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Doctor Introduction Scientific Research Foundation of AUST

THEORETICAL AND EXPERIMENTAL STUDY ON DISTURBANCE EFFECTS ON ROCK CREEP

(VOLUME I)

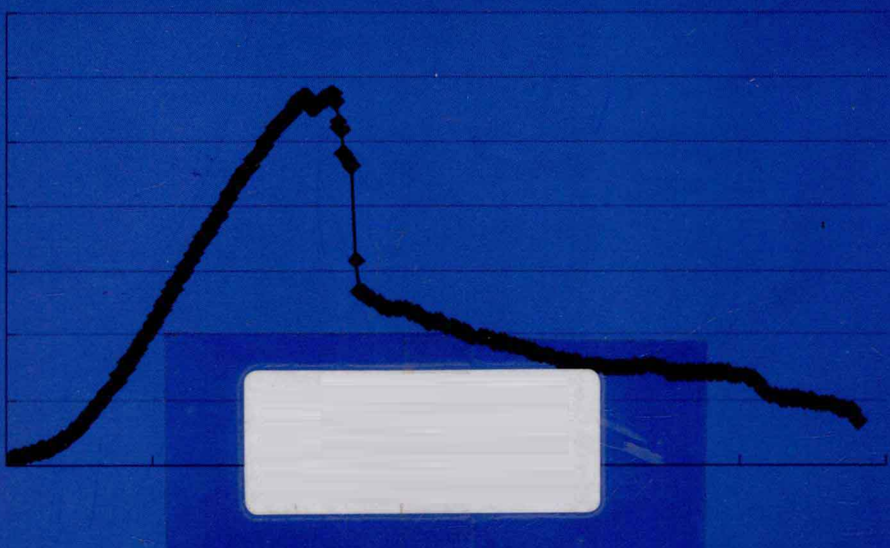
– INTRODUCTION TO DISTURBANCE EFFECTS ON ROCK CREEP

Fu Zhiliang Fan QingZhong Wang Suhua

岩石蠕变扰动效应理论及试验研究（ I ）

—— 岩石蠕变扰动效应导论

付志亮 范庆忠 王素华 著



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Forword

At present, coal mining depth is over 800 meters in China, while the maximum depth is 1,200 meters. Roadways are so frequently subjected to mining activities and excavation that produces larger deformation with a poor stability. Weak rock mass have characteristics of obvious ground pressure and strong rheological properties because compressive strength is lower. The magnitude of creep deformation is large enough to cause support to fail, costs of rock roadways are increased sharply, expenses reach up to 30,000 RMB per meter. One of key techniques of deep soft rock supporting is the coupling support. To achieve the coupling support, it is essential that predict accurately deformation of soft rock tunnels or roadways. Stress state of surrounding rock in roadways is in strength limit neighborhood, creep of surrounding rock is the main deformation, which can be caused by random disturbance loads(mining, excavating and blasting). Previous studies on creep include uniaxial compression, uniaxial tension, triaxial compression, weak plane shear and relaxation. Most of the theoretical researches focused on element combinations, empirical, endochronic model, and they were conducted under the condition of static load. So far, however, only a few empirical researches have been done to investigate rock respose to disturbance. The model can simulate damage characteristics of rock materials under impacting load and provide theoretical evidences for analysis of rock stability that has been disturbance by impacting load in geotechnical engineering. It is very significant for the stability of geotechnical engineering to study the creep characteristics under disturbance condition, and also for the development of rheology theory and the supporting of deep soft rock.

Surrounding rock of tunnels, roadways, chambers and caverns in deep mining or soft rock will produce large creep deformation when the stress in rock is close to its ultimate strength. Most of the creep deformation is caused by disturbance loads. Hence, studies on the creep properties of rock under disturbance loads, and it is of great importance to the supporting of soft rock or deep mining. This book is combined with the NSTC project "Experimental study on rock disturbance creep within the strength limit neighbourhood" and doctor dissertation "Experimental study on rock creep and its disturbance effects of rocks", which it focus on the disturbance effects to rock creep, as the load is approaching its ultimate strength are studied. Tests on rock creep under uniaxial compression, tensile loads are carried out by a new creep instrument with conventional triaxial and disturbance loading devices. Rock creep deformation of the peak strength neighbourhood under the tensile condition and its relation to disturbance load are studied significantly.

