Analyses of De-Confinement Mechanisms of Unstable Failures in Underground Mining Conditions

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ABSTRACT

The de-confinement mechanisms of unstable failures as they occur in deep coal mining conditions are investigated using a distinct element numerical modeling code. The Mohr-Coulomb and continuously yielding joint constitutive models were used to study the compressive failures in coal and slip behavior of coal-rock interfaces, respectively. The effect of strength variations within interfaces on the failure mechanism of mining faces is also studied. The stability of interface slip failures was found to have a significant role in the failure mode of coal sidewalls. When the interfaces experience stable slip failures, the sidewalls are more likely to fail in a stable manner. With occurrence of unstable slips at interfaces, unstable compressive failures of sidewalls are triggered. The numerical modeling results support the proposed de-confinement mechanisms and emphasize the importance of including the coal-rock interface behavior in the analyses of unstable compressive failures. The significance of the proposed mechanisms in underground mining conditions is that rock discontinuities with large cohesion drop can become potential factors, inducing unstable compressive failures at ribs and mining faces. Therefore, the de-confinement mechanisms should be taken into consideration in mine design.

Keywords: coal bump, rock burst, de-confinement, stable failure, unstable failure, CY model

INTRODUCTION

Compressive failures in rock are known to occur in deep underground mines and tunnels under the influence of changing stress fields because of mining excavations. (Kaiser, Yazici, and Maloney, 2001; Ellenberger, Heasley, Swanson, and Mercier, 2001; Gale, et al., 2001; Bajpayee and Schilling, 2009; Stiros and Kontogianni, 2009). Such failures can occur in a stable, gradual manner or an unstable, violent manner. Unstable failures can manifest themselves as coal bumps in underground coal mines. This paper presents numerical modeling methodologies developed with the objective of improving the understanding of mechanisms of such unstable failures as they occur in deep coal mines. The focus is on the unstable failures caused by sudden de-confinement of mining faces and sidewalls. The commercially available software Universal Distinct Element Code (UDEC) is used for the numerical modeling studies analyses. This model incorporates two softening constitutive laws that can be used for failure stability analysis. The continuously yielding (CY) joint model is suitable for simulating post-peak softening of coal-rock interfaces, and the Mohr-Coulomb strain softening (MCSS) model can be used for the studies of compressive failure behavior of rocks. The capability of UDEC, with its CY joint and MCSS models, in simulating stable and unstable failures was verified in previous studies (Gu and Ozbay, 2012; Gu and Ozbay, 2013; Kias, Ku, Garvey, and Ozbay, 2011). This study focuses on the possible mechanisms of unstable sidewall failures triggered by a sudden de-confinement resulting from unstably failing coal-rock interfaces.

STIFFNESS CRITERIA

For failure stability analysis, the stiffness criterion proposed by Salamon (1974) and then later modified by Rice (1983), which is shown in Figure 1, was adopted. The block on the left column in Figure 1 (ai) 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 determines the amount of elastic strain energy that can be stored in the spring. If the spring stiffness is greater than the post-peak stiffness of the interface, as in Figure 1 (aii), the block slides stably during sliding. The spring with a low stiffness, as in Figure 1 (aiii), results in an unstable shear failure. For the stability of rock compressive failures, the stiffness criterion proposed by Cook (1965) was used as shown in Figure 1 (b). According to this criterion, if the energy accumulated within the loading system, represented by the spring in Figure 1 (bi), is in excess of what can be consumed by the rock specimen, the failure occurs unstably. The shaded area in Figure 1(bii) is the excess energy available from the unstable failure.

SOFTENING CONSTITUTIVE MODELS

The CY joint model accounts for non-linear hardening and softening during shear failure of rock interfaces. The interface shear stress-displacement curve is set to approach a target shear strength τ_m by changing the instantaneous gradient of the curve based on the difference between strength and stress, as shown in Figure 2. As normal stress increases, target shear strength increases. The increase in the target shear strength results in an

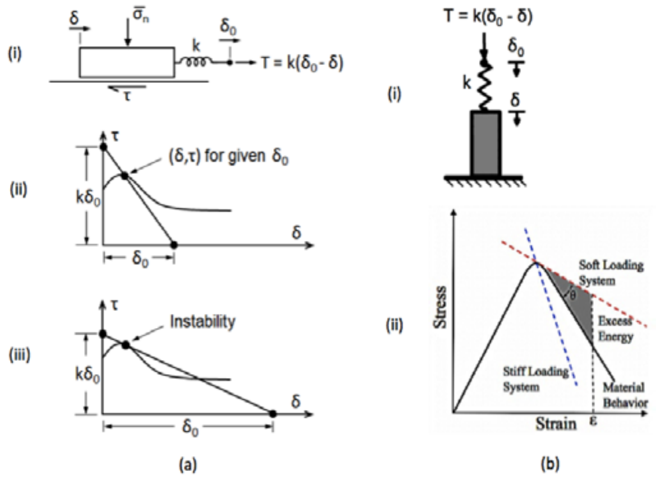

Figure 1. Conditions for stable and unstable failures: (a) interface slip failure (Rice 1983), (b) compressive failure (Cook 1965).

increase in shear strength of the modeled interface. The target shear strength continuously decreases with the increasing plastic shear displacement increment. This results in a softening behavior in the post-peak region of the interface.

