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Application of the four-dimensional lattice spring model for blasting wave propagation around the underground rock cavern

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A R T I C L E I N F O

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A B S T R A C T

This paper studies the propagation and attenuation of blasting wave induced by explosion in underground rock cavern by employing the newly developed four-dimensional lattice spring model (4D-LSM). The non-reflection viscous boundary condition was implemented in the 4D-LSM to reduce the computing resources of full-scale simulation of blasting wave propagation in the practical engineering. Then, a number of damping models were developed and implemented in the 4D-LSM to describe the attenuation of blasting wave in the rock mass. In addition, the influence of the loading form of blast load and damping models on the propagation and attenuation of blasting wave were studied by comparing with the field test data in details. It was found that the loading form of a triangular blast stress wave with an equivalent pressure wave and the coupled damping model could lead the 4D-LSM producing a reasonable fitting over the field test data in terms of both the blasting waveform recorded at a given measuring point and attenuation results from a number of measuring points. Our study provides a basis for the further application of the 4D-LSM as an alternative numerical tool in modeling the blasting wave propagation problems in rock engineering.

1. Introduction

Due to the shortage of land resources in metropolises and some special purposes of use, many facilities, e.g. oil and gas storage caverns, ammunition depot and air raid shelters, are built underground. An important thing that need to be considered is the potential effects of the ground vibrations induced by the rock blasting or accidental detonation of the oil/gas or ammunition depot on the adjacent structures and equipment when planning and designing such facilities (Wu and Hao, 2005; Lu et al., 2012). Consequently, predicting the rock mass vibration characteristics induced by underground explosions is very important.

In the research of the above problems, the propagation and attenuation of blasting wave in rock masses is one of the most essential topic. Researchers have done some theoretical works about the propagation and attenuation of the wave in the rock mass (McCall, 1994; McCall and Guyer, 1996; Li et al., 2010; Zhu et al., 2011b; Kuster, 2012; Li et al., 2015). Peak particle velocity (PPV) is usually used to measure the ground vibration and various empirical formulae for the prediction of PPV in given geological site conditions are proposed (Dowding, 1985; McMahon, 1994; Odello, 1998; Wu et al., 1998). These achievements provide valuable theoretical bases for the study of propagation and attenuation of the wave in rock. However, the hypotheses and boundary conditions of the theoretical analyses are relatively simple and the stress wave properties are affected by many inherent variables. The theoretical results are difficult to correspond with many specific problems in the practical engineering. On the other hand, in-situ tests can provide precious test data and parameters, however, it is constrained by the specific engineering geological conditions, which makes the field test data and parameters might not be widely applicable. Moreover, the cost of large-scale field blasting test is extremely high, restricting the universal use of this method. With the rapid development of computer science and technology, the numerical simulation method has gradually become an important alternative approach to solve practical engineering problems. The numerical method can overcome various drawbacks existing in theoretical analyses and field test, and it has already become a popular research tool in a variety of

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disciplines.

Recently, there are many numerical achievements concerning the rock mass vibration characteristics induced by underground explosions and the propagation and attenuation of the blast-induced wave. For example, Ma et al. (1998) used FEM-based simulator AUTODYN with a piecewise linear Drucker-Prager strength criterion and an isotropic continuum damage model to investigate the shock wave propagation in rock mass induced by an underground explosion. Ma et al. (2011) further investigated the influences of explosion conditions including loading density, explosive distribution pattern, cavern geometry, and cavern volume on explosion-induced stress wave propagation. Further improved anisotropic continuum damage models were presented by Hao et al. (2002a, 2002b) to model rock damage resulting from blast-induced stress wave. Based on these anisotropic damage models, Wu and Hao (2005) used Autodyn3D to study the blast motion characteristics on ground surface and in the free field, and they (Wu and Hao, 2006) also investigated the effects of various explosion conditions (distribution and location of explosives, cavern geometry and cavern volume, etc.) on the damage zones around the underground cavern, the safe embedment depth. Compared with the continuum-based models, the discontinuum-based models have distinct advantages in the study of wave propagation and attenuation in a rock mass with many discontinuities. There are some literatures about the propagation and attenuation of blast wave in rock mass available. Chen and Zhao (1998) used 2D discrete element program UDEC to study the propagation and attenuation of blast wave in jointed rock. Fan et al. (2004) investigated the effect of incident boundaries (stress-history input and velocity-history input) on the wave propagation and attenuation in both intact and jointed rock mass. Jiao et al. (2007) used discontinuous deformation analysis (DDA) method with viscous boundary to model the stress wave propagation in jointed rock mass. Deng et al. (2012) verify the capability of 3D Distinct Element Code (3DEC) to model wave propagation across rock joints in 3D space. Li et al. (2016) developed a particle-based numerical manifold method (PNMM) to study the propagation problems of waves induced by an underground explosion. It is worth noting that the rock masses in practical engineering are discontinuous, heterogeneous, anisotropic and inelastic, but most of the aforementioned numerical studies are basically based on the linear elastic models. Although there are some theoretical studies about the wave propagation in inelastic media (e.g., Carcione et al., 1988; Yuan et al., 2006; O'Brien, 2008; Li et al., 2010, 2015), the corresponding numerical studies are relatively rare.

