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Influence of unloading disturbance on adjacent tunnels

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A B S T R A C T

A theoretical model was first established in order to evaluate the physical possibility of a dynamic response occurring around an existing tunnel under conditions of unloading wave incidence. Based on the steady state solution of the wave expansion approach, transient solutions subjected to unloading waves with different unloading times were obtained. A three-dimensional numerical model was then constructed in order to simulate dynamic responses around an existing tunnel under unloading disturbance forces. In the simulation, dynamic unloading was carried out through a new excavation after stress redistribution had been finalized in the examined tunnel, and parametric studies were then conducted for various unloading times, stress levels and tunnel spacing configurations. The results show that dynamic effects are induced around an existing tunnel under high levels of initial stress and at high unloading rates. The results of the dynamic analysis show that the PPV of unloading-induced microseism can be as high as that of an explosion-induced wave, and damage can be inflicted on existing tunnel walls (especially on the incident side of a tunnel). This dynamic effect diminishes dramatically with an increase in tunnel spacing and unloading times.

1. Introduction

Adjacent tunnels are widely employed in underground engineering projects (e.g., hydraulic engineering projects and underground mines). As a means of saving space and controlling engineering budgets, there has been a growing demand for the construction of adjacent tunnels characterized by narrow tunnel spacing. A number of studies have examined excavation-induced movement, tunnel deformation and distortion and stress redistribution processes found in immediately adjacent tunnels.[1–5] Such studies have typically focused on stress interactions between tunnels without considering accompanying dynamic engineering disturbances. However, due to the existence of frequent underground hazards whereby adverse effects of dynamic disturbance have played an important role in triggering sources of instability over recent decades, the significant influence of dynamic disturbance is now increasingly being valued.

The most common dynamic disturbances relevant to the field of engineering are related to explosions and earthquakes. Some researchers have treated explosions as problems associated with the existence of elastic wave radiation subjected to radial pressures in a cavity of an infinite homogenous isotropic elastic solid. Sharpe[6,7] found a solution to problems of wave generation by explosion pressures and found this solution to be in qualitative agreement with elastic wave motion forces recorded near an exploding charge. Selberg[8] studied compressive waves generated as a result of step loading applied at the surfaces of spherical and cylindrical cavities using the Laplace transform method and the inversion integral theorem. Blake[9] identified a solution for compressional wave propagation from a spherical cavity using the reduced displacement potential. Eringen[10,11] studied elasto-dynamic problems resulting from the application of arbitrary dynamical tractions on the surfaces of both spherical and cylinder cavities using the Fourier transform technique. Miklowitz[12] used the Laplace transform to obtain a solution to sudden radial stress pressures in a thin elastic plate.

As physical processes involved in blast loading and mechanisms that trigger earthquakes are complex, realistic induced vibrations are difficult to express through an accurate functional form. In situ monitoring and numerical studies have thus become efficient ways to better understand such phenomena and to help interpret waveforms and their effects on underground tunnels. For example, Feldgun et al.[13] presented a comprehensive means of examining explosion effects on nearby infrastructure tunnel behaviours that involves using AUTODYN 12. The influence of explosion-induced microseism on the lining of an existing tunnel was studied in terms of both vibration velocity and dynamic strain, and the areas most prone to dynamic damage were found to be the arch crown and sidewall foot.[14] Dynamic modelling of tunnel

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responses to blast-induced vibrations has been conducted using a two-dimensional numerical method, and guidelines for blast protection zones have been presented in reference to soft rock.[15] Finite element analyses have been conducted in order to analyse the dynamic responses of buried tunnels of different depths and tunnel shapes, and the results show that the semi ellipse tunnel shape is most resistant to demolition.[16] The determination of separation distances for underground explosive storage and the dynamic responses of tunnel linings and buried structures to blast vibrations have also attracted much attention from academics and engineers.[17–20] Furthermore, some existing studies on underground structures subjected to seismic loads have also focused on tunnels.[21–23] It was found that earthquakes can damage underground structures when permanent ground movements occur along underground structures.[24] In recent years, damage characteristics of bedded salt cavern gas storage facilities during earthquakes have been numerically studied through the application of a dynamic elasto-plastic damage constitutive model to FLAC 3D, and the results show that the acceleration and duration of seismic waves serve as controlling factors that ensure cavern safety.[25] The discontinuous deformation analysis (DDA) method has also been used for the analysis of seismic dynamic responses of underground caverns.[26,27]