During the rock creep test of uniaxial compression, gravitation loading creep instrument and paper-based electric resistance strain gage methods are used; the tests of rock creep are made under the stepwise loading condition. These studies are focused on strain modulus under the creep condition, and on strain effects and time effects of Possion's ratio. The threshold values of lateral creep are about 60%~80% of axial creep. Lateral creep has an obvious acceleration phase, and it occurs earlier than acceleration creep phase. As strain level increases with strain modulus, Poisson's ratio increases remarkably. Furthermore, the tests are made by use of MTS, while red sandstone instantaneous loading-unloading test, short-term loading-unloading test and mudstone long-term tests are made by use of gravitation loading creep instrument, to validate time effects of rock mechanics parameters further.

The new rock creep model is established by introducing damage variable and hardening variable, and on the basis of component compound model (used extensively in the project practice). This model showed that there occur two competitive mechanisms, that is, damage and hardening, in the rock creep process. The hardening mechanism is dominant over the damping creep phase, the two mechanism keep its balance in the even creep phase, and then the damage mechanism becomes leading in the acceleration creep phase. Three phases of rock creep can be described by the uniform equation of new model.

The disturbance effects on creep are obtained by creep test of the static load. There is a strain threshold value during the process of rock creep. When strain is less than threshold value, disturbance accumulative remnant strain becomes stable gradually, and static creep develops stagnantly in a short time. When strain is lager than threshold value, the development of disturbance accumulative remnant strain is divided into three phases: damping phase, approximate even phase, acceleration phase. It is similar to the laws of static creep test. Strain is divided by

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the boundary of strain threshold value into extent of disturbance sensitivity and extent of disturbance insensitivity, which are defined as strain limit adjacent domain. Disturbance load strength has a lager influence on the remnant strain, whereas the development of the remnant strain is controlled by strain level.

Analysis of the offset law of neutral surface, and creep characteristics of the top and bottom of rock beam is made by the creep bending test. The laws of disturbance effects on creep are acquired from disturbance tests: residual strain reduces sharply on beam's tensile side when rock beam is received from continuous disturbance loads, and accumulative remnant strain becomes stable. Disturbance accumulative strain on beam's compressive side is less than that of the tensile side; as two interval repetitive disturbances occur, the larger two disturbances interact, the shorter disturbance time is. Creep is sensitive to disturbance within the strain limit. The left boundary of adjacent domain is determined by the continuous disturbance.

Contents

1 Introduction

Rheology is the nature of time-dependent deformation during the process of materials loading. It is well known that all materials show the rheological behavior. Rock mass, goes through long-term geological age, has the property of rheology, but it takes too long time to observe. Free surface displacement, deformation and convergence of roadways or caverns, surface subsidence and slope instability are caused by the excavation, all of which are rheological processes.

Distributions of stress fields and strain in underground geotechnical engineering have time-dependent effects. After excavation of caverns, the surrounding rock deformation increases over time progressively. Creep is rock deformation growth with the passage of time when rock is subjected to constant external force; it is a form of rheology. With an increase of mining depth, deep rock mass is in the complex environment with high temperature and high stress, making it increasingly difficult to support mine roadways. Among them, roadway rheological deformation caused by the high stress is one of the main factors leading to instability of roadways damage. The increase of mining depth makes rock engineering be in a more complex environmental field (stress field, temperature field, seepage field). In addition, the characteristics of deep and shallow rock mass show large differences, stress states of surrounding rock in roadways have been close to or in the strength limit. To study large rheological deformation of surrounding rock, the nature of rock creep should be explained through lots of rock creep tests. These studies are to establishe function relationship of disturbance effects on rock creep by bending creep tests and conventional uniaxial disturbance creep tests under low confining pressure and high-stress state.

Disturbance creep is defined as rock creep deformation, which is caused by external disturbance load (such as blasting tremor) when rock is in the states of certain stress. Disturbance load is one kind of vibration wave. Rock mechanics response to disturbance, at this time creep gradually came into being in a certain time. Soft rock is a kind of special mechanical medium, exhibits the characteristics of nonlinearity, discontinuous heterogeneity, large deformations, anisotropy and rheology. In addition, soft rock deformation shows new characteristics, which are obviously different from linear mechanics medium. The soft rock shows obvious randomness and the sensitivity to initial conditions, soft surrounding rock shows the sensitivty to initial engineering conditions, it is also very sensitive to engineering disturbance, blasting construction in the adjacent engineering will cause deformation rate of surrounding rock to increase sharply. For the sake of the problem, circular section roadways can be simplified (shown in Fig. 1. 1), R_0 isthe radius.

