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Evolution process of rock mass engineering system using systems science

1. Introduction

The rock mass engineering system (RMES) basically consists of rock mass engineering (RME), water system and surrounding ecological environments, etc. The RMES is characterized by nonlinearity, occurrence of chaos and self-organization (Tazaka, 1998; Tsuda, 1998; Kishida, 2000). From construction to abandonment of RME, the RMES will experience four stages, i.e. initial phase, development phase, declining phase and failure phase. In this circumstance, the RMES boundary conditions, structural safety and surrounding environments are varied at each phase, so are the evolution characteristics and disasters (Wang et al., 2014).

The objective world can be studied by systems science from the perspectives of whole and part, global and local and the hierarchical relationship (Qian, 2007). Yokobori (2003) attempted to solve the strength and fracturing problems of solids with defects using systems science. The application of systems science in Earth system has been taken extensively in the global scope (NASA, 1988; Wang, 2014). Earth system science based on remote sensing technology was described as "the second Copernican revolution" at the beginning of the 21st century (Schellnhuber, 1999).

From the viewpoint of systems science, new thoughts and implications for RME monitoring, disaster prediction and control can be provided by the study of the boundary, structure, environments and evolution characteristics of RMES. Meanwhile, the regulations of energy accumulation, transfer and relief in the processes of rockburst gestation and occurrence can be understood by systems science.

2. Analysis of evolution process of RMES

The RMES is an open system, which transfers energy, materials and information with external environment continuously (Huang, 1997). The evolution process of RMES during the excavation is significantly complicated, which mainly contains the following aspects.

2.1. Evolution process of RMES boundary

The range of RME changes during excavation, so do the ranges of support and solid accumulation. As the influence areas of excavation, support and solid accumulation become larger, the deformation, fracture and/or sliding may occur, which in turn will influence a larger area. Meanwhile, a large-scale excavation will result in development of joints and enhancement of permeability, which eventually leads to the change of the boundary condition of seepage field. With increasing excavation depth and coal's spontaneous combustion, the temperature of RMES will rise accordingly. Therefore, the change of the boundary condition of RMES is a typical topic of the dynamic system. The dynamics and nonlinear characteristics of the boundary conditions should be considered when selecting the size of system structure, boundary condition and initial condition.

2.2. Evolution process of RMES structure

The excavation and solid accumulation will change the components and structural morphology of RMES (Wang et al., 1998a), such as groundwater flow and distribution among strata. Large-scale structure failure, fault activation and sliding will influence the RMES structure as well. The change of the RMES structure is mainly represented by the geometric parameters, such as thickness and direction of strata, sizes of fault and goaf and failure zone in the RMES. The processes of excavation, solid accumulation, failure and/or sliding are dynamically nonlinear (Qin and Wang, 2005). Hence, the RMES has a strong nonlinear behavior. Generally, the RMES structure will experience macroscopically continuous deformation stage, rupture stage and stage of sliding failure along macroscopic discontinuity surface. The failure of RME may result in disasters. If the range of RMES structural failure is local and minor, and the degree of damage is low, the change of system structure caused by the structural failure of this kind can be ignored. Otherwise, the change of system structure caused by structure failure must be considered in the analysis.

2.3. Evolution process of RMES environment

The RMES environment contains internal and external environments (Wang and Zhu, 2013). The internal environment, which is regarded as the internal driving force of system evolution, contains homogeneity and difference of coal (rock) composition, system constitution, internal temperature, internal water pressure and internal chemical and physical actions. The external environment includes independent or coupling effects of mechanics, physics, chemistry and biology. The RMES is often influenced by the independent or combination effects of internal and external environments. The internal and external environments of RMES are changing with elapsed time during evolution process. For example, the spontaneous combustion of residual coal can heat coal and surrounding rocks, and thus cavitate the coal structure and loosen the surrounding rocks. These actions can decrease the integrity, strength and permeability of coal (rock) mass and make the coal more inflammable. It is a typical coupling process of chemistry, physics, mechanics and coal-rock structure interaction.

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2.4. Changes of strata parameters during evolution process of RMES

Besides the geometric parameters of RMES, the mechanical properties, e.g. permeability and thermodynamics parameters of strata, will change during the process of interaction between the system and its external environments. For example, the strengths of soft rock and fault gouge containing a large amount of mud will become weaker in presence of water, which belongs to softening effect of geomaterials. The parameters of strata under different temperatures and water contents or in different stages will also change, and this process is in essence nonlinear.

2.5. Interaction among RMES, internal and external environments and its evolution process

Actually, the occurrence of disaster is a strong nonlinear evolution process of interaction among RMES, internal and external environments. The excavation, solid accumulation and failure will change the boundary condition, structure and parameters of RMES during the whole evolution process. The sliding of RMES consists of several stages, i.e. gestation, initiation, eruption, continuity, attenuation and termination.

Seepage and hydrodynamic pressures are basically induced by water pressure and stress difference in the rock mass. There are various adverse effects of water on physico-mechanical performances of rocks. For example, water usually softens rocks, reduces rock strength, increases rock deformability and imposes hydrostatic and hydrodynamic pressures on rock slopes. Mudstone contacting with water will soften and disintegrate, which will weaken the strength and increase the deformability of soil slopes (Wang et al., 1998b). Water pressure acting on saturated rocks, which results from the hydrostatic pressure, will decrease the slope stability subsequently. The kinetic energy of dynamic water can transport and carry gravel and small granule, which will lead rock granule to be tunneled and form underground channel ultimately. With increases in water head and seepage velocity, the dynamic water pressure and the quantity of sand carried by dynamic water will increase as well, further contributing to slope instability.

