working conditions 7 and 8 are 119.63με and 124.28με, respectively, which have exceeded the limit tensile strains set in this paper, while the maximum tensile strains of other working conditions do not exceed the set limit tensile strains, i.e., the damage occurs in working conditions 7 and 8. The
strains showed a gradual increase with time, so we can speculate that the lining damage is also accumulated gradually with time.

Fig. 6 Loading history diagram

Fig. 7 Crown strain-time diagram

3.2. Analysis of damage process of tunnel crown

The experience diagram analysis method is used to analyze the changes of acoustic emission signal parameters with time or external variables to derive the activity and development trend of the acoustic emission source. Here, the experience diagram analysis method is used for the activity evaluation of acoustic emission sources and the description of the lining damage process.

The damage process of tunnel is analyzed by counts and energy change with time. Fig.8 is the time history diagram of acoustic emission parameters under various working conditions, Fig.8(a) is the counts-time curve, and Fig.8(b) is the energy-time curve. There are multiple high peaks in Fig8 (a) and (b) at the same time. The high peak represents the damage signal, and the corresponding strain exceeds the set allowable strain value, indicating that the crown is indeed damaged under these two working conditions. Through the above analysis, it is proved that it is reasonable to use acoustic emission technology in the study of damage process.

Fig.9 shows the cumulative energy time curve of acoustic emission. Here, we define the damage variable D, which can be expressed by the following formula:

\[ D = \frac{E_1}{E_2}, \]

where \( E_1 \) is the cumulative energy value before each time point and \( E_2 \) is the maximum cumulative energy value.

Combined with the cumulative parameter time curve in Fig.8, we can conclude that the cumulative damage evolution process of crown under earthquake can be roughly divided into three stages [17]:

Section AB: Microcracks and pores are compressed and closed at this stage, the lining is mainly elastic deformation; acoustic emission counts and energy is very small, indicating that the acoustic emission signal activity is weak at this stage, called the initial compression elastic stage; Section BC: When the seismic excitation input after a certain time, the microcrack in the lining accelerates to expand and the crack penetrates, acoustic emission counts and energy are very high at this stage, and the corresponding cumulative counts and energy values increase rapidly, which can be seen as a strong acoustic emission signal activity at this stage, called the yielding damage stage. After point C: Lining macroscopic damage phase, acoustic emission activity decreases, the counts and energy value decreases sharply, and the increase of cumulative counts and cumulative energy tends to be gentle, called the residual phase.

From the acoustic emission experience diagram, as the seismic action continues, the damage to the tunnel lining accumulates, and the energy is released relatively uniformly in all time periods. However, there are also some abrupt change points in the process of uniform energy release, which indicates that a longer period of energy accumulation has been carried out before the concentrated energy release, and the release of these higher concentrated energies should also be the moment when the tunnel lining damage undergoes drastic changes. Combined with the variation of the damage variable D with...
time, it can be concluded that the damage of tunnel lining is indeed an accumulative process, and the damage was also found to occur at the tunnel vault after the test. Fig.10 shows the field observation map.

![Field observation map](image1)

### 4. Conclusion

Based on the results and discussions presented above, the conclusions are obtained as below:

1. The source of acoustic emission is located at the crown by linear localization. Taking the crown of the cavern section as an example, the correlation analysis map parameter distribution characteristics were used to determine whether cracks appeared in the tunnel, and the results showed that the tunnel crown was damaged in working conditions 7 and 8.

2. The reasonableness of the acoustic emission parameters to judge the appearance of tunnel cracks is verified by whether the maximum strain in the arch of the same working condition exceeds 100με, and the verification results are consistent with conclusion (1).

3. In this paper, the activity evaluation of the acoustic emission source is carried out using the experience diagram analysis method, which also can further prove the judgment of the above conclusion and describe the development process of the tunnel damage. The damage variable D is defined for tunnel damage process analysis, and the damage process is divided into three stages: initial compression elastic stage, yield damage stage, and residual stage.

4. As a non-destructive testing method, the measurement results of acoustic emission technology can directly and comprehensively reflect the process of internal material defect development and change. In the process of seismic excitation, tunnel lining damage accumulates, and then macroscopic cracks appear. However, the damage process of concrete under seismic action is extremely complex, and its macroscopic damage phenomenon is a comprehensive expression of the accumulation of numerous microscopic damage phenomena, so further research is needed.
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