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Emphasizing the Creep Damage Constitutive Model of Hydro-Mechanical Properties of Rocks: A Case Study of Granite Gneiss

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Abstract: The constitutive model of rock materials can describe the mechanical behavior of rocks in creep tests. Also, it is one of the important means to study the deformation and strength characteristics of rocks in complex stress environments. This paper is based on the analysis of the porosity variation characteristics of the internal structure under the coupling effect of rock hydro-mechanical properties. The concept of the hydro-mechanical properties variable is proposed, and the relationship between the coupling variable, damage and plastic deformation is established. By introducing the coupling variable, instantaneous damage variable and time-dependent damage variable into the yield surface equation, as well as the plastic potential energy equation and the stiffness matrix of the elastic–plastic creep constitutive equation, a hydro-mechanical properties creep damage coupling model was established to simulate the creep mechanical properties of rock under coupling. Based on the triaxial creep test results of granite gneiss, the model parameters are determined. By comparing the test results with numerical results, it was revealed that the model can better describe the creep mechanical properties of rocks under the coupling effect of hydromechanical properties.

Keywords: creep; hydro-mechanical properties; damage; constitutive model; granite gneiss

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1. Introduction

The rock creep constitutive model can describe the creep mechanical behavior of rocks under long-term loading [1]. Its main research methods include directly applying empirical fitting formulas to creep test results, component models established through the combination of series and parallel connections of various components and the addition of nonlinear terms. Three kinds of constitutive models of rock are established by using the elastic–plastic theoretical framework, damage mechanics and endochronic theory [2].

The empirical constitutive model of rock rheology is established based on the results of creep experiments using function fitting. Among them, logarithmic and power exponential functions, as well as mixed functions, are the main forms of empirical formulas for rock creep. The existing research results indicate that the rock creep empirical model is simple, intuitive and applicable with high certainty, which is in good agreement with the experimental results [3–5]. However, it cannot fully reflect the accelerated creep stage. In addition, the empirical model is only an approximation of mathematical formulas, and the physical meaning of the model parameters is not very obvious, so it cannot obtain creep mechanical parameters that can be applied to engineering practice, greatly limiting its development [6,7].

The rock creep element model includincludedes basic elements such as elasticity, viscosity, and plasticity. Each basic element represents different creep properties of the rock. Integrating the basic components, in series or parallel, which is a composite component model that can reflect various creep characteristics can be obtained. The research on constitutive models of rock elements mainly focuses on the following three aspects: (1) introducing new nonlinear components to establish a new constitutive model of the components, (2) taking the parameters in the model as non-stationary values, and (3) introducing new methods and theories to establish the model [8–10]. In recent years, more and more experts and scholars have conducted in-depth research on the nonlinear creep mechanical behavior of rocks based on the advantages of component models, and established many new nonlinear constitutive models using methods such as substitution and addition [11,12]. However, the creep properties exhibited by rocks under complex stress states and geological environments are very complex. In practical engineering, it is not a simple combination of components that can comprehensively describe the constitutive relationship during the creep process of rocks. Therefore, several researchers, based on the fundamental principles of thermodynamics and from the perspective of energy dissipation in the rock creep process, established elastic–plastic constitutive models by defining the plastic yield surface and plastic potential energy equation in the rock creep process to describe the mechanical and deformation behavior in the rock creep process [13,14].

The study of elastic–plastic constitutive models based on thermodynamics has been widely used on the international scale [15]. By finding suitable yield surface equations and plastic potential energy equations, the establishment of elastic–plastic constitutive models can be achieved [16,17]. The coupling between plastic flow and damage through the introduction of damage variables is the foundation for in-depth research on the real structural changes in rock interior, which also provides a reasonable approach for studying elastic–plastic damage models [18]. The simulation of the creep behavior of rocks under permeable water pressure is the future trend and direction of the development of elastic–plastic constitutive models [19,20]. The rock seepage and coupling effect of hydro-mechanical properties caused by the interaction between seepage pressure and internal structure in a water environment is a key factor affecting the long-term stability and safety of rock engineering; rocks influence and interact with each other in an environment where multiple fields, such as the stress field in the Earth's crust, seepage, and chemistry and temperature coexist and are in a dynamic equilibrium, especially the interaction between hydro-mechanical property fields [21,22]. This interaction and influence is the coupling characteristic of rock's hydro-mechanical properties, which has an important impact on the safety and stability of foundations. Therefore, conducting research on the elastic–plastic creep damage model under hydro-mechanical properties has important research and engineering significance for describing the instantaneous and creep mechanical behavior of rocks in complex environments and stress conditions [23].

