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Summary of Rock Damage Mechanics Classification

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Abstract: As an important means to study the mechanical properties and failure mechanism of rock materials and engineering mechanics, damage mechanics is often used to assist in the analysis of the failure process and mechanism of rock, metal, and other materials in the current research. In the use of damage mechanics to study the properties of rock materials and explore the deformation and failure law of rock, important research results have been achieved. The research methods of damage mechanics can be roughly divided into three types: statistical damage model, mesoscopic damage model, and continuous damage model. Based on the existing literature in hand, according to the division of damage mechanics research methods in the academic community, this paper collates and considers that the existing damage model construction can be summarized from the mechanical point of view. The pure theory is derived or fitted from the mathematical point of view. One of them is derived from the mechanism point of view, and the other is derived from the phenomenon point of view. The stress, strain, acoustic emission, and other data are analyzed and reconstructed, and both have advantages and disadvantages.

Keywords: Rock Mechanics; Damage; Classification; Summary.

1. Introduction

As a common engineering material, it is of great significance to study the deformation and failure of rock. The development of damage mechanics provides a new way to study the mechanical properties and failure mechanisms of rock materials and engineering. Using damage mechanics to study the properties of rock materials and explore the deformation and failure law of rock has achieved important research results. The research methods of damage mechanics can be roughly divided into three types: statistical damage model, mesoscopic damage model, and continuous damage model.

The statistical damage model is characterized by the physical and mechanical properties such as material strength, obeying Weibull, Guass, Normal probability distribution, defining the damage variable under specific stress or strain conditions, and using the probability function curve to define the stress-strain whole process damage evolution equation. In terms of parameter determination, it is still necessary to extract parameters from specific conditions such as uniaxial stress-strain curves. Statistical damage is the only one of the three damage models that do not consider the internal mechanism in the process of rock failure. Starting from the phenomenon, it is progressive by mathematical method. The essence of this method will lead to the poor universality of the statistical damage model, which is generally not widely used.

The macroscopic (continuous) damage model is proposed in the framework of thermodynamics. A concept similar to plastic theory is used to construct the damage dissipation potential function, dually calculate the damage driving force, construct the damage criterion, and calculate the damage increment. The plasticity uses a different damage plastic potential function and plastic yield criterion to calculate the plastic strain increment. The coupling of damage and plasticity is realized by introducing damage and plastic internal variables into the damage dissipation potential function and the plastic potential function, respectively. The parameters of the model need to be obtained by forming a plastic yield surface in a large number of multi-confining pressure data points. Therefore, it is not easy to determine the parameters. The macroscopic (continuous) damage model, starting from the macroscopic energy, grasps the large and small and ignores the small boundary thought and its similarity in the Saint-Venant principle. From the perspective of macroscopic energy, the mechanism of rock failure can be grasped from a higher perspective, but it is relatively easy to ignore in some details.

The microscopic damage mechanics model, starting from the micromechanics mechanism of the micro-element (micro-cracks, micro-holes), studies its damage and plastic evolution. The homogenization methods such as strain concentration tensor, stress concentration tensor, energy reciprocity theorem, and self-consistent method are used to transform the micro-element damage and plastic effect into the tensor representation of macroscopic RVE. Because this method is completely the result of theoretical derivation, and the test will face various errors, there is often a huge deviation between the theoretical results and the test results.

2. Three Damage Models

2.1. Statistical Damage Model

The statistical damage model is a typical mathematical method to solve physical problems. It is not so much a physical problem as a mathematical problem. That is, under the test of a large amount of data, things will appear as the law of large numbers and the central law. The principle of statistical damage mechanics is to approximate a certain characteristic of rock by mathematical method and statistical probability function under the support of a large number of rock experimental data. For example, the Weibull probability function is used to characterize the elastic modulus and mechanical properties in the process of rock failure. This fitting generally selects one or two physical properties as variables, and the others are set to constant constants. High residuals are achieved by multiple processing of the data.

Deng Jian [1] defined the damage variable based on the Weibull probability function and used the D-P and M-C expressions to express the static or dynamic stress of the intrinsic meso-element to establish the whole process damage evolution model of stress-strain. Wang Zhi-liang [2] considered the residual strength in the statistical damage model. Yang et al [3] defined the damage variable and its evolution process by using the Weibull probability function and established the elastoplastic constitutive relation of rock by using the Eshelby equivalent inclusion method of micromechanics.

Xu Weiya [4] regarded rock as a unified whole composed of a finite number of micro-elements. The failure process of rock is composed of the failure of micro-elements. The proportion of the failure micro-elements to the total micro-elements is defined as the damage variable, which ranges from 0 to 1.

