Damage Evolution Analysis of Rock Slope in Tunnel Entrance Section Under the Seismic Action

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Abstract. Starting from the microscopic heterogeneity feature of the rock material, the paper applies the theory of continuous medium damage mechanics and deduces the constitutive relation for microscopic damage of rock material. Afterwards, this paper sets ANSYS development platform as its main body and puts forward the equivalent damage unit based on the assumption of macroscopic homogeneity to simulate the damage cracking process of the rock side slope at the tunnel portal section based on the principle of microscopic damage mechanics. It is shown in the calculation results that the side slope damage and destruction involve a continuous damaging process from the microscopic perspective. Under the impact of seismic load, there will initially be micro cracks on the side slope structure. As time goes by, these micro cracks will gradually expand into larger ones and finally form penetrated damage area; especially, there will be penetrated damage area formed above the tunnel vault, which can be deemed as that the vault has been completely damaged and poses a negative influence on the safe operation of the tunnel. Therefore, the vault top should be reinforced during design and construction, and the calculation method and analysis results of this paper can be applied to the analysis of damage destruction in similar complex structures.

1. Introduction
It has been shown by severe rock dynamic disasters which have occurred in recent years that collapse and destruction are mainly caused by the joint, fissure and their expansion inside the rock bodies (Guohuang Luo, Xiaozhao Li, Changhong Run, 2004; Mingtian Li, Xiating Feng, Hui Zhou, 2003). The joint and fissure inside the rock bodies serve as the substantial demonstration of the rock damage. Therefore, from the perspective of microscopic damage theory, it is of great significance to study the mechanism and evolutionary characteristics of microscopic damage inside surrounding rock mass for the evaluation and support design of the stability of rock mass engineering.

In 1958, Kachanov put forward the concept of damage mechanics. After keeping being developed for about five decades, some theories have been increasingly mature and applied in various disciplines and engineering technologies. In 1998, Weiyuan Zhou, Gongrui Shan and Ruoqiong Yang applied the theory of continuous medium damage mechanics and started from the damage mechanism for generation and expansion of micro cracks inside the rock bodies to establish constitutive model of anisotropic elastic-brittle damage coupled with elasticity-damage for hard rock bodies. In 2003, Wancheng Zhu, Chunan Tang and Tianhong Yang started from the microscopic heterogeneity feature...
of rocks and applied elastic damage mechanics to describing the evolution process of microscopic damage inside rock materials. In 2008, Bin Sui made use of FLAC3D software to simulate the dynamic response of rocks surrounding some underground cavern group under the impact of seismic load. In addition, he adopted new splitting failure judgement to predict the scope of splitting failure area which might be generated after the earthquake. In 2009, Shuangying Zuo and Ming Xiao carried out numerical simulation on the dynamic response of underground cavern group in Yingxiuwan Hydropower Station under the coupling impact of three-dimensional seismic load to obtain the damage distribution characteristics of surrounding rocks under the impact of seismic load based on the damage mechanism of surrounding rocks of deeply-buried large underground cavern group. In 2010, Zhiguo Zhang, Ming Xiao and Yuting Zhang adopted dynamic time-history analysis method to study the seismic response characteristics of underground cavern and combined the finite element theory of three-dimensional elastic-plastic damage to write the dynamic time-history calculation program and analyze the stability of surrounding rocks of underground plant cavern group beneath Yuzi Stream Hydropower Station.

Relying on the research results of above scholars, this paper applies the mechanical model of continuous medium elastic damage to describing the material properties of the unit based on the assumption of macroscopic homogeneity of rock materials and adopted the maximum tensile stress and the principle of Mohr-Coulomb failure criteria as the damage threshold value. In addition, this paper sets the finite element software-ANSYS development platform as its main body and applies the secondary development characteristics of UPFs. Besides, this paper introduces the damage unit method into ANSYS based on the function of user-customized unit in order to analyze the process from the generation of micro cracks, to expand into visible cracks and then to ultimate damage of the rock side slope at the tunnel portal section under the impact of seismic load.