Our paper proposes a hydro-mechanical properties variable by analyzing the porosity variation characteristics of the internal structure of rocks. The coupling variable, instantaneous damage variable, and time-dependent damage variable are introduced into the yield surface equation, plastic potential energy equation, and stiffness matrix of the elastic–plastic creep constitutive equation. A hydro-mechanical properties creep damage coupling model is established in order to simulate the creep mechanical properties of rocks, as a case study of granite gneiss. The granite gneiss used for test validation is a low-porosity rock. The tested granite gneiss has a compact structure with a mean porosity of 1.79% and an initial density of 2.61 g cm^{-3}. Through comparing the creep test of granite gneiss under hydro-mechanical properties coupling with the model simulation, the accuracy of the model can be verified.

2. Characterization of Damage Model and Hydro-Mechanical Properties Model

2.1. Damage Model in Rock Creep Process

The degree of rock damage is not only related to the stress level, but also to the internal structure of the rock, which continuously deteriorates under the action of time-dependent damage. The stress level includes its stress state, permeability characteristics, chemical corrosion and temperature changes. The internal structure mainly involves the friction of small particles within the rock, the generation and expansion of internal microcracks. It is necessary to establish a criterion for the evolution of time-dependent damage, which is used to describe the time-dependent damage law in the creep process of rocks. Here, the internal variable of time-dependent damage is introduced to describe the characteristics of time-dependent damage. Internal variable ζ is used to describe the time-dependent damage of rocks, which can explain the relative damage changes of micro contact surfaces between solid particles per unit volume unit of rock under stress. It can be seen as a time-dependent function describing the plastic deformation of rocks, which can be expressed as Equation (1):

$$\zeta(t) = \zeta(\boldsymbol{\varepsilon}^p, t) \tag{1}$$

where $\boldsymbol{\varepsilon}^p$ = plastic deformation and t = time. It can be seen from the creep characteristics of rock in the creep mechanical property test that with the increase of time, the time-dependent damage variable ζ will tend towards a state of equilibrium. Set the time-dependent damage variable function in this state to $\overline{\zeta}$, which represents an equilibrium state of the internal microstructure of the rock, that is, when time approaches infinity, ζ will tend towards $\overline{\zeta}$.

Assuming that the damage evolution of the microstructure inside the rock can be described by the deviation of the damage variable from the equilibrium state, then this feature can be achieved using $(\overline{\zeta} - \zeta)$. A simple linear model can effectively describe the time-dependent damage characteristics of the internal microstructure of rocks over time, as shown in Equation (2).

$$\frac{\partial \zeta(t)}{\partial t} = \gamma(\overline{\zeta} - \zeta) \tag{2}$$

In the equation, γ represents the experimental constant that ignores external factors such as temperature changes and chemical corrosion and can be taken as a certain value. The evolution characteristics of time-dependent damage are mainly determined by the equilibrium state function $\overline{\zeta}$ of time-dependent damage variables, which depends on the magnitude of stress levels and ranges from 0 to 1. The range of values for the time-dependent damage variable ζ is between 0 and, when time t = 0, ζ = 0; when t approaches infinity, ζ = $\overline{\zeta}$. According to the mathematical characteristics of the time-dependent damage variable, the time-dependent damage characteristics can be represented by Equation (3).

$$\overline{\zeta} - \zeta = \overline{\zeta} e^{-\gamma t} \tag{3}$$

In the equation, when time t = 0, both sides are equal to $\overline{\zeta}$; when t approaches infinity, $e^{-\gamma t}$ tends to 0, and both sides of the equation are equal to 0. At the same time, the exponential function represents the memory effect of the previous loading process, which can better express the change characteristics of time-dependent damage at each stage.

