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Influence of stress path on excavation unloading response

Xibing Li, Wenzhuo Cao *, Zilong Zhou, Yang Zou

School of Resources and Safety Engineering, Central South University, Changsha, Hunan 410083, People's Republic of China

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ABSTRACT

The unloading process of rock mass is critical to the research of excavation disturbances of tunnels in deep mines, and the dynamic effects induced by the release of in situ stress cannot be ignored. In this study, a mathematical physics model was applied to characterise the unloading mechanisms of brittle rock under different stress paths in two dimensions using the universal discrete element code PFC2D for numerical simulations. The excavation relaxation method was employed to control forces applied to the tunnel internal surface to investigate the influence of various in situ stresses, the unloading rate and path on the dynamic effects. Longer unloading time can mitigate the dynamic effects within a certain time range. Nonlinear unloading paths prevail over the linear path in releasing kinetic energy. Furthermore, the exponential path that represents "slow followed by fast" unloading induces the most peripheral displacement, while the cosine path that represents "fast followed by slow" unloading yields the most cracks around the tunnel. The results also indicated that increasing the ratio of horizontal and vertical in situ stresses can exacerbate the dynamic effects. The proposed model agreed well with the theoretical solution and provided a basis for understanding the evolution of the unloading response around the tunnel.

1. Introduction

Underground rocks and ores are subject to complex stress fields, including gravity stress and tectonic stress. Thus, destruction during excavation unloading is due to two factors, the initial in situ stress state and the excavation unloading process. Therefore, safety problems induced by unloading under high initial stresses have been a prominent focus in mining, tunnelling and hydropower engineering. Deep rock masses and very steep slopes are especially challenging to regular excavation and ore extraction.

Unloading under high-stress conditions is traditionally assumed to be a quasi-static process, and the magnitude of the excavation response depends on the initial stress and excavation area; the dynamic effects can be ignored to some extent (Lu et al., 2012). However, excavation in underground rock masses is a dynamic process in which energy released due to unloading is sufficient to give rise to dynamic failure in the surrounding rock (Li et al., 2011). The characteristics of stress evolution, displacement variation and energy dissipation in excavation are necessary precursors of numerous phenomena and disasters in deep tunnelling engineering. Furthermore, investigating tunnel excavation responses that consist of the deformation features and fracture characteristics of surrounding rock under different stress path helps to explain peculiar phenomena under high ground stress, e.g. large squeezing deformations (Cantieni and Anagnostou, 2009), rock bursts (Hua and You, 2001) and zonal disintegration (Zhou et al., 2009; Tao et al., 2013b).

One research area includes studies that focus on the variation laws of mechanical parameters and their characteristics under unloading conditions (Xie and He, 2004). The rock mechanical properties, such as the complete stress–strain curves, strength feature and deformation characteristics, markedly differ under complex stress paths (Guo et al., 2012a,b). Thus, a series of representative unloading tests on hard rock were carried out to study the destruction pattern and fracture features from the underground workshop excavation zone (Lv et al., 2012; Lv and Yan, 2011). Further studies demonstrated that a peculiar type of mechanical characteristics could be associated with the adjustment of excavation-induced stress. However, the field monitoring system could not easily capture all short-term excavation responses in a timely manner.

The mechanisms that govern unloading responses under different stress paths have also been an area of intense study. Previous studies showed that deformation and failure at the excavation surface is closely related to the unloading rate (Cai, 2008). It provided the fundamental numerical implementation for the transient and quasi-static unloading, and also uncovered the dynamic influence on the excavation. The speed of excavation positively correlates

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* Corresponding author. Tel.: +86 15200817900.
E-mail address: caowenzhuo08@126.com (W. Cao).

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Nomenclature

SED	strain energy density
ERR	energy release rate
ERS	energy release speed
FEM	finite element method
FDM	finite difference method
EDZ	excavated damaged zone
DEM	discrete element method
PFC2D	two-dimensional particle flow code
URL	underground research laboratory
D&B	drill-and-blast
TBM	tunnel boring machine
IBVP	initial boundary value problem
r	radial coordinate
t	time after the start of unloading (s)
σ_0	static initial stress (MPa)
P_0	magnitude of the static initial stress (MPa)
σ_r, σ_θ	radial and tangential components of stress applied to the tunnel surface (MPa)
u	radial displacement (m)
t_0	unloading time (s)
a	radius of the circular tunnel (m)
ρ	rock mass density (kg/m^3)
λ	Lamé parameter of the rock mass (GPa)
G	shear modulus of the rock mass (GPa)
μ	Poisson's ratio of the rock mass
E	elastic modulus of the rock mass (GPa)
c	propagation speed of the P-wave through the rock mass (m/s)
$\bar{u}$	transform of u
p	transformation parameter
k_n, k_s	contact normal and shear stiffness of particles (N/m)
$\bar{k}_n, \bar{k}_s$	parallel-bond normal and shear stiffness of particles (N/m)
σ, τ	contact normal and shear strength of particles (MPa)
$\bar{\sigma}, \bar{\tau}$	parallel-bond normal and shear strength of particles (MPa)
E_k	total released kinetic energy (kJ)
k	ratio of horizontal and vertical in situ stresses