As excavations have been carried out at deeper depths in recent years, rock masses have become much more pre-stressed under high levels of in situ stress. When a tunnel is excavated using a blasting method, both loading and unloading vibrations are induced in the vicinity of the tunnel. As illustrated in Fig. 1(b)(c), both loading and unloading waves travel away from the tunnel but with particles vibrating in opposite directions in the medium. Unloading problems occurring under high levels of initial stress have been an area of intensive study, and related results show that unloading under levels of high stress can lead to the generation of more excavation damaged zones (EDZ) and to the development of more hazards (e.g., spalling, tunnel lining collapse, rockbursts and zonal fractures around tunnels).[28–32] The authors have studied the effects of stress paths on time-varying variations in stress, displacement and fracture distributions along tunnel boundaries via theoretical investigation and numerical verification.[33] Despite the effects of damages and fractures in the vicinity of an excavated tunnel, unloading waves that travel into rock mass are also generated from tunnel boundaries. It was verified that the unloading of in situ stress on excavation boundaries is essential to the excitation of vibration, and safety distances were examined along the longitudinal direction of the tunnel examined.[34] The authors also revealed features of unloading wave propagation and found this process to be comparable to blast vibration processes owing to high levels of initial stress and short unloading times.[35] Therefore, it is postulated that high levels of unloading excitation can significantly induce geological dynamic hazards such as rockbursts and fault slips. However, research on the dynamic responses of existing tunnels subjected to unloading disturbance still appears to be limited.

The responses of tunnels subjected to wave excitation can be simplified as a plane problem of induced dynamic stress concentration around a circular hole by P wave incidence. Previous studies have focused on the diffraction of elastic waves since as early as the 1960 s. Baron et al.'s[36,37] pioneering work examined stress, displacement and velocity fields around a cylindrical cavity enveloped by a plane shock wave through the use of an integral transform technique and presented numerical results at the cavity boundary. The use of the wave function method was then successfully introduced for this type of problem, and theoretical static-steady and transient solutions were derived for circular cavity stress concentrations found during harmonic and transient plane wave loading processes, respectively.[38,39] The corresponding results reveal an overshoot of approximately 10% relative to the static value in both cases. In the fields of mining engineering and underground space engineering, vibration sources are typically positioned away from structures or tunnels of interest, and so the above research results can help facilitate stability evaluations conducted under processes of dynamic excitation. However, when distances from vibration sources are considered small (e.g., adjacent explosions or excavation unloading as illustrated in Fig. 1b and c), the curve of the cylindrical wave may produce a considerably different dynamic response. Jakub and Mow[40] studied interactions derived from a compressive cylindrical harmonic wave impinging on a cylindrical cavity based on cavity geometries. Their results show that a high stress concentration factor can be yielded in the presence of spherical or cylindrical waves (as opposed to plane waves primarily found in the low-frequency portion of the response curve, which denotes a more dangerous state). Yi et al.[41] extended this analytic solution to a circular lined tunnel with an imperfect interface. Li et al.[42] presented a theoretical method based on the principle of momentum conservation at wave fronts in order to predict tunnel stability levels in terms of peak particle velocity (PPV) and stress distribution levels, and safe separation distances between adjacent tunnels were determined based on PPV and tensile strength criteria. However, the dynamic responses of transient unloading wave incidence have not been systematically investigated.

This paper reports on a study that identifies the effects of unloading disturbance on immediately adjacent tunnels by means of a theoretical analysis and numerical simulation. The transient solution of dynamic responses of an existing tunnel due to an unloading wave was first obtained from an integral of the steady-state solution. More specifically, different unloading times were taken into consideration. The results were further explored using a numerical model wherein in situ stress redistribution and dynamic unloading excavation were performed in sequence. Parametric analyses were conducted with a focus on PPV, displacement, maximum principal stress and safety factors as affected by unloading time, stress level and tunnel spacing characteristics. We show that dynamic effects can be induced around an existing tunnel under high levels of initial stress and fast unloading rates

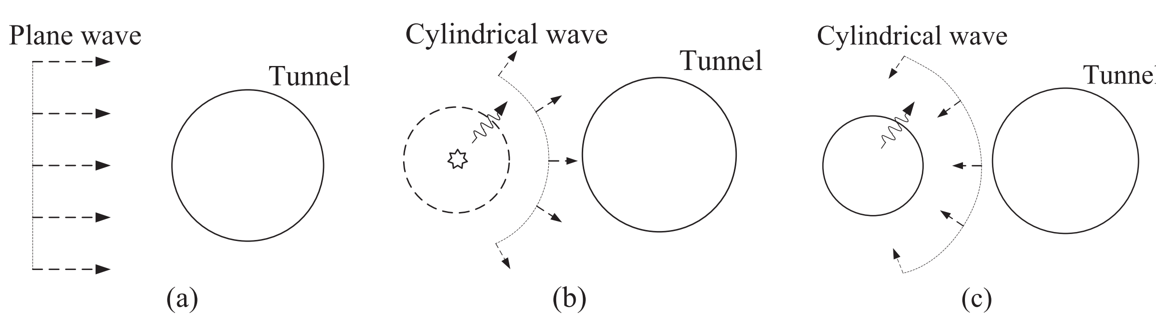

Fig. 1. Schematic illustration of the type of wave incidence.