In the establishment of constitutive models for rock creep damage, it is not only necessary to consider the time-dependent damage characteristics during the creep process, but also the instantaneous damage d during the instantaneous loading stage. J. Mazars [24] proposed a damage criterion to characterize the transient loading damage evolution of rock.

$$f_d\left(Y_d^p, d\right) = d_c \tanh\left(B_d Y_d^p\right) - d \leq 0 \tag{4}$$

In Equation (4), d_c is the maximum critical value of the damage variable, and B_d is the parameter that controls the rate of damage evolution. ${Y_d}^p$ is the driving force for the evolution of rock damage, expressed as Equation (5):

$$Y_d^p = -\frac{\partial \Psi}{\partial d} = \frac{1}{2}(\boldsymbol{\varepsilon} - \boldsymbol{\varepsilon}^p) : \mathbb{C}'(d) : (\boldsymbol{\varepsilon} - \boldsymbol{\varepsilon}^p) + \left(\gamma_p - \left(1 - \alpha_p^0\right) B \ln \frac{B + \gamma_p}{B}\right), \tag{5}$$

It can be seen that the expression of the damage-driving force is a function of plastic shear strain γ_p, indicating that once micro cracks undergo dislocation, it will cause the evolution of damage.

We assume that the total damage in the creep property test of rock is ω, then the total damage ω can be expressed as the sum of instantaneous damage d and time-dependent damage ζ, presented in Equation (6).

$$\omega = d + \zeta, \tag{6}$$

The equilibrium state function $\overline{\zeta}$ of rock time-dependent damage variables can be defined as being associated with the plastic hardening function. In creep property tests, α_p is the plastic hardening function, which is related to the internal friction angle of the material and is a function of plastic deformation. It is used to describe the plastic hardening phenomenon during plastic deformation, and can be expressed as Equation (7):

$$\alpha_p = \alpha_p^0 + \left(1 - \alpha_p^0\right)\frac{\gamma_p}{B + \gamma_p}, \tag{7}$$

where B is the parameter that controls the hardening rate of the material; ${\alpha_p}^0$ is the parameter that controls the position of the initial plastic surface of the rock; and γ_p is the plastic shear deformation value. Let $\overline{\zeta} = (1-\omega)\alpha_p$. The time-dependent damage expression in the elastoplastic creep damage constitutive model of rock can be obtained as below:

$$\zeta = \overline{\zeta}\left(1 - e^{-\gamma t}\right) = (1-\omega)\alpha_p\left(1 - e^{-\gamma t}\right), \tag{8}$$

In Equation (8), by describing the time-dependent damage variable in the creep process, an elastoplastic creep damage constitutive model that would describe the creep mechanical properties of rock can be established.

2.2. Hydro-Mechanical Properties Model

There is a certain correlation between the changes in volume porosity caused by rock expansion and the plastic deformation generated by the rock after entering the internal damage expansion and deformation failure stages. Worldwide, some researchers, such as Morris [25], and Rubin [26], have proposed this viewpoint in this regard. Among them, Rubin and other scholars proposed the relationship equation between the change rate of expanded porosity and strain increment through their research on the mechanical model and numerical simulation of viscoelastic plastic materials in porous media.

$$\mathrm{d}\phi_{dil} = \frac{m_d q\left(\phi_{dil}^{\max} - \phi_{dil}\right)\mathrm{d}\varepsilon_p}{p}, \tag{9}$$

In Equation (9), $\phi_{dil}^{\max}$ is the maximum threshold for expanding porosity, m_d is the parameter characterizing the rock expansion rate, and p and q are the average stress and deviatoric stress of the rock, respectively. It can be seen that in the linear elastic stage of the rock hydro-mechanical properties mechanical characteristics test, the rock does not exhibit the expansion phenomenon and plastic deformation characteristics and its expansion porosity is 0. When entering the stage of plastic deformation, namely internal damage propagation and deformation failure, Darcy's law is no longer applicable to the law of rock seepage at present, the increment of expanded porosity shows a significant increase with the increase of plastic deformation increment and deviator stress.

Based on the theory of porous continuous media, the instantaneous permeate flow rate inside rocks can be expressed as follows:

$$\Delta V_l = \frac{A_s \Delta p \Delta t}{\mu_l L_s} K, \tag{10}$$

In Equation (10), ΔV_l is the volume of infiltration water in the rock sample at the instantaneous moment (m^3); A_s is the cross-sectional area of the rock sample (m^2); ΔP is the difference of pore pressure applied at the upper and lower ends of the rock sample

(Pa); Δt is the time interval (s); K is the permeability of rock (m^2); μ is the dynamic viscosity coefficient of water at 20 °C (Pa · s), $\mu = 1 \times 10^{-3}$ Pa·s; L_s is the height of the rock sample (m).