with the amount of energy released and the energy release rate. But theoretical analysis and experimental verification were not presented. Kaiser et al. (2001) provided engineering data that illustrated the influence of stress path on tunnelling, but dynamic effects were not concerned. Further studies have examined unloading in one dimension. Tao et al. (2012) gave the unloading governing equation in one direction, which characterises the dynamic unloading process under different initial stress release rates and paths. The strain energy density (SED) rate was also introduced to quantify the unloading process in response to a 3D stress state (Tao et al., 2013a). The two-dimensional state has been intensively discussed. The pioneering work in this area can be traced to Miklowitz (1960), who began to study the problem of a stretched elastic plate with a suddenly punched circular hole based on elastic mechanics and Laplace-transform technique. Carter and Booker (1990) extended the study to demonstrate that gradual excavation reduces fewer dynamic effects. However, only a few unloading paths were considered and dynamic failure characteristics such as crack distribution at the periphery of a tunnel could not be derived. The roles of the energy release rate (ERR) and energy release speed (ERS) in the energy release process and the risk of rock-burst have also been examined in recent studies (Yan et al., 2012). Lu et al. (2012) proposed an equivalent simulation method to couple the blasting load and transient release of in situ stress to study the transient characteristics of the release process. But no systematic theoretical researches were presented to verify the field tests. Therefore, uncertainties persist in the quantitative relationship between the specific stress path and its corresponding unloading response.

Numerical modelling techniques have become an effective tool for investigating the excavation unloading response (Jing, 2003). Finite element method (FEM) (Doležalová, 2001), finite difference method (FDM) (Corkum and Martin, 2007) and coupled methods have usually been employed for traditional analyses. Most of the conventional methods simplified the excavated damaged zone (EDZ) as plastic zones, and the accuracy of this simplification depended on the meshing size. Comparatively, the discrete element method (DEM) allows the separation of particles, and crack generation around underground openings can be intuitively reproduced. In this study, the discrete element code PFC2D was used to simulate unloading responses in underground excavation. The macro-scale properties are associated with individual particles, which allow the time-varying loading condition on particle boundaries to be controlled. The feasibility of PFC2D in macro-scale problems, such as rock mass excavation and slope stability analyses, has been validated by the underground research laboratory (URL) project (Potyondy and Cundall, 2002; Read, 2004) and heavily jointed rock slopes (Wang et al., 2003). Furthermore, the built-in explicit solution scheme provides a stable convergence solution, which prevails over the implicit one in its ability to capture the true physical process in underground excavation (Cai, 2008).

This paper considered both the dynamic and quasi-static unloading processes that were initiated by different excavation methods, such as the drill-and-blast (D&B) method and tunnel boring machine (TBM) method. The theoretical results intuitively presented the dynamic effects as a function of the radial coordinate, r, and time, t, in three-dimensional contour maps. The results were further explored using a numerical model to represent influence on displacement variation, crack distribution and energy evolution. A primary yet efficient technique, i.e., the excavation relaxation method, was employed to implement the simulation. Based on this finding, the unloading mechanism was characterised in two dimensions, and the influence of stress release rate and unloading path on the dynamic effects was demonstrated.

2. Mechanism of excavation unloading under different stress paths

2.1. Problem layout and superposition principle

A cylindrical cavern excavated in a hydrostatic pressure environment via different excavation methods, such as the D&B method or the TBM method, can be simplified to a plane strain problem. For the two-dimensional case, different responses around the circular tunnel can be induced for different stress histories in the unloading process. To facilitate the subsequent calculation, the solution procedure was formulated in terms of the superposition of the initial in situ stress field and a tensile radial traction applied to excavation surfaces during the unloading process, as illustrated in Fig. 1. Because positive stresses indicate tension in the paper, the magnitude of the static initial stress, σ_0, is $-P_0$, and $\sigma_r = \sigma_\theta = -P_0$, $u = 0$ can be easily obtained at $r \geqslant a$, in which a is