2. Constitutive model of damage evolution

2.1. The heterogeneity characteristic of rock materials

As a natural geological entity, rock suffers from massive different micro deficiencies due to various factors. Therefore, the composition of rock medium is very complicated. Normally, it is very difficult to describe its composition from the mathematical perspective. In 1993, Chunan Tang assumed that statistical method could be adopted to carry out approximate description on the discretized rock medium. When the material microscopic heterogeneity random model is established, the so-called heterogeneity refers to the mechanical parameters of the material (such as intensity, elastic modulus and Poisson’s ratio, etc). After model is gridded in given space, two problems need to be solved in order to describe this spatial change of material parameters: the first is how to make the material parameters satisfy the heterogeneity distribution law in numerical terms; the second is how to divide the random distributions of these different parameters into different units. This paper regards the rock side slope as a large sample space and applies equivalent damage unit to discretize the rock materials in order the make the discretized unit form possess the characteristics similar to those of common finite unit. In addition, this paper regards them as homogeneous and continuous medium. Afterwards, this paper introduces the probability statistical method into sample space and assumes that the difference in material mechanical properties of each unit follows the Weibull probability statistical distribution, thus demonstrating certain heterogeneity and discreteness. In 2004, Tianhong Yang, Chunan Tang, Tao Xu and their partners assumed that Weibull random distribution can simulate the heterogeneity of material properties relatively well. This distribution can be defined according to following distribution density function:

\[
f(\mu) = \frac{m}{\mu_0} \cdot \left(\frac{\mu}{\mu_0}\right)^{m-1} \cdot e^{-\left(\frac{\mu}{\mu_0}\right)^m}
\]  

In the function, \(\mu\) refers to the random distribution mechanical property parameter of rock material (such as intensity, elastic modulus and Poisson’s ratio, etc); \(\mu_0\) refers to the average value of
mechanical properties of rock material base element; m refers to the density shape function of distribution function of rock mechanical properties, whose physical meaning reflects the homogeneity of rock material; \( f(\mu) \) refers to the statistical distribution function of rock mechanical property.\( \mu \).

Above function greatly reflects the distribution condition of microscopic heterogeneity in mechanical properties of rock material. As the homogeneity coefficient-m increases, the mechanical properties of primitive entity will be concentrated within a narrow range, which indicates that the unit intensity tends to be homogenized. When the homogeneity coefficient-m decreases, the distribution range of mechanical properties of primitive entity will be widened, which indicates that the properties of rock medium tend to be homogenized. Therefore, it can be seen that the value of m can reflect the discreteness degree of material structure in statistical model and relatively faithfully reflect the heterogeneity in rock materials.

2.2. Rock constitutive relation and yielding criteria

In 1993, Daqing Yu assumed that the rock stress-strain curve was caused by the generation and expansion of micro cracks which are led by constant damage to the rock under the impact of stress instead of the plastic deformation of the rock. Especially, its brittleness will become more obvious under the impact of stretch stress. Therefore, it is appropriate to adopt the constitutive model of elastic damage mechanics to describe the microscopic unit mechanical properties of rock materials. In this paper, elastic damage model is adopted for the stress-strain constitutive relation of equivalent unit. Before the seismic load is added, this paper uses elastic model and Poisson’s ratio to define every equivalent damage unit and assume it as linear, elastic, homogenous and undamaged. When the unit enters into damage stage, it can be assumed according to Lemaitre strain equivalent principle that the strain which the stress causes to the damaged material is equivalent to the strain which the effective stress causes to undamaged material. According to this principle, the constitutive relation of damaged material unit can be obtained from the nominal stress in undamaged material, which refers to:

\[
\begin{align*}
\varepsilon &= \sigma / E = \sigma' / E = \sigma(1 - D)E_0 \\
\sigma &= E_0(1 - D)\varepsilon
\end{align*}
\]

In above formula, E0 refers to the initial material elastic modulus; E refers to the elastic modulus after the material is damaged; D refers to damage variable. When D is zero, it is indicated that the material is in undamaged state. When D is 1, it is indicated that the material is in completely damaged state (failed or destroyed). When D is between 0 and 1, it is indicated that the material is in a state of different levels of damage. In the whole damage evolution process, the damage to unit material is assumed to be isotropic. Therefore, the mechanical properties of the material are assumed to be isotropic. In addition, E0, E, D are all scalar quantities. The different levels of unit damage decide the value of damage variable-D.