According to the study by Liu et al. [27] on the creep test of rock hydro-mechanical property characteristics, the relationship equation between permeability and the volumetric strain of rocks under hydro-mechanical properties can be obtained. The volumetric strain can be used to characterize the instantaneous infiltration amount of water into the rock sample, as follows:

$$K = \begin{cases} y = a_1 \exp(-b_1 \varepsilon_v) + c_1 & (t < t_A) \\ L & (t_A \leq t < t_B) \\ y = a_2 \exp[b_2(\varepsilon_{vB} - \varepsilon_v)] + c_1 & (t \geq t_B) \end{cases}, \tag{11}$$

In Equation (11), ε_{vB} is the volumetric strain at the volume strain dilatancy point, and ε_v is the volumetric strain. t_B is the time at the volume strain dilatancy point, and the permeability in the volume compression stage is expressed in the form of exponential function, while the permeability in the volume dilatancy stage is expressed in the form of a logarithmic function. The list of experimental parameters in reference [27] is shown in Table 1.

Table 1. Test parameters based on the creep test results of Liu et al. [27].

Pore Pressure	Parameters of the Test Data						
	a_1	b_1	c_1	L	a_2	b_2	c_2
1 MPa	3.471	1.011	0.301	0.894	0.144	0.557	1.145
2 MPa	7.213	1.164	−0.062	1.771	0.857	0.383	1.075
3 MPa	7.020	2.005	2.543	3.403	0.231	0.661	3.422

The effect of permeable water on rocks is mainly reflected in the water pressure in the microcracks and pores within the rock. Therefore, for saturated rocks that were fully saturated with water in a vacuum before the test, the ratio of the instantaneous seepage flow rate to the instantaneous pore water volume can be used to reflect the influence of permeable water on the internal stress field changes of the rock. We define a coupled variable of hydro-mechanical properties ξ to characterize the influence of instantaneous infiltration of water on the rock stress field.

$$\xi = \frac{\Delta V_l}{A_s L_s \phi}, \tag{12}$$

Equation (12) is the coupling variable expression of hydro-mechanical properties that we define. ϕ is porosity of rocks. It can be seen that the size of the coupling variable is influenced by multiple factors such as the stress, strain and damage variables in the hydro-mechanical properties test of the rock. The changes in volume strain, plastic strain and deviatoric stress directly affect the variation pattern of coupled variables. At the same time, changes in coupled variables under the influence of these variables will, in turn, change the stress field inside the rock, thereby affecting the variation pattern of volume strain, plastic strain and other variables, and achieve these coupling characteristics.

3. Establishment of Hydro-Mechanical Properties Creep Damage Constitutive Model

3.1. Plastic Yield Surface Equation

An improved Drucker–Prager quadratic function criterion is used as the plastic yield and failure surface function [2,28]. By introducing coupling variable ξ to achieve the hydro-mechanical properties characteristics, and considering the total damage ω introduced into the plastic yield surface equation, the plastic yield surface equation of the hydro-mechanical properties creep damage constitutive equation is obtained as Equation (13).

$$f = q^2 + A_0(1 - \alpha\xi)(1 - \omega)h(\theta)\alpha_p(p - C_0)p_0 = 0, \tag{13}$$

The parameters C_0 and A_0 represent the initial cohesion and internal friction angle of the material failure surface, respectively, while p and q represent the average stress and deviator stress values; p_0 is a normalized parameter, with a value of 1 MPa. The expression $h(\theta)$ is used to consider the effect of Rhode's angle θ on the plastic yield surface under complex stress conditions, and the expression $h(\theta)$ generally needs to be determined through experiments. In order to simplify the numerical calculation process, $h(\theta) = 1$ is taken in this model. α, α_1 and α_2 are the model coefficients and all the values are 1. α_p is the plastic hardening function, which is related to the internal friction angle of the material and is a function of plastic deformation.

