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Numerical study on tunnel damage subject to blast-induced shock wave in jointed rock masses

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ABSTRACT

In this study, numerical modeling on the damage of existing circular tunnel subject to blast-induced shock wave was carried out with DEM-based code UDEC. The disturbed zones including failure zones, open zones and shear zones around circular tunnel and peak particle velocities (PPVs) at tunnel surface are employed to analyze the damage of tunnel. The effects of joint spatial and mechanical properties, initial stress of rock mass, and magnitude of shock wave amplitude to damage of tunnel were evaluated in this study. The difference of damage between non-supported circular tunnel and bolt-supported circular tunnel subject to the same blast-induced shock wave was also studied. It is found that the orientations of joints in rock mass around the tunnel have great effects on tunnel damage. The initial stress around tunnel has relatively small influence on tunnel damage. The bolt support could greatly increase the stability of tunnel by changing the vibration form of particle velocity rather than the decreasing of PPV.

1. Introduction

An explosion, such as accidental explosion, drill and blast excavation or weapon attack, has large effect to adjacent underground structures. Generally, the effect includes overpressure, thermal effects, energized projectiles (fragments, debris, and missiles), ground shock, and caterings (Ronald et al., 2010). Especially, the ground shocks are of great interests to engineers concerning the design of underground and surface structures. Kutter et al. (1988) noted that the direct loading by a shock wave created due to explosion is the principal mechanism to cause damage to underground structures. Therefore, research on effects of blast-induced shock wave to underground tunnel damage is both significant and practical (Zhao et al., 1999).

Studies have shown that the peak particle velocity (PPV) is the most representative parameter to describe the ground motion and tunnel response (Dowding, 1984). Extensive studies on damage of non-supported underground tunnel in terms of definition of tunnel damage and the threshold values of PPVs have been performed (Persson, 1997; Li and Huang, 1994; Hendron, 1977; Coates, 1981; Kartuzov et al., 1975; Oriad, 1972; Phillips et al., 1992; Siskind, 1997). For damage of rock tunnel with support, studies carried out by Stjern and Myrvang (1998) and Ortlepp and Stacey (1998) have shown that PPVs up to 1 m/s will not cause any measurable damage to the tunnel. For lined tunnels, Dowding (1984) suggested that the threshold value of PPV was roughly double that for unlined tunnels.

However, most of the definitions are not well defined and various terms, describing of damage, often have significant differences in definition and practical meaning (Zhou, 2011). Little considerations of effects of discontinuities on tunnel damage is included in these experiment-based studies. Generally, rock mass contains various discontinuities such as bedding planes, foliation, faults, and joints. The behavior (deformation characteristics, stress development, etc.) of rock mass around the tunnel is mainly controlled by the spatial and mechanical properties of the discontinuities (Tülin, 2009).

Model tests, analytical methods, and numerical methods are generally employed to evaluate the behavior of rock mass around tunnel in jointed rock masses. Few model tests were performed in jointed rock masses because of the limitation in joints setting.

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Analytical methods, considering block behavior in tunneling, are mainly based on the block theory (Goodman and Shi, 1985). Although the capability of the analysis is increased with improvement of the block theory with respect to stress conditions, decrease of forces acting on the key block (Brady and Brown, 2004) and use of sophisticated joint models (Pötsch, 2002), they are not applicable to cases where ground shows stress induced failure or more complicated problems are involved. Compared with theoretical and experimental studies, numerical modeling provides a convenient, economical approach to study underground explosions, especially for complicated cases where experiments are difficult and expensive to conduct and theoretical solutions are impossible to derive (Zhu et al., 2011).

In this study, numerical modeling on the damage of existing circular tunnel subject to blast-induced shock wave in jointed rock mass was performed with DEM-based code UDEC. The disturbed zones around tunnel and PPVs at tunnel surface were employed to analysis the damage of tunnel. The aim of this study is to evaluate the effects of joint spatial and mechanical properties, initial stress of rock mass, magnitude of shock wave amplitude, and bolt supports to damage of tunnel.

2. UDEC model

In this study, before performing UDEC modeling, an AUTODYN-2D modeling was carried out firstly to generate blast-induced shock waves, which would be applied as the velocity boundary conditions in UDEC model. The shock waves were generated by detonation of high explosive TNT. Fig. 1 shows the configuration of AUTODYN-2D model, the width and height of this model are both 30 m. The radius of TNT material r, as shown in Eq. (1), depends on the scaled distance (SD) (Zhou, 2011) with assumption that the actual distance R is fixed at 25 m.