Based on the Drucker-Prager failure criterion and the unified strength theory, it is considered that the micro-element failure process conforms to Weibull, and the following (Formula 1) damage model is established.

$$D=\int_0^{f(\sigma)}\frac{m}{F_0}\left[\frac{f(\sigma)}{F_0}\right]^{m-1}e^{-\left[\frac{f(\sigma)}{F_0}\right]^m}df(\sigma)$$
$$=1-e^{-\left[\frac{\alpha_0 I_1+J_2^{1/2}}{F_0}\right]^m} \quad (1)$$

Here, ***m*** and F_0 are Weibull distribution parameters.

Substitute Equation 1 into Unified Strength Theory Equation 2

$$\sigma=(1-D)E\varepsilon \quad (2)$$

The rock damage evolution equation and the following three-dimensional elastic damage statistical constitutive equation (Equation 3) are obtained:

$$\sigma=\left[C_n e^{-\left[\frac{\alpha_0 I_1+J_2^{1/2}}{F_0}\right]^m}+1-C_n\right]E\varepsilon+\mu(\sigma_2+\sigma_3) \quad (3)$$

Cao Wengui [5] abstracted the rock material under stress into two parts: failure and non-failure. According to the different stress conditions of these two parts, the energy principle of rock material yield or failure is introduced, and the statistical damage evolution equation of rock is determined by the Weibull distribution of rock micro-element strength.

Assuming that the strength of the rock element obeys Weibull distribution, the damage variable of rock can be obtained, that is, the statistical damage evolution equation (Eq. 4).

$$D=\int_0^F P(x)dx$$
$$=1-e\left[-(F/F_0)^m\right] \quad (4)$$

It is assumed that the damaged rock material under stress is composed of two parts, namely, undamaged material and damaged material. Both parts can bear a certain bearing capacity, and the total load of rock material is shared by these two parts. Assuming that the stress and strain of rock materials are σ_i and ε_i, respectively, and the action area is *A*; the stress and strain of the undamaged material are σ_i' and ε_i', respectively, and the corresponding action area is *A*'. The stress and strain of the damaged material are σ_i'' and ε_i'' respectively, and the corresponding action area is *A*" and the expression of the damage variable is derived:

$$D=\frac{2E\varepsilon_1+2\mu\sigma_3-\sigma_1}{2E\varepsilon_1} \quad (5)$$

Xiang Li [6] introduced the basic theory of damage mechanics to deal with the strain-softening deformation of rock. Then, by combining statistical considerations, the evolution equation of rock damage was formulated, and the influence of the damage threshold was characterized by measuring the strength of mesoscopic elements. The statistical damage constitutive model of rock is further proposed.

Based on the rock damage model of Lemaitre strain equivalence theory, Zhu [7] assumed that the strength of rock micro-elements subjected to thermal damage obeys Normal distribution. Considering the influence of temperature on rock mechanical parameters, the thermal damage variable is introduced. Under the condition that the micro-element failure conforms to the Mohr-Coulomb criterion, the statistical thermal damage constitutive model of rock after the high temperature is established to solve the development and protection problems of high-temperature rock mass engineering.

2.2. Continuum Damage Model

The continuous damage model is an extension of the continuous mechanics method. In the framework of thermodynamics, different potential functions are constructed. As a quasi-brittle material, rock has no obvious plastic deformation macroscopically, but has local plastic deformation microscopically. Therefore, it is not perfect to assume that the rock mesoscopic unit satisfies the elastic damage constitutive. The continuous damage model is a combination of mechanics and statistics to analyze a series of characteristics of rock after entering the plastic state.

Yuan Xiaoping [8] used the continuous damage mechanics method to express the damage variable with the volume strain, and the damage evolution was expressed by the Weibull function. It is considered that the softening of rock damage is caused by the volume expansion caused by the development of micro-fractures. It is proposed to characterize the evolution of rock damage variables by volume strain, which is an exponential function of volume strain.

The volume strain and evolution equation of time t are expressed as follows.

$$(\varepsilon^v)_t=\max\left\{\varepsilon_0^v,\max_{s\in[0,t]}(\varepsilon^v)_s\right\} \quad (6)$$

$$(D)_t=1-\exp[-a_4((\varepsilon^v)_t-\varepsilon_0^v)] \quad (7)$$

Here, ε^v and ε_0^v are volume strain and the corresponding volume strain threshold respectively, volumetric strain threshold ε_0^v=0 That is, there is damage when the volume expands, a_4 is the normal number obtained from the experiment.

The elastoplastic damage constitutive program of rock is compiled by using the mapping implicit integration algorithm. The classical plastic mechanics method is used to define the plastic strain. The D-P yield criterion is used as the plastic potential function, and the Borja stress invariant tensor is used to represent the hardening function. By introducing the damage variable into the D-P criterion, the coupling of plasticity and damage is realized.

Chen Liang [9] established a plastic dissipation potential equation with damage driving force and damage variable as conjugate quantities in the framework of thermodynamics. The plastic strain is derived from the plastic potential equation in the framework of classical plastic mechanics. The coupling of plasticity and damage is realized by introducing plastic internal variables and damage variables into two potential equations, namely non-associated plastic flow equations, to reflect the transformation process of volume deformation of rock from compression to expansion under compressive stress.