Rock weathering can be mainly divided into physical, chemical and biological weathering, or mixed weathering. Chemical change of rock reacting with acid or alkaline water will change the chemical properties of rock. Water is the main factor for chemical weathering. Temperature is a major factor for physical weathering. For example, it can be as low as -40 °C in winter and as high as 40 °C in summer in mining area in North China. Thus the temperature difference can be over 80 °C in a year. The temperature during coal combustion can even reach over 800 °C. The gradual or sudden change of temperature leads to frost heave and thermal expansion, which makes rock expand or shrink and fracture.

In other words, groundwater and weathering play major roles in the process of interaction among RMES, internal and external environments.

2.6. Coupling effects of deformation, failure and sliding of RMES

In the RMES, the interaction of subsystems belongs to internal coupling effect, and the interaction between the system and its surrounding environments is considered to be external coupling effect. The coupling effects mainly exist in the interaction among the elements of the system, and that between the system and environment. The process of mutual interaction between the system and its surrounding environments can be unidirectional, bidirectional or random. At present, the thermo-hydro-mechano-chemical (THMC) coupling effects are commonly investigated in deep RMES under high in-situ stress, temperature, osmotic pressure and complex water chemistry environments (Jing and Feng, 2003; Liu et al., 2014).

2.7. Feedback of RMES deformation, failure, sliding and stability

The deformation, failure and sliding of the RMES can be regarded as system feedback processes. For example, due to the inhomogeneity of rock mass, presence of water and dynamic excavation, a slight change of external force for the landslide of open-pit mine can be regarded as an unstable process, in which the feedback of creep deformation induced by weak planes transforms to the feedback of sliding by slip surface. Consequently, the feedback studies can be conducted in three aspects: (i) when the rupture of surrounding rock system stops, the system is in a stable stage of negative feedback; (ii) the rupture and adjustment of stress state of surrounding rock system are in a balance state of dynamic variation; and (iii) under a slight disturbance, the system in the stage of positive feedback will be induced, where disasters occur finally.

2.8. Controlling factors in RMES

When focusing on the RMES evolution, the main structure that may induce disasters should be first considered to be the internal controlling factor. The effects of weak stress field resulting from dynamics, solid accumulation, water and external actions should be considered as the external controlling factors, which are realized by the external environment imposed on the system structure. Theoretical analysis and measurement show that, the controlling factors of static force induced deformation disaster system is the matrix of system structural stiffness and external loading (Wang et al., 1998c). The controlling factors of dynamic stress induced deformation disaster system can be described by the frequency and amplitude of the matrix of external loading, system structural stiffness and damping.

2.9. Evolution process of overall sliding in slope engineering system

In general, the overall sliding process in slope engineering system will experience two stages, i.e. deformation stage and sliding stage (Xu et al., 1998). The characteristic of deformation stage is that the structure of slope engineering system is continuous from the macroscopic perspective. The characteristic of the sliding stage is that the structure of slope engineering system is discontinuous from the macroscopic perspective.

3. Case study

The mechanism of rockburst, a challenging issue across the world (Zhang et al., 2011), is used as an example in this study. The focus of quite a few studies has been on the mechanical characteristics of rocks under loading and unloading conditions in terms of energy (e.g. Huang et al., 2012). However, application of systems science to the study of rockburst mechanism is rarely reported.

Site-specific tunnel in deep RME during excavation will induce stress concentration, and part of the coal (rock) mass is located in softening zone (Zhang, 1987). Most of the surrounding rocks are still in the elastic deformation stage when rockburst occurs, while the rockburst body has been in the plastic deformation and even failure stage (Gu et al., 2014). Due to the extremely short time of rockburst occurrence, there is no additional displacement at loading point, which means there will be no extra energy input. Therefore, a closed system will consist of elastomer and rockburst body when heat exchanging with the external environment can be neglected. Analysis shows that macro-elastic strain energy stored in the rockburst body under excavation is less than the total energy released in the process of rockburst (Xu et al., 2003). Therefore, the energy is mainly concentrated on the rockburst body during rockburst.

The elastic strain energy, U_e, can be obtained by theory of elastic mechanics:

$$U_e = \frac{1}{2E}\left[\sigma_1^2 + \sigma_2^2 + \sigma_3^2 - 2\mu(\sigma_1\sigma_2 + \sigma_1\sigma_3 + \sigma_2\sigma_3)\right]$$

where E and μ are the initial elastic modulus and Poisson's ratio, respectively; σ_1, σ_2 and σ_3 are the major, intermediate and minor principal stresses, respectively.

The elastic strain energy of elastomer will be transferred to the rockburst body after the coal (rock) mass under stress concentration reaches the peak strength. This can be basically induced by dynamite or other vibration sources, which will accelerate the deformation rate of the rockburst body. Meanwhile, the deformation of the rockburst body will result in relief of elastic strain energy of elastomer and the energy will further contribute to the deformation of the rockburst body, which is a positive feedback process.

When the releasing rate of elastic strain energy is far greater than the consumption rate of the surface energy, the excess energy will lead to ejective rockburst. The elastic strain energy of elastomer is positively correlated with the elastic modulus of elastomer and the deformation of rockburst body. The intensity of rockburst is also positively correlated with the elastic strain energy released by the elastomer.

4. Conclusions

(1) The RMES consists of RME, water system, surrounding environments, etc. The method to investigate RMES evolution characteristics is put forward in terms of systems science.
(2) The boundary, structure and environments of RMES develop dynamically and the associated parameters change continuously in the process of excavation. For a site-specific project, the coupling effects between RMES and surrounding environment should be considered.
(3) The controlling factors and evolution process of RMES are described practically by a case of rockburst gestation and occurrence, in which feedback analysis is employed.

Conflict of interest

The authors confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

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