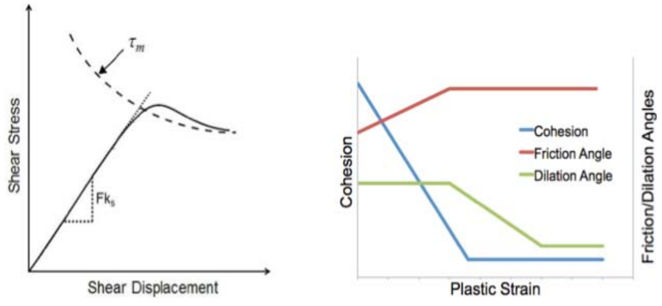

Figure 2. (a) The shear stress–displacement curve and the target shear strength τm of the CY joint model (Itasca Consulting Group, 2010); and (b) a conceptual representation of variations of cohesion, friction angle and dilation angle in the MCSS model.

MCSS model is used for simulating full load-deformation behaviors of rocks under compressive loading. In this model, cohesion, friction angle, and dilation angle can harden and soften at the onset of plastic yield, as shown in Figure 2 (b), as compared to perfectly plastic Mohr-Coulomb (MC) model, in which such properties are set to remain constant during failure.

UNSTABLE FAILURE AND DE-CONFINEMENT MECHANISMS

Many researchers have shown that the resistance provided by the coal-rock interfaces could be an important factor that affects the strength of coal materials (Mark and Bieniawski, 1986; Gale, 1998; Su and Hasenfus, 1999; Lu, Ray, Morsy, and Peng, 2008). As such, the failure stability of mining faces and sidewalls is likely to be affected by the shear properties of the interfaces. Taking into consideration the mechanical response of interfaces, a de-confinement mechanism is forwarded for use for failure stability analysis of coal faces. The emphasis is on the de-confinement effects resulting from unstable slip failures at the interfaces (Figure 3). The variation of shear strength along interfaces is also considered for stability assessments of both interface and sidewall failures.

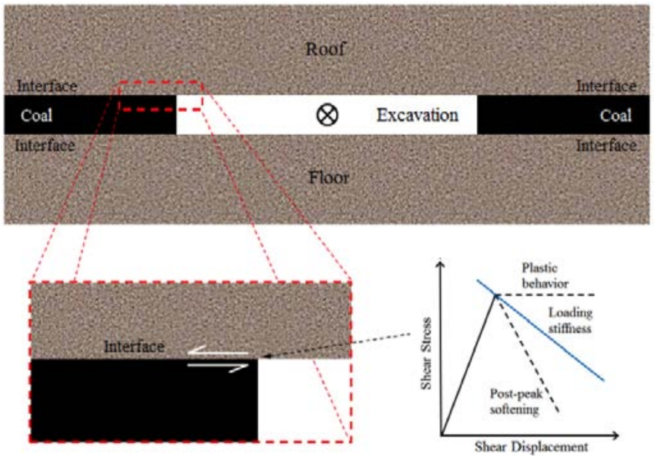

Figure 3. Mining geometries used for modeling of de-confinement induced unstable compressive failures in sidewalls (mining advances perpendicular to the plane causing shear stress increase at the interfaces close to the sidewalls).

NUMERICAL MODELING

Failure stability modeling using MC and CY joint models

When modeling coal-rock interfaces to exhibit elastic-perfectly plastic behavior, the possibility of unstable slip failure occurring along interfaces is inherently ignored. Potential compressive unstable failures in a coal seam would also be unaccounted for under perfectly plastic interface conditions. To signify the differences between perfectly plastic and softening post-behaviors, an idealized interface (Figure 4) was modeled first using the MC model and then using the CY softening model.