3.2. Plastic Potential Energy Equation and Flow Law

The plastic potential energy of materials determines the increment of plastic strain and the plastic flow law. For ideal materials, the maximum plastic power consumption principle can derive the relevant flow law. However, for rocks with complex internal structures, the direction of plastic flow does not comply with conventional thermodynamic rules, and the strain rate is closely related to the stress state. The associated flow rule cannot describe them well. It is necessary to choose an appropriate plastic potential energy function to define a non-correlated flow rule. S. Pietruszczak and other scholars [29] considered the conversion between rock volume compression and expansion and introduced a non-correlated plastic potential energy equation. The role of damage evolution and coupling effects is still achieved by introducing damage variable and coupling variable. The specific expression of the plastic potential energy equation under hydro-mechanical properties creep damage is as follows:

$$g = q + A_0(1-\alpha_1\xi)(1-\omega)\eta h(\theta)(p - C_0)\ln\left(\frac{p - C_0}{I_0}\right) = 0, \tag{14}$$

In Equation (14), I_0 is the intersection value of the plastic potential surface and the mean stress p-axis, η is the numerical value corresponding to the critical point ($\partial g/\partial p = 0$) of plastic volume compression and expansion.

3.3. Model Establishment

According to the time-dependent damage characteristics of the creep process under the coupling effect of rock hydro-mechanical properties, the expression of the hydro-mechanical properties creep damage coupling constitutive model is as follows:

$$\boldsymbol{\sigma} = \mathbb{C}(\xi,\omega) : (\boldsymbol{\varepsilon} - \boldsymbol{\varepsilon}^p) = (1-\alpha_2\xi)(1-\omega)\mathbb{C}^0 : (\boldsymbol{\varepsilon} - \boldsymbol{\varepsilon}^p), \tag{15}$$

In Equation (15), the description of hydro-mechanical properties creep damage constitutive law is divided into two stages, instantaneous loading and creep, and the total strain is decomposed into the elastic strain, plastic strain and time-dependent strain to describe the following:

$$\boldsymbol{\varepsilon} = \mathbb{S}(\omega,\xi) : \boldsymbol{\sigma} + \boldsymbol{\varepsilon}^{\xi p} + \boldsymbol{\varepsilon}^{\xi t}, \tag{16}$$

In the equation, $\mathbb{S}(\omega,\xi)$ is the total damage fourth order flexibility matrix under the coupling of hydro-mechanical properties, $\boldsymbol{\varepsilon}^{\xi p}$ and $\boldsymbol{\varepsilon}^{\xi t}$ represent the plastic strain and time-dependent strain in the coupled creep process of rock hydro-mechanical properties, respectively. The simultaneous plastic multiplier λ_s can also be divided into instantaneous plastic multipliers $\lambda^{\xi p}$ and time-dependent plasticity multiplier $\lambda^{\xi t}$.

3.3.1. Instantaneous Loading Stage

$\mathrm{d}\zeta = 0,\ \lambda^{\xi t} = 0$, according to the conditions of damage, coupling and plastic consistency can be obtained with Equation (17).

$$\begin{cases} \mathrm{d}f_s = \frac{\partial f_s}{\partial \sigma} : d\boldsymbol{\sigma} + \frac{\partial f_s}{\partial \omega}\mathrm{d}d + \frac{\partial f_s}{\partial \xi}\mathrm{d}\xi + \frac{\partial f_s}{\partial \alpha_p}\frac{\partial \alpha_p}{\partial \gamma_p}\mathrm{d}\gamma_p = 0 \\ df_d = \frac{\partial f_d}{\partial d}\mathrm{d}d + \frac{\partial f_d}{\partial Y_d^p}\left(\frac{\partial Y_d^p}{\partial \varepsilon^p} : \mathrm{d}\boldsymbol{\varepsilon}^p + \frac{\partial Y_d^p}{\partial \gamma_p}\mathrm{d}\gamma_p\right) = 0 \\ \mathrm{d}\xi = \frac{\partial \xi}{\partial \omega}\mathrm{d}d + \frac{\partial \xi}{\partial \sigma} : \mathrm{d}\boldsymbol{\sigma} + \frac{\partial \xi}{\partial \varepsilon^p} : \mathrm{d}\boldsymbol{\varepsilon}^p \end{cases}, \tag{17}$$

By substituting the plastic flow rule into the damage, coupling and plastic consistency conditions, the instantaneous plastic multiplier $\lambda^{\xi p}$ can be obtained as Equation (18):

$$\lambda_s = \frac{\left(\frac{\partial f_s}{\partial \sigma} + \frac{\partial f_s}{\partial \xi}\frac{\partial \xi}{\partial \sigma}\right)\mathrm{d}\boldsymbol{\sigma}}{H_{\xi d}}, \tag{18}$$