In rock material damage evolutionary process, as the equivalent damage unit stress keeps increasing, when the unit stress or strain state satisfies some given damage threshold value (criteria), the unit begins to be damaged. Hereunder, two damage threshold criteria are selected: the first one adopts the maximum tensile strain criteria, when the maximum principal stretch strain of the microscopic unit reaches its given strain threshold value, this unit begins to suffer from stretch damage; the second one adopts Mohr-Coulomb criteria, when the stress state of the microscopic unit satisfies Mohr-Coulomb criteria, this unit begins to suffer from shear damage. It should be noted that only after the damage unit does not satisfy the stretch criteria can it be judged whether it satisfies the Mohr-Coulomb criteria considering that the tensile strength of rock material is far lower than its compressive strength and that the unit stretch damage and shear damage will not occur under the same load step simultaneously. Figure 1 and 2 respectively show the unit material stretch constitutive relation curve and compression constitutive relation curve. Formula 3 and 4 show the damage variable expressions respectively corresponding to when the unit satisfies the tensile damage model and when the unit satisfies the Mohr-Coulomb criteria:
In above formula, $f_{tr}$ refers to the unit participation intensity; $\varepsilon_{io}$ refers to the threshold value for tensile damage strain; $\varepsilon_{tm}$ refers to the extreme stretch strain of unit material; $\varepsilon_{c}$ refers to the major strain when the unit stress satisfies the single-axial compressive strength of unit material; $\varepsilon_{cm}$ refers to the extreme strain of unit material; $\varepsilon_{e}$ refers to the unit single-axial compressive strain; $N$ refers to the parameters related to the shape of decline section.

3. Realization of equivalent damage unit in ANSYS
The adoption of constitutive relation and yielding criteria of equivalent damage unit is the greatest difference setting this paper apart from common finite unit. This paper is based on equivalent unit particularity, including generation of random quantities and Weibull distribution which the mechanical parameters of unit material follow. Therefore, UPFs development tool should be used to carry out secondary development on ANSYS development platform. Figure 3 shows the flowchart to establish equivalent damage unit based on secondary development on ANSYS platform. In the figure, the contents in the dash line frame are realized by the functions of UPFs. The detailed program flow is as follows:

After establishing finite element model for rock side slope at tunnel portal section, the user carries out unit compiling and linkage, and then imposes displacement boundary conditions, controls the solution process and output of structure (this part is accomplished by GUI and APDL); afterwards, enter into the solution stage of seismic dynamic analysis and impose seismic load vector; finally, input all the information of the unit established in ANSYS database into the portal subprogram UserElem.f and then complete following steps:

① Check if the equivalent damage unit subprogram is entered for the first time. If it is entered into, use Monte Carlo method to generate random number for material parameter which follows Weibull distribution and then generate the ultimate unit material mechanical parameter. Then store the data into an array and use the COMMON command in FORTRAN Programming Language to define the array as global variable for convenience of later invoking of balanced iteration step and load step. Later, enter into ②; if it is not entered into, directly obtain the material mechanical parameter in the last iteration step and then enter into ②;

② Calculate the unit strain-$\varepsilon$ through the actual node displacement- $\{u\}_t^i+\{\Delta u\}_i^\alpha$; judge whether this unit has been damaged by damage variable- $D_{ij}^\alpha$; $D_{ij}^\alpha$ represents the tensile damage; $D_{ij}^\alpha$ represents compressive damage, in above variables, “$i$” represents the current iteration step while “$l$” represents
the current load step), which means whether \( D^i \) is larger than \( D^0 \) ("0" represents the final iteration step of the last load step). If no, it is indicated that this unit has not been damaged before and then enter into \( ③ \); if yes, it is indicated that this unit has been damaged before and then enter into \( ④ \);

③ Check if tensile damage is caused by the strain- \( \varepsilon \) obtained in \( ② \). If yes, then enter into \( ⑤ \); if no, then check if compressive damage is caused; if yes, then enter into \( ⑥ \); if no, then calculate the overall structural response in ANSYS database;

④ Judge the type of damage caused: if it is tensile damage, then calculate the compressive damage variable- \( D^t_l \);

⑤ Calculate the corresponding tensile damage unit- \( D^t_l \) and weakened elastic modulus-E;

⑥ Calculate corresponding compressive damage unit- \( D^c_l \) and weakened elastic modulus-E;

⑦ Finally, calculate the unit matrix, including unit stiffness matrix, damping matrix, mass matrix and unit equivalent load vector. Then return the above data into ANSYS database and calculate the overall structural response until the seismic load analysis is finished.