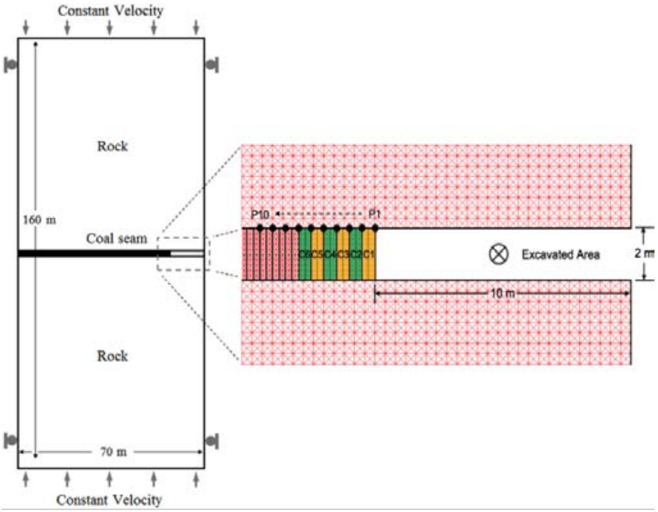

Figure 4. Model for studies of de-confinement mechanisms for the stability of sidewalls.

The input parameters for both MC and CY joint model are shown in Table 1. For both cases, the coal seam is modeled as a MCSS material using the input parameters that are listed in Table 2. The roof and floor are assigned the elastic model with a Young's modulus of 50 GPa and a Poisson's of 0.3. The model shown in Figure 4 was loaded by applying a constant velocity at the top and bottom to simulate mining advancing perpendicular to the plane. Six measurement points in the coal seam, labeled C1 to C6 in the figure, are used to record the vertical stresses carried by the coal during mining. Ten measurement points on the coal-roof interface (i.e., P1 to P10) are used to record the shear stress on the interface.

Table 1. Input parameters of the MC and CY joint model.

	Parameter Symbols	Description	Value
MC	jkn	Joint normal stiffness	50 GPa/m
	jks	Joint shear stiffness	50 GPa/m
	jfric	Joint friction angle	20°
	jcoh	Joint cohesion	2.5 MPa
CY	jkn	Joint normal stiffness	50 GPa/m
	jks	Joint shear stiffness	50 GPa/m
	jen	Joint normal stiffness exponent	0
	jes	Joint shear stiffness exponent	0
	jfric	Joint intrinsic friction angle	30°
	jif	Joint initial friction angle	59°
	jr	Joint roughness parameter	0.1 mm

Table 2. Input parameters of the MCSS model for the coal.

Cohesion (Plastic strain (in millistrain), cohesion (in MPa)	0.00, 2.2 0.05, 2.2 36.00, 0.2
Friction angle (Plastic strain (in millistrain), friction angle (in deg.)	0.00, 23.0 0.02, 30.0 7.80, 30.0
Dilation angle (Plastic strain (in millistrain), dilation (in deg.)	0.0, 15.0 0.5, 15.0 1.0, 5.0 1.5, 5.0

Figure 5 and Figure 6 show the variation in shear stress and normal stress as loading increases over the coal face. With the MC model at the coal-rock interfaces, the interfaces exhibit stable slip failures, as indicated by the gradual and continuous changes in the shear stress in Figure 5 (a) (Gu and Ozbay, 2014). The coal seam at points C1, 2, 3, and 4 also experience stable compressive failures as shown in Figure 5 (b). With the CY joint model at the coal-rock interfaces, the softening behavior results in unstable slip failures of the interfaces, as indicated by the rapid and discontinuous decreases in the shear stress as shown in Figure 6 (a) (Gu and Ozbay, 2014). The unstable slip failures cause unstable compressive failures at the coal seam as indicated by the rapid and discontinuous changes in the vertical stress, as shown in Figure 6 (b).

Role of interface strength properties in failure stability

The interfaces between different rock materials can include strong regions with clean but rough surfaces or weathered weak surfaces. To study the role of interface surface properties in failure stability, an idealized model was developed in UDEC. Figure 7 shows the approach used for modeling interface strength variation by implementing strong rock bridges (barriers) and weak regions along the coal-rock interfaces.

Figure 8 shows the model geometry used for the analyses of the interface strength variations and their effects on the stability of coal face failures. The excavation advances for 10 m in the direction indicated by the white arrow. The white and red lines on the interfaces represent weak regions and barriers, respectively.

The results from UDEC simulations indicate that both the stability and intensity of the failures at mining faces are significantly affected by the presence of weak regions along the roof-coal and coal-floor interfaces. Figure 9 shows the vertical stress records from a simulation without weak regions and a simulation with a weak region length of 2.0 m and a barrier length of 0.5 m. Comparing the results given in these figures, it can be seen that, when there are weak regions present along the interface, as shown in Figure 9 (b), more unstable compressive coal failures can occur. The magnitude of these failures is larger than those with no weak regions on the interfaces, as shown in Figure 9 (a). Increased sections of coal material tend to fail over a short time period, and they fail earlier than those with no weak region do.