Among them, the instantaneous plastic hardening modulus under hydro-mechanical properties can be expressed as Equation (19):

$$\begin{aligned} H_{\xi d} = &\left(\frac{\partial f_s}{\partial \omega} + \frac{\partial f_s}{\partial \xi}\frac{\partial \xi}{\partial \omega}\right)\left(\frac{\partial f_d}{\partial Y_d^p}\left(\frac{\partial Y_d^p}{\partial \varepsilon^p} : \frac{\partial g}{\partial \sigma} + \frac{\partial Y_d^p}{\partial \gamma_p}\right) / \frac{\partial f_d}{\partial d}\right) \\ &- \left(\frac{\partial f_s}{\partial \alpha_p}\frac{\partial \alpha_p}{\partial \gamma_p} + \frac{\partial \xi}{\partial \varepsilon^p} : \frac{\partial g}{\partial \sigma}\right) \end{aligned}, \tag{19}$$

3.3.2. Creep Stage

$\mathrm{d}d = 0,\ \lambda^{\xi p} = 0$, according to the conditions of damage, coupling and plastic consistency, can be obtained from Equation (20):

$$\begin{cases} \mathrm{d}f_s = \frac{\partial f_s}{\partial \omega}\mathrm{d}\zeta + \frac{\partial f_s}{\partial \xi}\mathrm{d}\xi + \frac{\partial f_s}{\partial \alpha_p}\frac{\partial \alpha_p}{\partial \gamma_p}\mathrm{d}\gamma_p = 0 \\ \mathrm{d}\zeta = \mathrm{d}\left[(1-\omega)\alpha_p\left(1-e^{-\gamma t}\right)\right] = \left(\frac{\partial \zeta}{\partial \alpha_p}\frac{\partial \alpha_p}{\partial \gamma_p}\mathrm{d}\gamma_p + \frac{\partial \zeta}{\partial t}\mathrm{d}t\right) / \left(1 - \frac{\partial \zeta}{\partial \omega}\right) \\ \mathrm{d}\xi = \frac{\partial \xi}{\partial \omega}\mathrm{d}\zeta + \frac{\partial \xi}{\partial \varepsilon^p} : \mathrm{d}\boldsymbol{\varepsilon}^p \end{cases}, \tag{20}$$

By substituting the plastic flow law under the coupling effect of hydro-mechanical properties into the damage, coupling, and plastic consistency conditions, the time-dependent plastic multiplier $\lambda^{\xi t}$ can be obtained as Equation (21):

$$\lambda^{\xi t} = \frac{\left(\frac{\partial f_s}{\partial \omega} + \frac{\partial f_s}{\partial \xi}\frac{\partial \xi}{\partial \omega}\right)\frac{\partial \zeta}{\partial t}\mathrm{d}t}{H_{\xi t}}, \tag{21}$$

Among them, the time-dependent plastic hardening modulus $H_{\xi t}$ under the coupling effect of hydro-mechanical properties can be expressed as Equation (22):

$$H_{\xi t} = -\left(\frac{\partial f_s}{\partial \omega} + \frac{\partial f_s}{\partial \xi}\frac{\partial \xi}{\partial \omega}\right)\frac{\partial \zeta}{\partial \alpha_p}\frac{\partial \alpha_p}{\partial \gamma_p} - \left(\frac{\partial f_s}{\partial \xi}\frac{\partial \xi}{\partial \varepsilon^p} : \frac{\partial g}{\partial \sigma} + \frac{\partial f_s}{\partial \alpha_p}\frac{\partial \alpha_p}{\partial \gamma_p}\right)\left(1 - \frac{\partial \zeta}{\partial \omega}\right), \tag{22}$$

Based on the plastic flow rule, the derived instantaneous plastic multiplier λ^{cp} and time-dependent plastic multiplier λ^{ct} can be substituted into the total strain decomposition Formula (15) to obtain the coupled constitutive model of hydro-mechanical properties creep damage. The hydro-mechanical properties creep damage constitutive model includes factors such as instantaneous damage, time-dependent damage and the coupling variable, which can describe the creep deformation characteristics of rocks under the hydro-mechanical properties effect.