Figure 3. Flowchart of ANSYS implementation of the ED element method

4. Rock side slope damage evolutionary simulation

4.1 Side slope calculation parameters and finite element model
After establishing finite element model for rock side slope at tunnel portal section, the user carries out unit compiling and linkage, and then imposes displacement boundary conditions, controls the solution
process and output of structure (this part is accomplished by GUI and APDL); afterwards, enter into the solution stage of seismic dynamic analysis and impose seismic load vector; finally, input all the information of the unit established in ANSYS database into the portal subprogram UserElem.f and then complete following steps:

Calculation of model parameters: elastic modulus $E=3000\,\text{GPa}$; Poisson’s ratio $\nu=0.23$; mass density $\rho=2300\,\text{kg/m}^3$; dynamic tensile strength $f_t=1.5\times10^5$. The random mechanical parameters selected for the material are: the homogeneity extent of elastic modulus and tensile strength $m=2$, $m$ for the Poisson’s ratio is 100. Rayleigh damping is selected for calculation. In calculation, the formation damping ratio of the inherent frequency of the first order and the tenth order is 0.05. The inclination angle of the side slope is 45° while the slope is 20m high. The calculation length in front of the slope is selected as 20m while the calculation length behind the slope is selected as 44m. Besides, the part beneath the slope foot is selected as 20m. Under planar strain status, equivalent damage unit (whose geometrical shape is similar to the four-node planar strain unit) is adopted to discretize the finite element grid. The discretized unit size is about 0.4m*0.4m. In addition, there are 18589 units and 18941 nodes in the model. Afterwards, horizontal restraint is imposed on both sides of the model while the bottom is reinforced. The input of seismic wave is divided into horizontal input and vertical input. The acceleration of horizontal peak value is 0.474g while the acceleration of vertical peak value is 0.312g. The overall duration of seismic load is 10.56s. Figure 4 shows the finite element model for the side slope while Figure 5 shows the acceleration time-history curve.

4.2. Side slope seismic damage evolutionary analysis
This paper selects 6 typical time points (2.64s, 2.92s, 5.78s, 6.96s, 8.98s, 9.42s) from the whole process of seismic load impact to analyze the overall process from emergence of micro cracks, to visible cracks, to constant crack expansion and finally to the formation of damage area at the rock side slope of tunnel portal section. The damage evolutionary process and the distribution of principal strain stress are shown in Figure 6. In the analysis of damage evolutionary process at rock side slope of tunnel portal section, impose seismic load on the basis of static force load (only gravity load is added in this paper). In the initial stage of seismic load incentive, the majority area of the side slope is under
compression. Although there is no severe crack in the structure, a few units with weaker material intensity suffer from damage of different levels due to the influence of random distribution of unit material and micro cracks begin to show up on the slope surface. Generally speaking, the side slope structure is in a sound state as a whole. As the seismic load incentive time increases, the micro cracks which have occurred keep expanding and new micro cracks begin to show up constantly. These micro cracks gradually expand and finally form several visible cracks behind the slope as shown in Figure 6 (a) and (b); with the continual shaking of seismic load, the scope of cracks behind the slope keeps expanding and the damage area gradually gets larger on the slope surface; besides, cracks begin to show up above the portal vault and at the middle of slope surface and then expand into larger ones, thus forming multi-penetrated damage area while causing a re-distribution of principal tensile stress as shown in Figure (c) and (d); finally, the cracks above the vault keep expanding and ultimately form a damage area penetrating the whole vault top under the impact of continual shaking of seismic load. At this time, it can be assumed that the vault top has been totally destroyed, which will influence the safe operation of tunnel; the crack formed at the middle of slope surface from upwards to downwards can be approximately regarded as the sliding trend which the impact of strong earthquake causes to the side slope structure as shown in Figure (e) and (f).

Figure 6. Failure process of slope with principal tensile stress: (a) 2.64s;(b) 2.92s;(c)5.78s;(d) 6.96s;(e) 8.98s;(f) 9.42s
5. Conclusions

(1) This paper theoretically obtains the constitutive relation of microscopic rock damage, which can reflect the rock heterogeneity and the process of macroscopic failure and loss of stability, by introducing microscopic damage representative elemental entity and applying the theory of continuous damage medium.

(2) The damage to rock side slope under the impact of seismic load is the result of constant generation and accumulation of microscopic material damage. In the initial stage of seismic load incentive, the majority of side slope area is pressed by stress. Although there is no severe crack in the structure, a few units with weaker material intensity suffer from damage of different levels due to the influence of random distribution of unit material. In addition, micro cracks begin to show up behind the slope and then gradually connect with each other to form several visible cracks. With the continual shaking of earthquake, new cracks begin to emerge above the cavern vault and at the middle of slope surface. Finally, a continuously-penetrated damage area will be formed above the portal vault. At this time, it can be assumed that the vault top has been totally destroyed, which will influence the safe operation of tunnel. Therefore, the vault top should be necessarily reinforced during portal design and construction; the crack formed at the middle of slope surface from upwards to downwards can be regarded as the sliding trend which the impact of strong earthquake causes to the side slope structure. Consequently, it should also be focused on during design and construction.

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