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Rock failure induced by dynamic unloading under 3D stress state

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ABSTRACT

A commercial finite element program, LS-DYNA, was employed to simulate the unloading process of rocks under three dimensional (3D) stresses. The continuous surface cap model (CSCM), was used to model rock behaviour. Using this model, the unloading failure mechanisms of hard rock in a confined state were investigated during the unloading process. The results indicated that when rocks under 3D stress state experience unloading, the process is dominated by strain energy density (SED) rate. The effects of different unloading paths and different confining stresses can be characterised by the SED rate. A significant finding of this study is that the SED rate can quantify the unloading process. Based on the findings, rock failure can be induced by rapid unload of initial stress. In the practical underground excavation engineering, dynamically controlling the SED rate can increase the excavation potential of rocks, minimising the required external excavation energy by using the energy of the stressed rock.

1. Introduction

With increasing depths of underground mining and civil engineering tunnelling projects, unloading-induced rock failure is a well-known phenomenon in mines and tunnels [1,2]. When rock is excavated, stresses previously existing in the rock mass are disturbed, and begin a period of readjustment, naturally 'seeking' a new state of equilibrium. The process consists of two types of deformation: creeping movements and violent failures [3].

The theory of classical rock mechanics was established based on load stress in rock masses [4]. The failure mechanisms during the unloading process have also been studied, and an important unloading parameter has been identified as the strain energy [5]. And zonal disintegration was verified under dynamic unloading process [6]. SED failure criterion also has been introduced to analysis the failure processes [7,8]. The role of the stress unload path has also been examined in mining or tunnelling engineering [2,9]. The stress unload path or the response of the rock body to stress over time has been characterised by the equivalent initial stress rate in a previous study, which can be used to quantitatively describe rock failure behaviour during the unloading process in an unconfined state [10]. However, the conclusions are not yet clear in terms of understanding rock strength and deformation during stress or energy unload. There are still many uncertainties related to the stress unloading process that need to be investigated.

In practice, rock in deep excavations is in a state of 3D stresses, and confining pressure is an important unloading parameter. It is generally thought that confining stress decreases rock drill-ability [11,12]. When the TBM excavation was simulated by [13], it was found that a small increase in the confining stresses induces a large increase in the inclination of this point on the indentation axis. The subject of the relationship between the failure of boreholes and the tectonic stress field has been addressed [14,15]. However, these studies did not quantitatively predict the unloading characteristics of any particular unloading process occurring in rock in a confined state.

In the laboratory, the failure characteristics of confined rock under pressure when stressed by impact have been studied [4,8,16,17]. The process of rock-burst has also been studied under true triaxial unloading conditions [18]. It is difficult, however, to achieve unloading failure in hard rock under uniaxial or true triaxial conditions in the laboratory.

For simulating performance of brittle materials, such as rock or concrete in confined or unconfined states, numerical modelling has proved both popular and powerful. Modelling the initiation and propagation of stress unload and its consequences is a necessary precursor to any underground excavation. The initial state of the underground rock mass is generally assumed to be in static or quasi-static. For a static or quasi-static initialisation-dynamic unloading problem, the implicit solver is commonly used to perform the static initialisation of an explicit dynamic calculation. Recently the implicit and the explicit finite element methods have been performed in sequence to analyse the unloading characteristics of rocks in an unconfined state [10]. However, in actual engineering situations, rocks in deep excavations are under confined pressures. Therefore, it is necessary to investigate the unloading process of rocks in a confined state.

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This paper reports on an investigation into the failure behaviour of hard rock during the unloading process. The implicit and explicit solvers of the finite element method are sequenced to simulate rock unloading when placed under 3D stress. The effect of the initial SED and SED rate on the behaviour of the rock mass during unloading process is investigated. The numerical results indicate that rock failure can be induced by unload the initial stress, but the potential for rock failure decreases with the reduction of SED in the unloading direction. The dominant factors of the dynamic unloading process are clearly identified. Furthermore, it is also found that the rapid unload of the initial stress can be self-induced rock failure. Based on this finding, the failure criteria of hard rock under stress in a confined 3D state was obtained, and the characteristics of the unloading mechanism identified.

2. Elastic theory and governing equation

Although underground rocks are in a state of 3D stresses, mining excavation and civil tunnelling are generally conducted along a single axis. To simplify the problem, it is assumed that the axial and circumference of the rock sample is stressed, and the dynamic unloading process in only performed along the x-axial direction. Therefore, the initialisation-unloading process is estimated using the sample shown in Fig. 1.

