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Distinct element analysis of unstable shear failure of rock discontinuities in underground mining conditions

R. Gu*, U. Ozbay

Mining Engineering Department, Colorado School of Mines, 1500 Illinois Street, Golden, CO 80401, USA

A R T I C L E I N F O

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A B S T R A C T

The work presented in this paper focuses on improving the understanding of shear failure stability associated with underground mining by considering the relative stiffnesses of wall rocks and the failing discontinuity in addition to important shear strength and stress drop parameters. The study uses the Universal Distinct Element Code (UDEC) with the optional constitutive law, the continuously yielding joint model. The mine-scale numerical model consists of an advancing tabular excavation below a large horizontal discontinuity. Using this model, extensive simulations were performed to study the failure stabilities at selected points along the discontinuity as a function of mining geometry and the material properties of the discontinuity and its wall rocks. The results show that the failure stability is governed by the relative stiffnesses of the failing discontinuity and the loading stiffness of the wall rocks. The proneness and intensity of unstable failures is found to increase with increased normal stress and decreased loading stiffness. The findings also indicate that the loading stiffness is reduced with increased mining, decreased distance to discontinuity, and decreased elastic modulus of the rock resulting in an increased probability of unstable failures along the discontinuity.

1. Introduction

Pre-existing large rock discontinuities, such as faults, dyke contacts and bedding planes must be considered in mining and excavation operations in order to prevent instabilities from occurring in underground working areas [1]. Underground mining disturbs the equilibrium of the surrounding rock and leads to stress redistribution [2], which brings pre-existing rock discontinuities that are near failure to the point of failure [3–8]. Such failures can occur in stable or unstable manner, depending on characteristic discontinuity shear stress–shear displacement behavior, stress field, and stiffness of the surrounding mine environment [9].

Failure stability has not been studied extensively and is still less understood than the concepts implied by the commonly used terms “strength” and “failure”. This should be remedied, as failure stability impacts the occurrence of rockbursts and thus the damage they can do [10–15]. Understanding failure stability should be a priority in locations where rockbursts are likely, such as under high stress and in the presence of brittle discontinuity surfaces.

Past researchers have recognized unstable failures as the main cause of rockbursts, and identified post-peak softening as a contributor to unstable failure. But, rock discontinuities are still commonly treated as if they exhibit either elastic–plastic behavior or, less frequently, elastic-post peak softening behavior in their shear stress–shear displacement behaviors. Taking into account the correlation between unstable failure and softening post-peak behavior, Salamon [9] proposed a criterion for unstable shear failure based on the relative stiffness of the loading system and post-peak softening regime to express the conditions that result in rockburst events. Later, Rice [16] illustrated that the conditions for stable and unstable fault slips using a single degree-of-freedom system consisted of a slider and a spring. Both researchers suggested that an unstable shear failure of rock discontinuities occurs if the post-peak stiffness of the discontinuity shear stress–displacement curve is larger in absolute value than the loading stiffness.

The objectives of this study are to develop a methodology for analyzing stable and unstable shear failures, and to apply this methodology to better understand the mechanisms involved in slip-type rockbursts that are influenced by excavations, using an appropriate numerical model.

To complete mechanistic analyses of unstable shear failures on rock discontinuities, we used the Universal Distinct Element Code (UDEC) [17–20]. UDEC was specifically developed for failure analyses

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* Corresponding author. Tel.: +1 720 323 8370; fax: +1 303 273 3719.
E-mail address: raygu1985@gmail.com (R. Gu).

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in discontinuous rock mass, and incorporated a discontinuity “softening” constitutive model known as the continuously yielding (CY) joint model. The work done by Lemos [21] and Cundall and Lemos [22] indicated that UDEC with the CY joint model could be used to simulate unstable failure of rock discontinuities in the program's dynamic analysis mode. We believed it might also be feasible to apply UDEC to model unstable failures in the more commonly used “quasi-static” mode. To evaluate this possibility, numerical simulations of laboratory shear test were performed, using a test geometry similar to that of a typical double shear test configuration. The stiffness of the loading system was varied by changing the elastic modulus of the rock specimen, and the CY joint model developed by Cundall and Hart [23] was adopted as the softening constitutive model. The results verified the program's capability to simulate stable and unstable shear failures of rock discontinuities.

Following this, a model was built to achieve the second objective of the study: a better understanding of the mechanisms involved in slip-type rockbursts that are influenced by excavations. The model consisted of a geological discontinuity in the vicinity of an advancing underground excavation. Additional analysis aimed to determine how factors such as excavation extent, location of the discontinuity, and rock elastic modulus would influence loading stiffness and failure stability of the discontinuity.