CONCLUSIONS

Coal failure stability in underground coal mines is studied using the distinct element-based numerical model UDEC. The modeling approach makes use of the softening constitutive laws, namely the Mohr-Coulomb strain softening model for the compressive failures and the CY joint model for the slip failures along coal-rock interfaces. The main findings of the study include the following:

- During loading, unstable failures are signified by sudden losses of load, while stable failures follow a relatively smooth and gradual reduction in load.

- Unstable interface failures provide a sudden de-confinement to coal rib, thus triggering unstable compressive failures in sidewalls.

- Competent, rough interfaces are more likely to fail unstably compared to weaker, planar interfaces, which are likely to fail as perfectly plastic material.

- Strength variation of coal-rock interfaces can promote unstable compressive failures in mining faces.

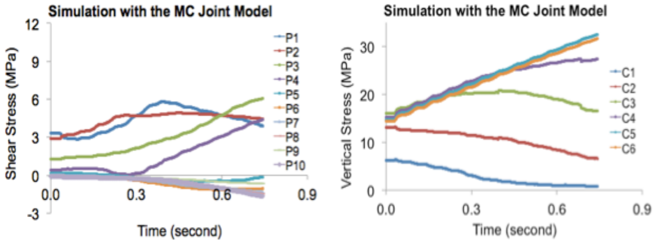

Figure 5. Stress - time curve of in the simulation with the MC model on coal - rock interfaces: (a) shear stress - time curve of the interface measurement points, and (b) vertical stress - time curve of the coal measurement regions.

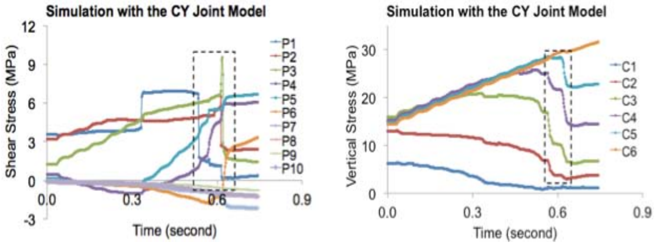

Figure 6. Stress - time curve of in the simulation with the CY model on coal - rock interfaces: (a) shear stress - time curve of the interface measurement points, and (b) vertical stress - time curve of the coal measurement regions.

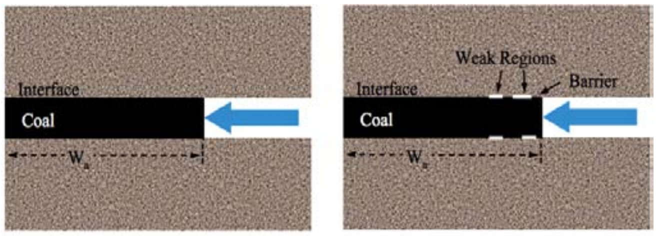

Figure 7. Interface representation used for de-confinement mechanisms simulations.

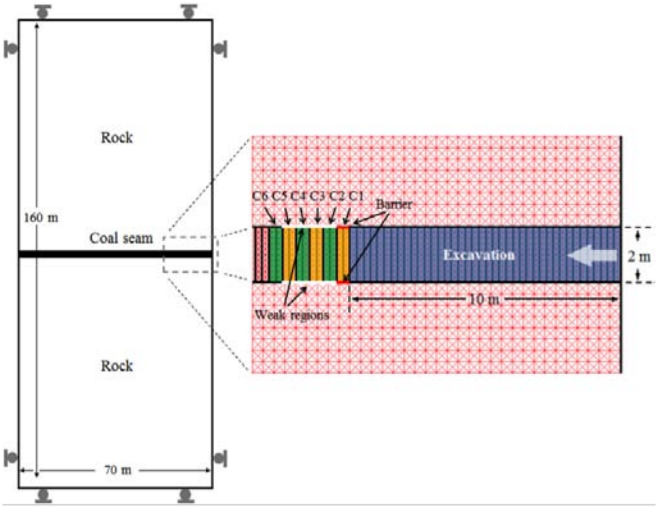

Figure 8. Model for studies of de-confinement mechanisms involving weak regions for the stability of mining faces.

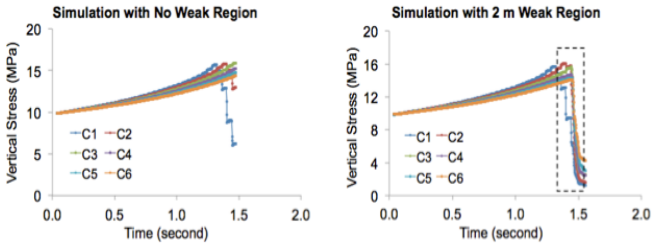

Figure 9. Vertical stress - time curves of the measurement regions in the simulation: (a) without weak region, and (b) with a weak region of 2.0 m and a barrier of 0.5 m.

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