Stress states in unit A are changed from three dimensions to two dimensions after excavation, the unit strength decreases. Stress concentration results from stress transfer, which is caused by increase of unit stress. The stresses in unit A exceed limit, failures occur; bearing capacity is lower, stress is transferred to the deeper area. Unit A is similar to unit B, what's the difference between them there is a smaller radial stress in unit. Plastic zone, elastic zone and fractured zone in surrounding rock of roadways are formed from the inside to the outside. Rock has good integrity in elastic zone, it has very strong anti-disturbance capability, or think it is very insensitive to engineering disturbance. For plastic zone of the rock mass, because rock is close to strength limit state, smaller disturbance loads make plastic deformation develop into further fracture. For the fractured rock, because rock is in post-peak region, it is very unstable; it is very sensitive to outer disturbance. Under non-supporting condition, rock doesn't maintain the self stability; radial force provided by the supporting is smaller, small disturbance make deformation rate increase, deformation is increasing. The deformation induced by disturbance loads is defined as disturbance deformation.

Test results show that when load is less than a certain limit value(10. 10MPa in Fig. 1. 2),strains become constant after some time, keep constant while there is no correlation with duration time, creep is stable. Load is lager than this limit value, creep is unstable, this means creep continue to increase until rock specimen cracks. This limit is called rock long-term strength, it is strength limit of stable creep. When load is close to certain neighborhood of strength limit, or when load is within certain neighborhood of strength limit, it is difficult to determine if rock creep time is finite or infinite. Rock creep stability is very sensitive to outer disturbance loads. Thus it can be concluded that a small

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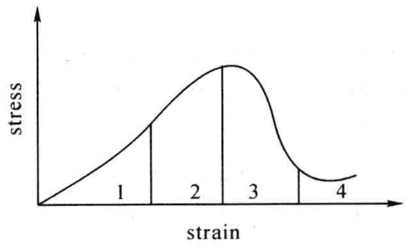
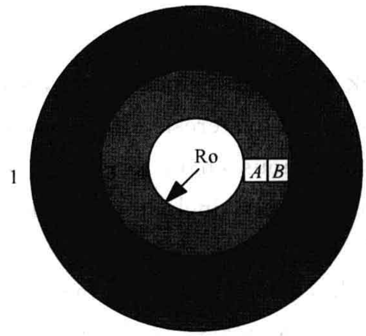
disturbance can change stable creep into instable creep under uniaxial stress state. Creep is very complex under three dimensional stress states.





1: original rock stress zone; 2: elastic zone; 3: plastic zone;
4: fractured zones; A, B: unit stress

Fig. 1. 1 Mechanics state of surrounding rock

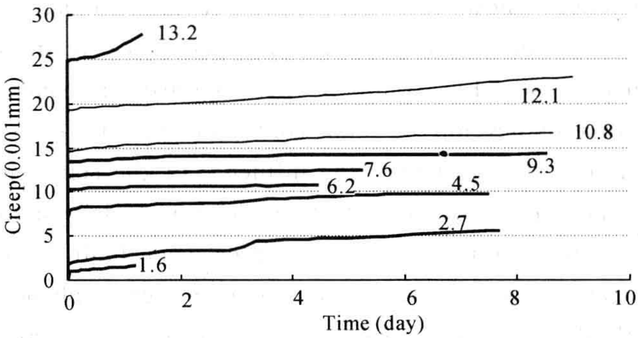


Fig. 1. 2 Curves of creep test

Rock creep stability is related to both rock stress conditions and rock strength limit neighborhood. The so-called strength limit neighborhood, that is, rock has a strength limit σ_0 when it is in tension, compression and tension shear states. $\Delta\sigma$ is given according to certain assumed conditions, that is $\sigma_0 \pm \Delta\sigma$. If rock is in three dimensions stress state, its strength limit neighborhood in stress space is defined as

$$(\Delta\sigma)^2 = (\Delta\sigma_1)^2 + (\Delta\sigma_2)^2 + (\Delta\sigma_3)^2$$

Rock limit strength neighborhood and disturbance sensitivity can be determined by the tests.