In Fig. 1, assuming that is a homogeneous elastic bar with length l and one end of the bar is fixed, when the bar is unstressed, the state denoted by A_0. Hydrostatic stresses are imposed in the outer horizontal and vertical boundaries by three orthogonal compressions σ_{x0}, σ_{y0}, and σ_{z0} imposed on A_0 to produce a finitely stressed equilibrium configuration denoted by A_1. To this end, in the other end of x axis direction it quickly unload the initial stress σ_{x0} and keeps σ_{y0} and σ_{z0} constant, it will produce dynamic pulse propagation in the bar and the resulting configuration is denoted by A_t. Thus, the position vectors in x axial of a representative particle relative to a Cartesian coordinate system are denoted by X_A, $x_i(X_A)$ and x_d (X_A, t) in A_0, A_1 and A_t respectively, the can be written as

$$x_d(X_A, t) = x_i(X_A) + u_i(x_j, t) \tag{1}$$

where $u_i(x_j, t)$ is a time-dependent displacement associated with the deformation $A_1 \to A_t$. Then, the deformation gradient arising from the state $A_0 \to A_t$ is denoted by F and defined by

$$F_{iA} = \frac{\partial x_i}{\partial X_A} \tag{2}$$

Additionally, in absence of the body forces, the associated principal stress in x axial is given in term of the derivatives of the SED function W by [19]

$$\sigma_x(t) = \frac{\partial W}{\partial F_{iA}} - \sigma_{xo} \tag{3}$$

Meanwhile, in the practical engineering, in the initial stress unload process, there are lot of unloading paths and SED is time dependent, i.e., $W(t)$. Thus, the stress induced in the unloading processes is associated with the SED change. Therefore, in the present study, $W(t)$ changing in the unloading process is defined as the unloading path corresponding with the initial stress unload path, and the ratio of the SED to the time (dW/dt) is defined as the SED rate to verify the characteristics of the unloading process. In other words,

$$\mathrm{SED}(t) = \frac{dW(t)}{dt} \tag{4}$$

Eq. (4) indicated that the SED rate is a constant for a linear unloading path, and denoted by k. However, SED rate is a function of time in a nonlinear unloading process. Therefore, this study first investigated linear unloading paths with constant SED rates. Nonlinear unloading paths are then studied to characterise by equivalent SED rates, subsequently denoted by $\overline{K}$.

3. Material model and numerical process

The LS-DYNA program was used to simulate the unloading process of rock in a state of 3D stress. The continuous surface cap model (CSCM), validated in the previous studies, and has been found to be suitable for use with rock [10]. In this model, a cap model with a smooth intersection between the shear yield surface and hardening cap. The material model includes an isotropic constitutive equation, yielding and hardening surfaces, a damage formulation to simulate the softening and the modulus reduction, and a rate effect formulation to express the increasing strength resulting from the strain rate [20]. A complete theoretical description can be found in the introduction and example problem presented by [21]. Here, the basic model features are described. The shear failure surface is defined as

$$\sqrt{J_2'} = F_e(J_1) = \alpha - \lambda \exp(-\beta J_1) + \theta J_1 \tag{5}$$

where J_1 is the first invariant of the stress tensor, J_2' is the second invariant of the deviatoric stress tensor, respectively. The parameters of α, β, λ and θ are selected by fitting the model surface to strength measurements taken from tri-axial compression tests conducted on plain rock cylinders.

The strength of the material is modelled by a combination of the cap and shear surfaces in the low to high confining pressure regimes. The isotropic hardening cap is a two-part function that is either unity or an ellipse, and is modified

$$\sqrt{J_2'} = F_c(J_1, k) = 1 - \frac{[J_1 - L(k)][|J_1 - L(k)| + J_1 - L(k)]}{2[X(k) - L(k)]^2} \tag{6}$$

The equation for $L(k)$ restrains the cap from retracting past its initial location at k_0, and k_0 is the value of J_1 at the initial intersection of the cap and shear surfaces before hardening moves. The function is unity for $J_1 < L(k)$ and elliptical for $L(k) \leqslant J_1 \leqslant X(k)$. Herein, k is a hardening parameter that causes the cap surface to move. $X(k)$ is the position on the J_1-axis where the cap surface intersects the shear failure surface.

For the continuous shear and compaction surface, the functional forms of the shear failure and cap surface are multiplied together as

$$\sqrt{J_2'} = F_f(J_1, k) = F_e\sqrt{F_c} \tag{7}$$

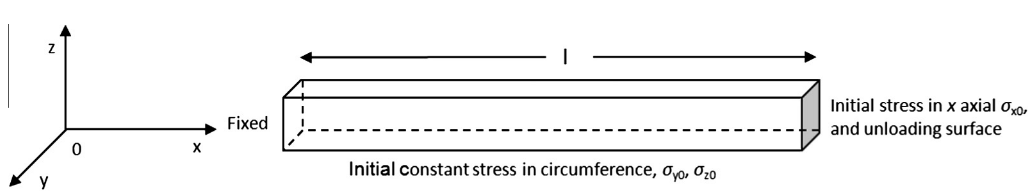

Fig. 1. The loading and unloading model of rock.