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Numerical investigation of unstable rock failure in underground mining condition

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ABSTRACT

Underground coal mining affects the stress distribution in rock mass and may induce slip failures along large existing rock discontinuities and sizable compressive failures of coal in mining faces and sidewalls. When such failures occur in an unstable and uncontrollable manner, they can be accompanied by a significant release of strain energy from the surrounding rock and potentially create coal burst events. This paper focuses on identifying failure stability of rock and rock discontinuities in terms of their manifestation as stable and unstable manner in coal mining settings. The studies use numerical modeling and consider failure stability of both rock discontinuities in slip and coal material in compression. The influence of the slip failure stability on the compressive failure stability is also investigated. The Universal Distinct Element Code (UDEC) is used with its optional constitutive models the Continuously Yielding joint and the Mohr–Coulomb strain softening model. A laboratory scale numerical model of a double shear test setup is developed and used to assess the ability of the numerical code in detecting the stability during discontinuity slip failures. The studies performed using this model confirmed the ability of the numerical code in differentiating stable and unstable slip failures when using the failure stability criterion based on the relative stiffnesses of loading system and failing discontinuities. Using the numerical double shear test models, criteria and tools are developed for identifying the failure stabilities in larger in situ scale numerical models. The in situ scale models allowed studies of the failure stabilities of existing rock discontinuities under the influence of an advancing excavation. The results show that both stable and unstable slip failures can occur at an existing rock discontinuity depending on the post-failure characteristic of the discontinuity and the loading stiffness of the surrounding rock. The loading stiffness is observed to continuously reduce with increasing mining extent. Additional in situ models are also built to study the effect of coal seam–host rock interfaces on the failure stability of sidewalls and mining faces in coal mining settings. The results show that unstable sidewall failures may occur when a sudden de-confinement is triggered by an unstable slip failure at the coal–rock interfaces. The existence of weak regions along such interfaces can also contribute to unstable compressive failures of mining faces and sidewalls.

1. Introduction

Slip failures along large scale rock discontinuity planes and compressive failures in rock are known to occur in deep underground mines and tunnels under the influence of changing stress fields due to advancing excavations [2,8,11–14,20,21]. Such failures can occur in a gradual and nonviolent manner, which is referred to as stable failure hereinafter. They can also occur in a rapid and violent manner with a large amount of strain energy released in a very short time period. This type of failure is referred to as unstable failure. Unstable failures may lead to coal bursts/bumps in coal mines or rockbursts in hard rock mines. This paper presents numerical modeling methodologies developed with the objective of improving the mechanistic understanding of unstable failures in deep coal mining conditions. The main parameters considered for discontinuity slip failures are the slip failure characteristics of discontinuity planes and the loading characteristic of the mining geometry in terms of its system loading stiffness. For compressive failures, the focus is on the failures caused by sudden de-confinement of mining faces and sidewalls as a result of unstable slip failures along coal seam–host rock interfaces. The numerical model Universal Distinct Element Code (UDEC) is selected for the simulations of discontinuity and rock failures. This code incorporates the Continuously Yielding (CY) joint model that can be used as a softening constitutive model for the rock discontinuities

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and coal–rock interfaces, and the Mohr–Coulomb strain softening (MCSS) model that can simulate the elastic-softening of coal during compressive failures.

As for the stability of slip failures, the stiffness criterion proposed by Salamon [19] and then later modified by Rice [17] for discontinuity shear loading was adopted. Fig. 1 illustrates the stiffness criterion for stable and unstable slip failures. In Fig. 1a, the block shown is subjected to a horizontal pull force T applied on the spring, resulting in a movement of δ_o. Depending on the magnitude of the normally applied stress σ_n, the block slides by an amount δ along the contact surface. The stiffness k of the spring is analogous to the loading stiffness in the case of a geological discontinuity, thus determines the amount of energy that can be stored in the discontinuity wall rocks. The characteristic response of the discontinuity to shear loading in the post-peak region is represented by a softening shear stress–displacement behavior shown in Fig. 1b and c. In Fig. 1b, the spring stiffness remains greater than the post-peak stiffness of the contact surface shear stress–displacement curve, which allows stable slip failure to occur along the surface. In Fig. 1c, a spring with a relatively low stiffness results in unstable slip failure at the contact surface, triggered at the point marked “instability”. The energy in excess of what can be absorbed by the discontinuity during an unstable slip failure, which is defined by the area between the loading stiffness line and the post-peak curve of the discontinuity, governs the intensity of the unstable failure.