$$SD = R/(m)^{1/3} = R/(4\pi r^3 \rho/3)^{1/3} \tag{1}$$

where SD is the scaled distance, m/kg$^{1/3}$, R is the actual distance from the explosive center, m is the weight of explosive, ρ = 1630 kg/m^3 is the density of TNT material. In this study, the scaled distance is assumed to be 0.5, 0.75, 1.0, 1.5, 2.5, and 5.0 m/kg$^{1/3}$, respectively. The actual distance R (25 m) used for shock wave generating is identical to the distance from upper boundary to the circular tunnel in UDEC model as will be shown in Fig. 4(b). The gauge A, recording time-velocity history, is located at bottom boundary 5 m far from detonating point. As will be shown in Fig. 4(c), the gauge distance (5 m) is identical to the radius of circular boundary, upon which the shock wave is incident in UDEC model. The rock material is assumed to be elastic with Young's modulus E = 94.75 GPa, Possion's ratio ν = 0.27 and density ρ = 2620 kg/m^3.

The equation of state (EOS) of TNT conform to the JWL state expressed as Eq. (2) (AUTODYN, 2005),

$$p = A\left(1 - \frac{\omega}{R_1 V}\right)e^{-R_1 V} + B\left(1 - \frac{\omega}{R_2 V}\right)e^{-R_2 V} + \frac{\omega}{V}E \tag{2}$$

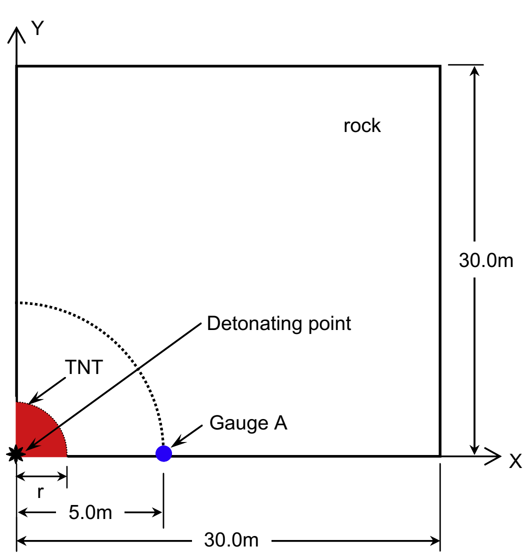

Fig. 1. Configuration of AUTODYN-2D model for blast-induced wave generating.

Table 1
Properties of TNT material used in AUTODYN-2D modeling (AUTODYN, 2005).

Parameters	Value
Density (g/mm^3)	1.6
A (kPa)	3.7377e8
B (kPa)	3.7471e6
R_1	4.15
R_2	0.9
ω	0.35
Detonation velocity (m/s)	6930
Energy/unit volume (kJ/m^3)	6.0e6
CJ pressure (kPa/m^3)	2.1e7

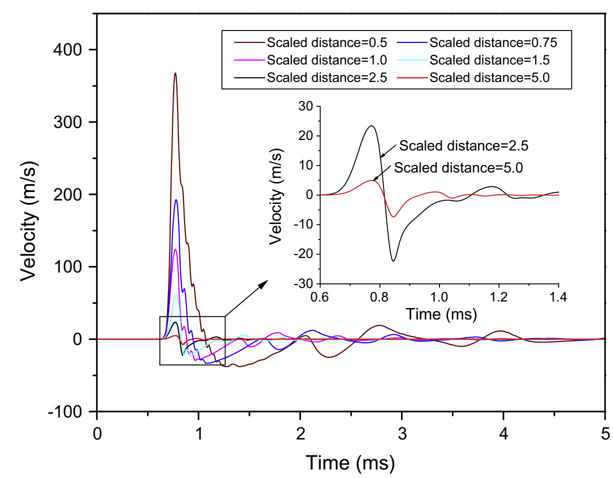

Fig. 2. Particle velocity–time histories obtained from AUTODYN-2D modeling at gauge A in terms of different scaled distances.

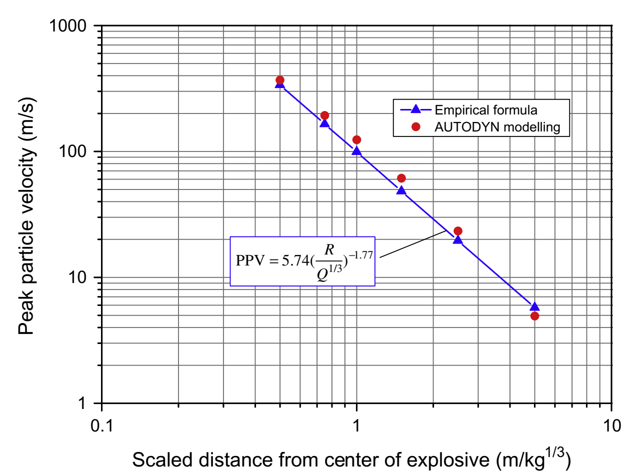

Fig. 3. Comparison of PPV between numerical modeling results and empirical formula.