The model is based on the analysis of mechanical tests and acoustic emission characteristics, which can accurately describe the main mechanical properties of Beishan granite, including the transformation process of rock mechanical behavior from brittleness to ductility with the increase of confining pressure, post-peak stress softening and damage evolution under different stress conditions.

Zhao [10] defined the damage variable based on the ratio of the equivalent plastic strain of rock and introduced the damage variable into the plastic potential function to realize the coupling of plasticity and damage. Weibull function distribution is used to describe the mechanical properties of rock meso-element such as strength and elastic modulus. The meso-mechanics method and numerical calculation method are organically combined to study the nonlinear mechanical behavior of rock by considering the characteristics of non-uniformity.

Fang et al. [11] used Yunying rock salt to carry out triaxial compression tests under multiple confining pressures and analyzed the deformation characteristics of rock salt under different confining pressures. Based on the experimental analysis, an elastoplastic damage coupling model is proposed to describe the characteristics of rock salt. The model describes the coupling relationship between the evolution of rock salt damage and plastic deformation and introduces a non-associated plastic flow rule to describe the transformation of rock salt from plastic volume compression to expansion. The model was used to simulate the stress-strain relationship of rock salt under triaxial compression, and compared with the experimental data. The results show that the model can better describe the main mechanical and deformation characteristics of rock salt. A unified thermodynamic potential function including damage and plasticity is established to achieve the coupling of damage and plasticity. The modified form of D-P is used as the plastic yield function, and the hardening function is introduced. The plastic strain is obtained in the framework of traditional plastic mechanics, and then the thermodynamic potential function expression reflecting plastic hardening is obtained. The thermodynamic function of damage driving force is obtained by duality, and the damage criterion is obtained by the Marzars function.

Molladavoodi H. [12] defined the thermodynamic conjugate force of damage in the thermodynamic framework and considered the coupling with frictional plasticity. According to the characteristics of the rock stress-strain curve, the damage evolution was defined, and the damage yield functions under compression and tension conditions were defined respectively.

Zhou H. [13] defined the damage increment in the thermodynamic framework. The effect of damage on plasticity is reflected after the peak. There are two plastic mechanisms, friction slip and micropore collapse. Their yield functions are the D-P criterion and the Gurson plastic hole yield criterion, respectively.

2.3. Micromechanical Damage Model

Chen Xin [14] established the elastoplastic vector relationship between the stress vector and the strain of the joint surface. The tensor relationship between macro-stress and macro-strain is established by the macro-meso framework-geometric constraint model. Damage and plasticity on the microsurface occur under two stress states. When in the tensile state, the micro-surface produces tensile damage, and the tensile strength is also weakened. When under compressive stress, plastic sliding and shear damage occur on the micro-surface. The calculation of damage and plasticity adopts the framework of plastic mechanics.

Zhu [15] established the relationship between fracture geometry and mechanical properties and macroscopic flexibility tensor according to Betti's energy reciprocity theorem and modified self-consistent method. The crack is a three-dimensional coin crack, and the damage evolution equation based on fracture energy expansion is established.

Yuan [16] first established the transformation relationship between the effective stress around the microcrack and the macroscopic stress tensor of RVE by the self-consistent method. The method is to introduce the stress concentration tensor. The damage evolution and plastic strain of micro-cracks are based on the plastic plastic theory framework. The damage variable is represented by the volume of energy released by crack propagation. A meso-mechanical model of rock elastoplastic damage based on microcrack propagation is established. The self-consistent method is used to consider the interaction between cracks. The stable propagation of wing cracks at the tip of microcracks characterizes the micro-damage of rock.

Xie N. [17] realized the homogenization transformation from meso to macro by introducing the Eshelby strain concentration tensor from the friction slip of micro cracks. The frictional plastic potential function is adopted, and a more refined Mohr-Coulomb criterion is defined on the micro-slip surface as a plastic yield function. Based on the macroscopic thermodynamic potential function, the damage driving force is defined, and the damage criterion in exponential form is given. It is considered that damage is accompanied by plasticity, and the consistency equations of the plastic potential function and damage-driven potential function are listed.

3. Conclusion

The classification of rock damage mechanics has not given a more detailed classification standard, and the three research methods are not completely independent. The construction of a continuous damage mechanics model will also use the probability function, and there is no clear boundary between the three.

(1) Three different models have their limitations. First of all, most of the statistical damage models are not related to the nature of the rock itself from a mathematical point of view. They are the apparent description of the phenomenon of rock failure. Therefore, most of the statistical damage models can only describe one or several properties and do not involve the mechanism of rock failure.

(2) The continuous damage model is derived from continuous mechanics. It has a good description of many characteristics of the plastic state, but its limitations are also greater. The establishment of the continuous damage model is very dependent on the experimental data. Many models are

established under specific confining pressure, which reduces the universality of the model.

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