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Vibrations induced by high initial stress release during underground excavations

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ABSTRACT

Excavation unloading under high initial stress is a typical dynamic process subjected to the combined effects of different factors. In this study, a mathematical physics method for a two-dimensional circular excavation was developed to investigate the mechanism involved in unloading vibration, which is capable of providing insights into the quantitative relationships between vibration features and correlative factors such as the initial stress, cross-sectional area of the tunnel, unloading rates and unloading paths. Then the dynamic unloading excavation process was implemented in the discrete element program PFC 2D for numerical analysis after verifications against the theoretical results. In particular, the characteristics of unloading waveform under high initial stress were investigated for various ratios of horizontal and vertical in situ stresses and aspect ratios of rectangular tunnels. The temporal and spatial characteristics of the excavation process can also be illustrated. In a practical project which considered the combined action of both the blast and unloading vibration, the finite difference program FLAC 3D was further adopted to investigate the contribution of unloading vibration to the character of the seismogram. Results are presented which indicate the 2D numerical analysis provides satisfactory approximation to the excavation process. While the peak particle velocity (PPV) is in direct proportion to the in situ stress variation, it decreases significantly along with the increase of unloading time. In addition, excavation by drill-and-blast (D&B) method should be taken as a dynamic process of blast loading before unloading in a period of time, instead of instantaneous unloading. Although unloading vibration can be generated and significant damage around the tunnel can be induced in the process, distinct unloading vibration can only be generated under high in situ stress and unloading rate.

1. Introduction

The exhaustion of resources in the shallow and the boom of mining and hydropower engineering have tremendously stimulated large-scale tunnel excavations extending to the depth. However, owing to the special geological environment in which the deep engineering locates, tunnel unloading excavation induces widely different phenomenon against engineering in the shallow, and the traditional theory based on the engineering at a shallow level is no more suitable to guide the excavation practices. The unloading problem in a high-stress environment is one of the urgent issues which closely related to the stability of the surrounding rock, effective regulation and control of the energy stored in rock and the transfer of the strain energy around the tunnel. Therefore, it can not only provide gist for fundamental research but also for practical application to investigate the surrounding rock failure under excavation disturbance and the characteristics of disturbance propagation.

In practice, underground rocks are highly stressed under in situ stress. When an underground cavern or tunnel is excavated, the initial stress field is disturbed and redistributed. In the proximity of the excavation tunnel boundary, the displacement and deformation of rock granules occur, the micro cracks extend to macro fracture and the excavation damaged zone (EDZ) is formed (Fakhimi et al., 2002; Kim et al., 2013; Read, 2004). The mechanism involved in the fracture in the surrounding rock has long been an area of intense investigations (Corkum and Martin, 2007; Lee et al., 2012; Tao et al., 2012).

When the drill-and-blast (D&B) method is used in underground excavations, the radial principal stress is released in a short time with subsequent tangential principal stress increase, in which process the excavation releases strain energy that will be dissipated completely in the rock mass (Lu et al., 2012). According to elastodynamics, unloading vibration might be triggered and propagates to the deep in the form of stress wave. Zhu et al. (2014) proposed

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a general damage model considering the dynamic stress redistribution, and studied the formation of the EDZ around an opening in a deep rock mass. Our previous study also suggested that different unloading rates and unloading paths have a significant influence on the excavation unloading responses, and that long unloading time can mitigate the dynamic effects and induce less cracks around the tunnel (Li et al., 2014a). Some evidence also suggested that some phenomena such as zonal disintegration are associated with dynamic unloading (Zhou and Bi, 2012). These works focused on the stress redistribution and associated damage around the tunnel. Not much attention, however, has been dedicated to the induced vibration signals in both the near field and far field. If in situ stress release does have a significant vibration signal, the low nature frequencies of structures render them more prone to damage subject to unloading vibration. As a tensile wave, the unloading vibration also poses a strong threat to neighboring underground caverns or tunnels, thus its influence can never be ignored.

To characterize the unloading process in the laboratory, true-triaxial unloading experiments following the stress path that resembles dynamic unloading at the tunnel boundary were performed by He et al. (2010). Acoustic emission (AE) signals emanating from the origin points within the rock sample were captured by utilizing AE monitoring technique. The work of Zhao et al. (2014) indicated that the rock failure mode and AE characteristics associated with the cumulative energy and frequency–amplitude distributions would be different under different true-triaxial unloading conditions.

In field tests, microseismic monitoring technique has been extensively utilized in the monitoring of nuclear explosions (Mueller and Murphy, 1971; Werth and Herbst, 1963), earthquakes (Whitcomb et al., 1973), microseismic events induced by rock failure and blast vibrations (Xu et al., 2012). Through analysis of the vibration signal, some valuable information can be gained about the rock mass unloading relaxation, such as the formation of micro-fractures in deep rock masses prior to the macroscopic rock instability failure (Cai et al., 2001). Furthermore, a better understanding of the correlation between seismic source locations and mining-induced stress redistribution in working areas can also be revealed (Ge, 2005).