1.1 Research Background and Significance

Rock rheology includes creep, stress relaxation, long-term strength, elastic after-effect and hysteresis effect generally. It is well known that the surrounding rock have obvious characteristic of slow deformation in the deep underground caverns or tunnels, including ground pressure and damage, which are dependent on the time. The rock rheology is one of the most important mechanical properties of the rocks, geotechnical engineering is closely related with the rock rheology. Rock and rock mass as foundation for building or medium for slope and surrounding rock for roadways, its mechanical property and stability play a direct important role in the safety for buildings and underground structures. Professor Chen Zongji (1982) pointed out that engineering damage is often a time process. In other words, it is controlled by the rock rheology. A large number of engineering practices show that the instability and damage of geotechnical engineering not occur immediately before and after the excavation, but to lag for some time in many cases. For example, After the drift and shaft are excavated, rock mass deformation develop over time continuously. After some time, roadway may be unstable or collapse. Under the influence of the self-weight stress, the tectonic stress and the stress concentration are produced by mining, rock with lower intensity, swelling mudstone, soft interlayer, fault fractured zone and fissured rock strata and so on, which their significant creep phenomena will occur with the growth of time. The deformation and the stress of surrounding rock for roadways and overburden in the stope adjust and change with the time constantly, deformation tends to stability or instability is often a process of time.

With the expansion of the scale of underground works, especially the mining projects advance to the depth, so rock engineering is in the more complex environment field. As far as stress is concerned, stress in the deep original rock is much greater than that in the shallow one. Excavation unloading will inevitably increase surrounding rock stress; the stress of surrounding rock is close to or reaches the failure strength of the rock mass.

In many cases, the problems of underground works stability are encountered either in high ground stress or large depth environment. In this case, the rock rheology has become very sensitive to external disturbance; disturbance effects on rock creep is extraordinarily prominent.

At present, mining depth of many mines in China is over 800m, the deepest mine reach 1300m. Surrounding rock of moderate intensity roadways, which stress states are close to the rock strength limit, roadways have poor stability, it is easy to arise from large deformation when tunneling or mining disturbance, so the cost of roadway increased dramatically.

This book will focus on the following issues:

(1) The acceleration creep stage of rock, when the stress is close to the rock strength limit state, the rheological behaviors of rock provide references for research on the disturbance effects on creep.

(2) Disturbance effects on rock creep under the static creep load when rock is subjected to small dynamic disturbance, which determine the sensitivity of the creep to the disturbance.

1.2 History and Present Study

The rheology theory was established in the 1930s. In 1922, Bingham published"Fluidity and Plasticity",as well as proposed the Rheology Association in 1928, marked the rheology become an independent discipline. In the 1950s and 1960s, Professor Chen Zongji became the first man to apply rheology to the field of geotechnical engineering. In 1979, Professor Langer made a comprehensive exposition of the basic concepts, methods and laws of the rock rheology in the rock engineering.

1.2.1 Rheology Test for Rock

Rock rheology test is the main way to understand the nature of rock rheology. Laboratory test possesses different characteristics of the long-term observation, strict testing conditions, repeatability and low cost. Rock creep test can be traced back to the 1930s. In 1939 Griggs concluded that sandstone, argillite and siltstone occur creep, when the load reaches 12.5% to 80% of failure load. Ito. H and Sasajima. S had made the bending creep test on the granite for decades since 1957; Chen Zongji conducted creep test on Yichang sandstone for 8400 hours.

A large number of rheological test studies have shown that the majority of the rock exhibits the viscoelastic solid properties under the uniaxial compression when the constant load is low; when the compressive stress is more than a certain value, and then they show visco-plastic fluid behaviors. Lateral creep of rock is more obvious than the axial creep, some sandstone and tuffs under uniaxial compression have more obvious volume creep properties. Curve shapes of axial and lateral creep for some rocks at different stages are similar. As the compression creep develops, the long-term strength, elastic modulus and Poisson's ratio of rock reduce greatly, and change over time.

Under the conditions of uniaxial tension, torsion and bending constant load, rock creep occurs more evidently. Even at a lower stress level, it is also easy to show creep behavior of visco-elastic-plastic fluids. In the unloading condition, a part of deformation under the higher stress recover immediately, that is, resilience; while the other parts restore gradually after a period of time, this deformation is called inverse creep.

In the complex stress state of the biaxial and triaxial compression, rock and rock mass will produce creep, its creep behaviors are affected by stress in all directions and loading path. Under constant axial pressure and confining pressure, axial creep increases with time significantly. Keep confining pressure constant and increase the axial load, the characteristics of the time-strain curves are similar to that of uniaxial compression. In short, the rheological properties of rock and rock mass in the complex stress state are closely related to differential stress, when the differential stress is small, the deformations go by the decay creep stage to the stable creep stage; differential stress is larger, which resulting in acceleration creep and damage.

The shear rheology behaviors of weak intercalated layer and structural plane along the joints are a key to determine the rheological characteristics of discontinuous rock mass. When normal stresses, which are orthogonal to the joint plane, are different constant values, the shear stress-shear strain curves along the tangential direction of joints plane are obtained, they show that the shear stiffness of joints plane decreases with time, shear strain rate increases with the shear stress.

