International Journal of Mining Science and Technology 24 (2014) 737–745

Contents lists available at ScienceDirect

International Journal of Mining Science and Technology

journal homepage: www.elsevier.com/locate/ijmst

Fluid–solid coupling analysis of rock pillar stability for concealed karst cave ahead of a roadway based on catastrophic theory

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ARTICLE INFO

Article history:
Received 17 February 2014
Received in revised form 25 April 2014
Accepted 21 June 2014
Available online 22 November 2014

Keywords:
Rock mechanics
Catastrophic theory
Shear strength reduction method
Karst water inrush
Safety factor

ABSTRACT

In order to study the mechanism of water inrush from a concealed, confined karst cave, we established a fluid–solid coupling model of water inrush from a concealed karst cave ahead of a roadway and a strength reduction method in a rock pillar for preventing water inrush based on catastrophic theory. Fluid–solid coupling effects and safety margins in a rock pillar were studied. Analysis shows that rock pillar instability, exerted by disturbance stress and seepage stress, is the process of rock pillar catastrophic destabilization induced by nonlinear extension of plastic zones in the rock pillar. Seepage flow emerges in the rock pillar for preventing water inrush, accompanied by mechanical instability of the rock pillar. Taking the accident of a confined karst cave water-inrush of Qiyi Mine as an example, by studying the safety factor of the rock pillar and the relationship between karst cave water pressure and thickness of the rock pillar, it is proposed that rock pillar thickness with a safety factor equal to 1.5 is regarded as the calculated safety thickness of the rock pillar, which should be equal to the sum of the blasthole depth, blasting disturbance depth and the calculated safety thickness of the rock pillar. The cause of the karst water inrush at Qiyi Mine is that the rock pillar was so small that it did not possess a safety margin. Combining fluid–solid coupling theory, catastrophic theory and strength reduction method to study the nonlinear mechanical response of complicated rock engineering, new avenues for quantitative analysis of rock engineering stability evaluation should be forthcoming.

1. Introduction

Water inrush disasters give rise to large direct economic losses, which are predominant amongst other kinds of mine disaster. Karst water, water in abandoned-mines and surface water are the main causes of water inrush disasters in South China. There exists a complicated correlation amongst them, one of which always leads to other water inrush disasters. Amongst all kinds of water sources, an underground karst water inrush generates the most serious destruction, because of high pressure and rapid occurrence. During mine excavation, when a large-scale water filled karst (such as an underground river, water-filled cave and karst crush belt) is broken into, a mine water inrush occurs. The process of karst water inrush is sudden, instantaneous, difficult to predict, and has great risk and damage. A water inrush in Qiyi Mine of Lianyuan city in Hunan province in 2003 and in Guida Mine of Guiyang county in 2005 are cases in point, and were induced by high-pressure karstic water in a filled cave in late Permian Makou limestone and dolomitic limestone. At present, most studies on karst water inrushes have mainly focused on the motion features of karst water, karst water discharge forecasting, forecasting of water inrush occurrence and case analysis of karst water inrushes [1–10]. Zhu et al. proposed a coupled hydromechanical model for predicting water inrushes controlled by geologic structures during underground coal mining [11]. Also, based on numerical simulations, a procedure for determining the critical size of the water-proof pillar was proposed. Based on rock mechanics and seepage mechanics, a geological model for karst water inrush was established by Liu et al. [12]. The current mechanical mechanism study on karst water inrushes has mostly focused on karst tunnels, while studies on karst water inrush occurring on a working face induced by the breakdown of the rock pillar during the process of tunneling is less common in mines. In karst mines, karst water is explored and discharged by arranging drilling holes for exploring discharging water. Also the karst water is controlled by creating a rock pillar. A method of calculating the safe thickness

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http://dx.doi.org/10.1016/j.ijmst.2014.10.002
2095-2686/

of water-proof rock pillars for confined caves is not given in regulations covering mine water control [13]. The study of the stability of rock pillars for preventing water inrush and its safe thickness is of great significance for controlling karst water inrushes in mines.

Based on rock mechanics and seepage mechanics, a fluid–solid coupling method has been adopted to consider the fluid–solid coupling effect of a rock pillar on a concealed karst cave ahead of a roadway under disturbance stress and high hydraulic gradient, and the evolution of rock pillar instability under high hydraulic gradient. Meanwhile, the theory of strength reduction method is introduced to propose the concept of safety factors applied to rock pillars. In the strength reduction method, the strength of a rock pillar for preventing water inrush is not reduced continuously until the rock pillar fails. The decreasing rate of strength is a safety factor of the rock pillar for preventing water inrush. Combining the fluid–solid coupling theory for a rock mass with cusp catastrophe theory, this paper proposes the safety thickness of a rock pillar for preventing water inrush from concealed karst cave by means of the strength reduction method. The study provides a theoretical basis for designing rock pillars.