2. Stiffness criterion of failure stability

The failure stability criterion used in this study was based on Cook's [24] widely accepted criterion for unstable compressive failures of rocks, commonly known as strain-type rockbursts. Salamon [9] and Rice [16] extended this concept to account for unstable shear failures of discontinuities, commonly known as slip-type rockbursts. Fig. 1 illustrates the stiffness criterion for stable and unstable shear failures. In Fig. 1a, the block 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 of the spring k is analogous to the loading stiffness in the case of a geological discontinuity. The characteristic behavior of the contact surface is represented by a post-peak softening stress–displacement behavior as shown in Fig. 1b. In this figure, the spring stiffness remains greater than the post-peak stiffness of the shear stress–displacement curve of the contact surface, which allows stable shear failure to occur at the contact surface. In Fig. 1c, a spring with a smaller stiffness than the post-peak stiffness of the contact surface can result in unstable shear failure at the surface, triggered at the point marked “instability”.

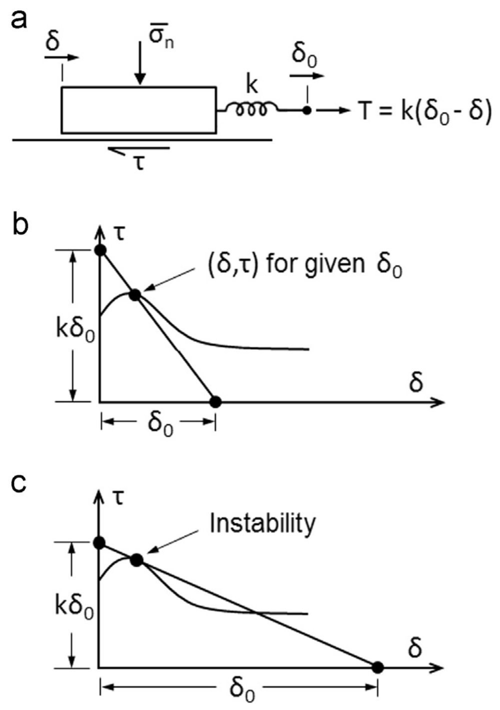

Fig. 1. Conditions for stable and unstable shear failure in a single degree-of-freedom system (after [16]).

3. UDEC and continuously yielding joint model

UDEC is a two-dimensional numerical program based on the distinct element method of modeling discontinuous media, such as a jointed rock mass. The discontinuous medium is represented as an assemblage of rigid or deformable discrete blocks separated by discontinuities [20]. One of the main reasons for using UDEC in this study is that post-peak softening behaviors of discontinuities can be effectively simulated by the CY joint model in the program. The CY joint model was originally intended to simulate internal mechanisms of progressive damage of discontinuities under shear (Cundall and Hart [23]). Unlike the Mohr—Coulomb plasticity model, the CY joint model accounts for joint shear and normal stiffness dependence of normal stress and non-linear hardening and softening behavior in the post-peak stage, as normally observed in physical discontinuity shear tests.

The discontinuity shear stress–displacement curve in a CY joint model 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). Dilation angle is considered as the difference between the apparent and the residual friction angles. 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 as the accumulated plastic shear displacement increases. This results in a softening behavior in the post-peak region of the discontinuity shear stress–displacement behavior. In this study, shear stiffness of a discontinuity is defined as the ratio of applied shear stress to shear displacement in a linear elastic regime, and has a unit of Pa/m. The shear stiffness of the CY joint model is controlled by the shear stiffness parameter k_s. Normal stiffness of discontinuity is defined as the

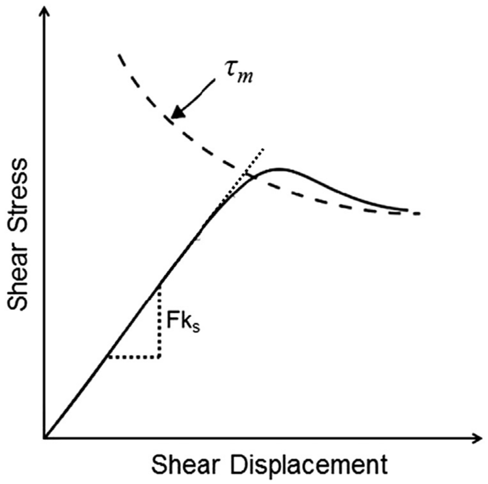

Fig. 2. Schematic of typical shear stress–displacement curve and the target shear strength τ_m of the CY joint model (after [20]).