Li Yongsheng and Xia Caichu made creep and relaxation tests on siltstone, marble, red sandstone and mudstone by the servo-rigid machine under uniaxial compression, pointed out that creep rates of the rock material appear generally three stages, decrease, stability and increase under a certain conventional stress, are related to the rock nature and the stress level.

Zhang Xiandong used gravity lever-type rock creep test machines to carry out triaxial creep test on mudstone, concluded that weak rock triaxial creep shows a non-linear relationship, whose creep deformation is more than three times of the instantaneous deformation. Xu Ping, Yang Ting-qing and Xia Xi Lun carried out uniaxial creep test on the Three Gorges granite, there is a threshold value stress σ_s. When the stress level is lower than the σ_s, it can describe the creep characteristics of the Three Gorges granite by using a generalized Kelvin model; when the stress level is higher than the σ_s, it is described by the Nishihara model.

As the rock excavation is an unloading process, it will cause tension damage of the rock, and the rheology effect is very significant. Li Jianlin thought that the rheological deformation sustains more than 6 hours when the tensile stress is 30 % of the rock tensile strength.

Results show that the rock elastic parameters and the creep parameters are not fixed values, but rather a function of time; soft rock strength and elastic modulus decrease with time extension, and their changes show similar natures.

Rock macrodamages are expansion and connection of the medium cracks; rock rheological damage and fracture have aging characteristics. Tang Guang-Zhe, ZHU Weishen built a basic relationship between strength weakening of fractured rock mass and crack propagation, the emergence and expansion of cracks are important factors contributing to rock weakening, crack extension and creep of fractured rock mass have phase threshold value. Zhang Xiaochun considered that the rock show softening properties in deep mine.

1.2.2 Constitutive Models of Rock Rheology

Constitutive model of rock rheology is to describe the physical and mechanical relationships of the stress-strain-time on the rock material. Constitutive model of rock rheology should reflect the rheological properties of rock accurately, also has feasibility in engineering application. Constitutive model of rock rheology can be divided into empirical models, combined model and endochronic model.

1.2.2.1 Empirical model of rock rheology

The relationships between stress, strain and time of rheological body are complex, and it is not easy to use general function to express them. The empirical model is a mathematical expression, which is obtained by different experimental conditions and different rock types.

Aging theories assume that stress, strain and time exist a functional relationship. The total strain is the sum the elastic strain and creep strain.

$$\varepsilon=\frac{\sigma}{E}+f(\sigma)g(t) \tag{1-1}$$

g (t) represents the deformation growth mitigate with time, essentially reflects the material properties change over time, that is, aging. $f(\sigma)$ represents deformation behavior varies with the stress. Aging theory not only reflects the creep process, but also shows the relaxation process.

The state equations of flow theory, which describe a relationship between strain rate, stress and time.

$$\dot{\varepsilon}=f(\sigma,t) \tag{1-2}$$

where $\dot{\varepsilon}$ is creep rate for materials. When the stress does not exceed the material elastic limit, the total deformation rate is the sum of elastic deformation rate and the creep deformation rate, that is

$$\dot{\varepsilon}=\dot{\varepsilon}^{e}+\dot{\varepsilon}^{c}=\frac{\dot{\sigma}}{E}+f(\sigma)x(t) \tag{1-3}$$

where $f(\sigma)$and $x(t)$ are functions of the creep strain rate change with stress and time, respectively. If creep is in the decaying phase, $x(\infty)=0$; if creep accerlerates, $x(\infty)=\infty$; if creep becomes stable, $x(\infty)$ is constant. f and x can be determined by the tests, and often take the form of power function. Flow theory is also called the second aging theory, whose equations include the time factor obviously, and when the initial moment changes, the equation of the flow theory changes accordingly. Generally, the theory is applied to smooth changes in stress conditions.

Hardening theory suggests that the creep rate, stress and strain have a functional relationship, namely,

$$\dot{\varepsilon}=f(\sigma,\varepsilon) \quad or \quad \dot{\varepsilon}=f(\sigma)/\phi(\varepsilon) \tag{1-4}$$

With the increase of strain, strain rate decreases, material appears to be hardened.

Elastic continuation and plastic flow theory is also named as memory theory or genetic creep theory. Suppose material is homogeneous and isotropic and consider the historical process of load and deformation, in accordance with Boltzmann superposition principle, material is subjected to the load, its deformation from a certain time in the past to any time is equal to the sum of deformation caused by irrelevant moment load at the moment. For any loading

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