2. Fluid–solid coupling mechanism for water inrush from concealed karst cave

In the southern mines of China, the influence of karst to the arrangement of a coalmine mining system is complex. The lithology of the Maokou limestone in the underlying rocks of southern mines in China is hard. When karst is least developed, the Maokou limestone can be regarded as a relative impermeable layer. Because the Maokou limestone layer is close to the coal seam, there are several good reasons for constructing roadways in this layer: on the one hand, because the lithology is hard, roadway maintenance is simplified, and the extent of engineering work required in shafts and tunnels is reduced. On the other hand, because the development and distribution of karst is inhomogeneous, the location and development of karst are difficult to predict and are the major problems related to mine water inrush.

When confined karst cave is concealed ahead of a roadway, disturbance stress induces a sharp change in the stress and seepage fields in the surrounding rock. There will be a strong coupling effect in the surrounding rock mass between karst cave and the working face. This kind of coupling effect is explained as follows: the action of the high hydraulic gradient (high seepage stress) on the surrounding rock results in change in the stress field and due to crack propagation in surrounding rocks under the high hydrostatic pressure and stress field, the seepage properties are greatly increased. A schematic diagram of a rock pillar for preventing water inrush is shown in Fig. 1. From a consideration of rock fluid mechanics under disturbance stress, high dynamic and static hydraulic pressure, a confined karst water inrush can be considered as a catastrophic instability of the rock pillar between the karst cave and the working face, accompanied by a karst water inrush. The strength of the rock pillar declines continuously under the disturbance stress and seepage action. When the system is in a critical state, perturbation can generate the destruction of the control water layer, and a water inrush occurs.

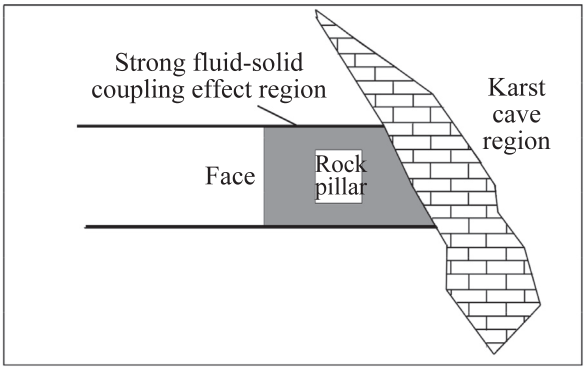

Fig. 1. Schematic diagram of rock pillar for preventing water inrush.

2.1. Nonlinear seepage analysis for confined karst water inrush

The differential control equation of seepage analysis for rock pillar [14]:

$$\frac{\partial p}{\partial t} = -M\frac{\partial}{\partial x_i}\left(k\frac{\partial p}{\partial x_j}\right) - \alpha M\frac{\partial \varepsilon}{\partial t} \tag{1}$$

where p is the seepage pressure; k, is the hydraulic conductivity; M, is the biot modulus; ε, is the volumetric strain, and α, is the biot coefficient of effective stress.

The influence of seepage pressure and stress on hydraulic conductivity can be presented as [15]:

$$k(\Theta, p) = \xi k_0 e^{-(\Theta/3-\beta p)} \tag{2}$$

where k_0 is the initial value of hydraulic conductivity; $k(\Theta, p)$ is the hydraulic conductivity by means of coupling analysis; $\Theta = \sigma_1 + \sigma_2 + \sigma_3$, is the volumetric stress; ξ is the hydraulic conductivity sudden jump coefficient.

In coupling analysis, for elastic units, hydraulic conductivity is regarded as the negative exponential function of volumetric stress. In Eq. (2), ξ is 1.0, β is 0.5.

For plastic yielding units, hydraulic conductivity increases greatly and the hydraulic conductivity sudden jump coefficient becomes greater. In Eq. (2), ξ is 1000, β is 1.0.

Eq. (2) reflects the coupling effect of the rock mass stress field on the seepage field. Particularly, the strong coupling effect of a plastic unit on the seepage field is reflected.

2.2. Elastic–plastic analysis for a rock pillar in confined karst cave

The constitutive relation of elastic–plastic mechanics for a rock mass under the coupling effect of stress and seepage fields can be denoted as [16,17]:

$$\sigma_{ij,j} + F_i + (\alpha p)_{,j} = 0 \tag{3}$$

In Eq. (3), $(\alpha p)_{,j}$ is that hydraulic gradient taken as an equivalent volumetric stress acting on the rock framework, which reflects the coupling effect of the seepage field on the stress field.

The shear failure criteria are represented as:

$$f^s = \sigma_1 - \sigma_3 N_\varphi + 2c\sqrt{N_\varphi} = 0 \tag{4}$$

$$N_\varphi = \frac{1+\sin\varphi}{1-\sin\varphi} \tag{5}$$

The tensile failure criterion is:

$$f^t = \sigma_t - \sigma_3 = 0 \tag{6}$$

In Eqs. (4)–(6), φ is the internal friction angle of the rock mass, c is the cohesion force and σ_t is tensile strength.

2.3. Fluid–solid coupling program design for water inrush from confined karst cave

The fluid–solid coupling analysis for confined karst water inrush in a mine is conducted by adopting an indirect coupling method. Firstly, the elastic–plastic stress field of the rock pillar is calculated when time is t_i. Hydraulic conductivity of the rock pillar