3.4. Model Validation

Based on the creep test results of Liu et al. [27] on the coupled characteristic of rock hydro-mechanical properties, the rock hydro-mechanical properties creep damage constitutive model established in this paper is validated. The parameters in the hydro-mechanical properties model are given in the paper, as shown in Table 1 in Section 2.2, and the model parameters can be determined through the experimental results in the paper. The parameter values and definitions of the constitutive model are shown in Table 2.

Table 2. The lists of model parameters.

Parameters	Values	Definition
A_0	950	They are obtained by obtaining the trajectories of the peak strength of each rock sample in the plane of average stress p and deviator stress q from triaxial tests under different confining pressure conditions.
C_0	18 MPa	
α_p^0	0.021	It describes the initial yield surface position of rocks.
B	0.0005	It is a parameter characterizing the plastic hardening rate of rock.
η	−0.0025	It represents the slope of the boundary line between the compression and expansion regions of the rock sample.
d_c	0.9	It represents the maximum critical value of the damage variable.
B_d	125	It can be determined by the relationship between the damage driving force and the damage variable.
γ	5.0×10^{-7}/s	It is determined by the creep rate.

The simulated rock specimens are chosen from the test specimens of creep mechanical properties of granitic gneiss under the coupling effect of hydro-mechanical properties in the literature [27]. Namely, the confining pressure is 4 MPa, and the pore pressure is 1 MPa, 2 MPa, and 3 MPa, respectively. The program of rock creep damage constitutive model of hydro-mechanical properties is written in Fortran language. The model is verified by numerical simulation analysis of the creep mechanical property test curve of granite gneiss under different seepage pressure conditions. The specific numerical simulation results are shown in Figure 1.

It can be seen from Figure 1 that the creep mechanical behavior of granite gneiss under different seepage pressures can be well described. The numerical simulation result based on the hydro-mechanical properties creep damage coupled constitutive model is in good agreement with the corresponding experimental results. Granite gneiss is a homogeneous rock material with consistent triaxial mechanical behavior under the same conditions. The model parameters in Table 2 are determined by the basic mechanical properties of granite gneiss and do not change with external force conditions, only related to the mechanical properties of the rock material itself. From the simulation results, it can be seen that this model is suitable for simulating the creep mechanical behavior of granite gneiss under the coupling effect of hydro-mechanical properties. Mansouri et al. [30] and Firme et al. [31] simulated salt rock by establishing corresponding constitutive models, defined parameters based on different rock material properties, and simulated them. The simulation results were good, which is consistent with the phenomenon presented in the manuscript. In general, the coupled constitutive model of rock hydro-mechanical property creep damage can accurately describe the instantaneous damage, time-dependent damage and creep deformation characteristics of rocks under the coupling effect of hydro-mechanical properties, further verifying the accuracy of the theory and simulation of this model.