As for the stability of compressive failures, the stiffness criterion proposed by Cook [3] was used. According to this criterion, under compressive stresses, if the energy accumulated within the rock surrounding the excavations is in excess of that can be consumed during failure, unstable failures occur in the rock. The characteristic response of compressive rock failure is analogous to that given in Fig. 1 and can be obtained by renaming the vertical and horizontal axes as compressive stress and compressive displacement. Another mechanism for the unstable compressive failures is the sudden confinement loss that can happen in mining faces and sidewalls. Under high vertical stress conditions, if a bedding plane or coal rock interface contains randomly distributed patches of weakness, unstable slip failures may occur along these interfaces, which in turn may trigger sudden de-confinements to mining faces or sidewalls and thus, powerful unstable failures.

In this paper, we first verify the capability of the numerical code with its constitutive models in simulating stable and unstable failures in both shear and compressive loading conditions. Then, the study identifies the important factors contributing to unstable slip failures and possible mechanisms of unstable compressive failures in underground coal mining conditions.

2. Numerical code and constitutive models

UDEC is a two-dimensional numerical modeling program based on the distinct element method of calculating stresses and displacements in discontinuous media, such as a jointed rock mass [4,5,7,22]. The discontinuous medium is represented as an assemblage of rigid or deformable discrete blocks separated by discontinuities [22]. There are other numerical modeling programs, such as Finite Element (FEM), Boundary Element (BEM) and Finite Difference (FDM) programs that can model rock discontinuities by using interface elements or specially defined forms of discontinuous elements. In most of these models, the discontinuity elements experience difficulties in modeling multiple intersecting interfaces, efficiently recognizing new contacts, or effectively modeling large displacement and rotation of blocks [22]. One of the main reasons for using this numerical code in the study is its ability of its constitutive models CY joint and MCSS to model post-peak softening behaviors of both rock discontinuities and rock.

The CY joint model was originally intended to simulate internal mechanisms of progressive damage of discontinuities under shear loading conditions [6]. Unlike the perfectly plastic models, the CY joint model accounts for non-linear softening behavior in the post-peak stage. In a CY joint model, the discontinuity shear stress–displacement curve always approaches a target shear strength τ_m by changing the instantaneous gradient of the curve based on the difference between strength and stress (Fig. 2). The target shear strength τ_m is a function of normal stress and accumulated plastic shear displacement of the simulated discontinuity. As normal stress increases, target shear strength increases. The increase in the target shear strength results in an increase in shear strength of the modeled discontinuity. The target shear strength continuously decreases with the increasing plastic shear displacement increment. This results in a softening behavior in the

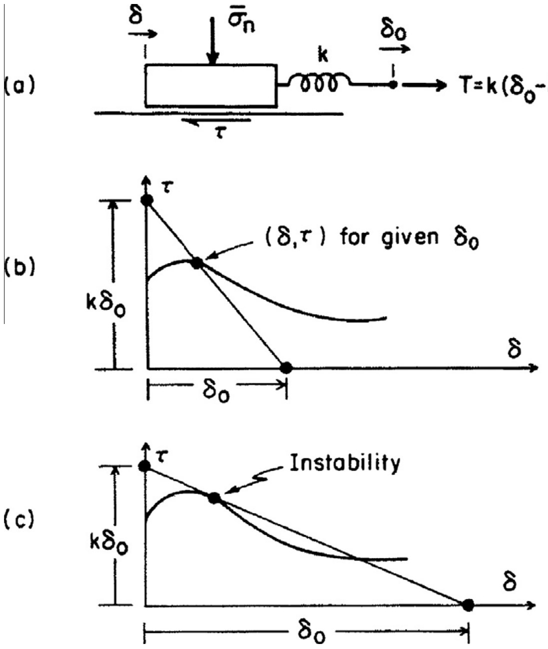

Fig. 1. Conditions for stable and unstable slip failures in a single degree-of-freedom system [17].

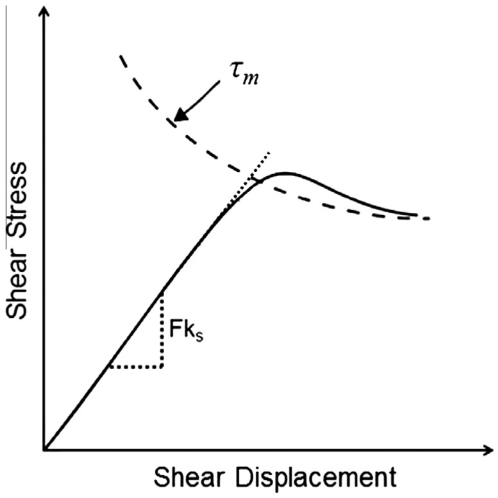

Fig. 2. Schematic of typical shear stress–displacement curve and the target shear strength τ_m of the CY joint model [22].