Nevertheless, some indications showed that the release of preexisting tectonic strain near the explosion affects the character of seismograms to some extent in underground projects. Two general models for tectonic release have been proposed: triggered displacement on a nearby fault, or the stress relaxation from fractured rock during formation of the explosion cavity (Burger et al., 1986). In the latter process, microseismic signals can be generated from the tectonic stress redistribution during or after the excavation, accompanying with the blast vibration signals. In large underground nuclear explosions, evidence of tectonic release was present in both long-period P waves and S waves (Bache, 1976; Burger et al., 1986). The tectonic component of the surface waves even exceeded those due to the explosion in several cases (Toksöz and Kehrer, 1972). Abuov et al. (1988) stated that when carrying out explosive operations on the rocks, the dynamic tensile stresses caused an increase in the thickness of the weakened zone and evoked rockbursts. It was also found that the vibrations induced by deep-buried cavern excavations had a higher main frequency and more scattered energy distribution than that in open pit (Lu et al., 2011a). In a deep rock mass excavation by blasting, the microseismic vibrations induced by the instantaneous release of in situ stress were successfully identified and separated from microseismic signals by comprehensive application of time-energy density analysis, amplitude spectrum analysis and finite impulse response (FIR) digital filter (Yang et al., 2013).

However, irrespective of some observations accounted for by plausible tectonic release models, a series of studies demonstrated that there was still no unambiguous evidence of tectonic release effects on short-period P waves (Wallace, 1991). Lay and Welc (1987) stated that there was no direct evidence of significant tectonic release contribution to the character of seismograms for more than 1600 short-period P waves from 46 underground nuclear explosions. For most circumstances, although tectonic stress relaxation does occur, it has no appreciable effect on the amplitude and frequency content of the short-period P waves (Lay et al., 1984; Press and Archambeau, 1962). Even with these experiments and observations at hand, the question of whether the in situ stress relaxation can trigger unloading disturbance in the far field is still a subject of active debate. It also remains a concern that whether the conventional D&B method can generate a significant unloading signature under high-stress conditions. Therefore, the physical plausibility and conditions under which unloading wave can be generated should be examined.

Theoretical analyses are helpful to interpret the mechanism of unloading vibration as well as how it influences the whole seismogram. The work of Salamon (1974) stated that while 62.5% of the released energy would turn into seismic energy if the opening was excavated in one mining step, only 3.4% would be seismic if the tunnel was excavated in 64 steps. So it can be deduced that the characteristics of unloading vibration, such as the waveform, the peak particle velocity (PPV), and the unloading duration, are closely associated with not only the geological environments (including the in situ stress fields and the physical properties of the rock mass, etc.), but also the unloading conditions (including the tunnel layout, the tunnel size, the excavation methods and sequences, etc.). Besides, verifying the mechanism of unloading disturbance and describing how it functions can be traced to as early as the 1960s, since which time the problem of a stretched or stressed elastic plate with a suddenly punched hole has been intensively studied (Miklowitz, 1960). Primarily laying their emphasis on the stress variation around the proximity of the punched hole (Barclay et al., 1981; Jiang and Haddow, 2003; Mioduchowski et al., 1978), previous research works were severely handicapped by a lack of investigations into the unloading vibration. As the propagation of forces in deep rock mass, the unloading disturbance can be represented by the stress or velocity time-history curves of measurement points. However, several questions about the unloading-induced vibration, such as the PPV and magnitude of the unloading wave, how the unloading wave propagates and attenuates, and whether it poses a potential danger to the far field, are not clear until now and further theoretical analysis is needed.

The study started with the analysis of a two-dimensional dynamic excavation, and theoretical waveforms were deduced for different tunnel dimensions, in situ stresses and unloading conditions. Then a discrete element method (DEM), by PFC 2D, was introduced for numerical analyses to verify against the theoretical solution, after which parametric analyses were carried out to investigate the unloading characteristics under various conditions, by varying the ratio of horizontal and vertical in situ stresses and the aspect ratio of rectangular tunnels. In the following practical project, the whole process of unloading by the conventional D&B method was discussed, which better mimics the advancement in a mining face. A finite difference method (FDM), by FLAC 3D, was applied to further investigate the unloading-induced damage around the tunnel and determine the contribution of the in situ stress release to seismogram character. Based on this investigation, the quantitative relations between the initial stress state, the unloading conditions and the unloading vibration are established, which can provide insights into the unloading mechanism. The present study indicates that the unloading vibration is closely