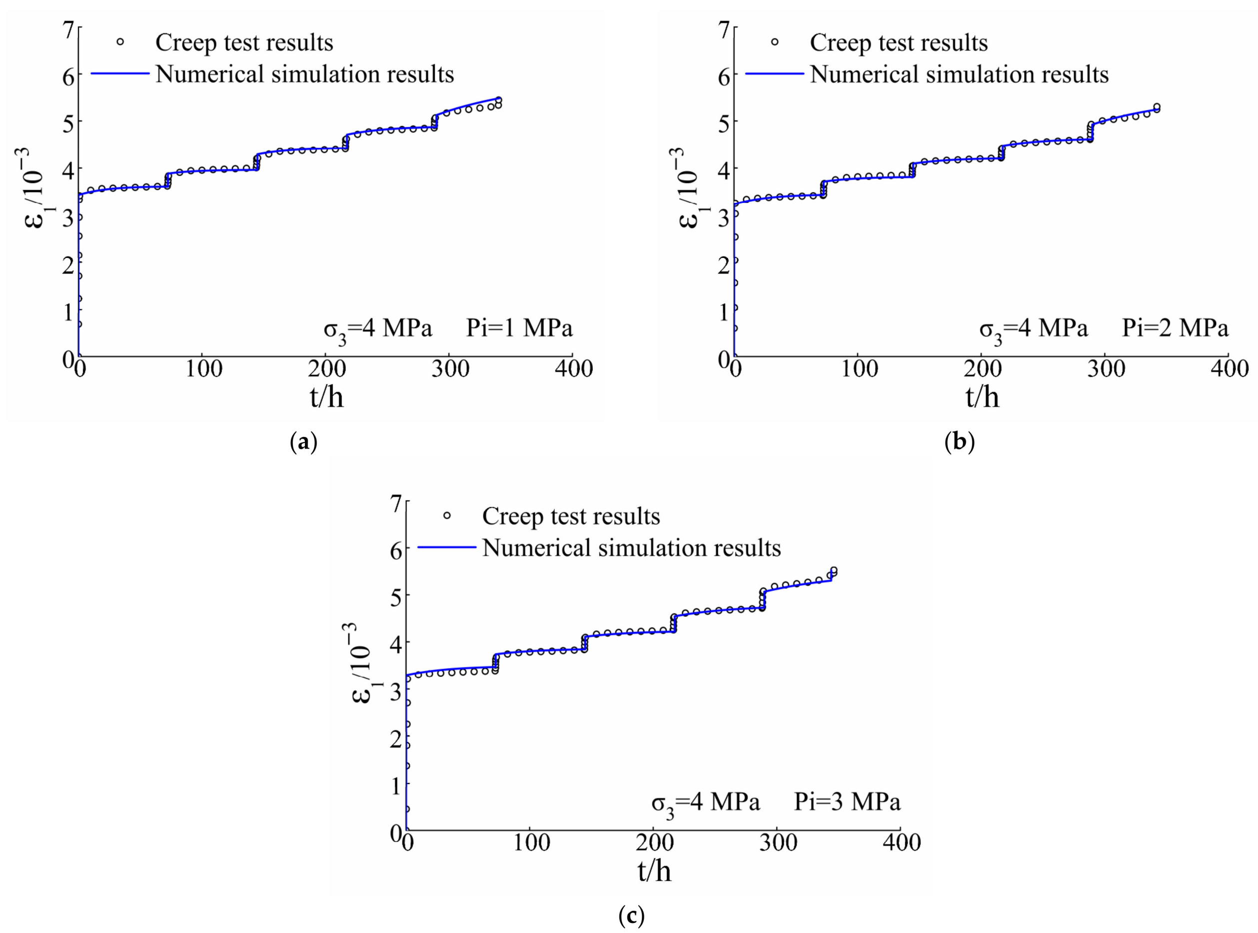

Figure 1. Model validation: (**a**) Confining pressure 4 MPa, seepage pressure 1 MPa; (**b**) Confining pressure 4 MPa, seepage pressure 2 MPa; (**c**) Confining pressure 4 MPa, seepage pressure 3 MPa.

4. Conclusions

In order to describe the creep behavior of rocks under the coupling effect of hydro-mechanical properties, based on the basic theory of rock hydro-mechanical property coupling, there are several conclusions as follows:

(1) In accordance with studying the variation characteristics of porosity in rocks under the coupling effect of hydro-mechanical properties, as well as the relationship between permeability and volumetric strain, this paper proposes the concept of hydro-mechanical properties variable.

(2) Through introducing the instantaneous damage variable d as the internal variable parameter of the thermodynamic state equation, the internal variable ζ is introduced in order to describe the time-dependent damage of rocks.

(3) With introducing the coupling variable, instantaneous damage variable, time-dependent damage variable into the yield surface equation, plastic potential energy equation and stiffness matrix of the elastoplastic creep constitutive model, a hydro-mechanical properties creep damage coupling constitutive model is established, which can describe the creep deformation characteristics of rocks under the coupling effect of hydro-mechanical properties damage, and is consistent with the creep deformation characteristics of rocks under the coupling effect of hydro-mechanical properties.

(4) Based on the triaxial creep test results of granite gneiss, the model parameters are determined. By comparing the constitutive simulation results with the experimental results, the numerical simulation results are in good agreement with the corresponding experimental results, which can better interpret the creep behavior of granite gneiss under the coupling effect of hydro-mechanical properties.

However, the constitutive model established in this paper only considers the coupling effect of hydro-mechanical properties, while in practical engineering, there are usually factors such as temperature and chemistry that affect the long-term safety and stability of the project. In future research, the constitutive model considering the coupling effect of multiple factors will be further developed to provide a more favorable basis for engineering safety construction.

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