The numerical method adopted in this work is the four-dimensional lattice spring model (4D-LSM) developed by Zhao (2017). The LSM has been applied to model wave propagation through jointed rock mass (Zhu et al., 2011a), failure in a jointed rock mass (Zhao, 2015), dynamic crack propagation in PMMA (Kazerani et al., 2010) and soil desiccation cracking (Gui and Zhao, 2015). Compared with classical LSMs, the 4D-LSM overcomes the Poisson's ratio limitation of the conventional LSM methods by implementing the fourth-dimensional interaction, and there is no need to calculate the local strain, which can save large calculation resources. Another important advantage of 4D-LSM is the applicability for dynamic large deformation problems. Combined with well-developed damping models, the 4D-LSM could be a promising approach for rock dynamic problems, especially the blasting wave propagation problems involving the dynamic large deformation.

The aim of this work is to extend and verify the capability of 4D-LSM on modeling the propagation and attenuation of blasting wave in the rock mass. The context is organized as follows. First, the 4D-LSM is introduced and the non-reflection viscous boundary condition is implemented in 4D-LSM. The non-reflection boundary condition is compared with the fixed boundary condition and free boundary condition, which verifies that it is effective to add the non-reflection boundary condition to 4D-LSM. Then, different damping schemes were introduced including the adaptive damping, the viscous damping, and the mass viscous damping. In addition, different explosive loading forms are compared and discussed, which concluded that the blasting load can be well represented by using a triangular blast stress wave and an equivalent pressure wave. Lastly, the numerically predicted velocity histories and attenuation of peak particle velocity with adaptive damping, viscous damping, and mass viscous damping are discussed and compared with the corresponding field test data. With these numerical results, a coupling damping is further proposed and verified. Finally, we conclude that 4D-LSM with proper enrichment can be used to model the propagation and attenuation of blasting wave in the rock mass.

2. Method

2.1. Four-dimensional lattice spring model

A parallel world concept is used in 4D-LSM (Zhao, 2017) and the physical world is assumed as a 4D hyper-membrane consisted of a visible three-dimensional world and an invisible parallel world. The model in visual 3D space and its mapped model in parallel world are closely connected through the 4D interactions, and there are three types of 4D interactions for a cubic lattice model (see Fig. 1(c)). The first type is to link the original mass point (such as A) to its mapped point (A′) with spring stiffness denoted by k_α (see Fig. 1(c) type A). The second type is formed from the orthotic springs with stiffness denoted by k_β (see Fig. 1(c) type B). The third type is formed from diagonal springs with stiffness denoted by k_γ (see Fig. 1(c) type C). The force and normal vector of each particle has three components in 3D-LSM, whereas, the components of force and normal vector increase to four in 4D-LSM. It is worth noting that the springs representing the interactions between particles in the original 3D model all use the same spring stiffness (k^{3D}), while the springs representing the fourth interactions use different stiffness and the above three types of stiffness can be described with 4D stiffness ratio (λ^{4D}). Through theoretical derivation, Zhao (2017) proposed a formula for determining 4D spring stiffness to represent the isotropic elasticity, which can be expressed as:

$$k_\alpha = k_\beta = 4/3k_\gamma = \lambda^{4D}k^{3D} \tag{1}$$

In 4D-LSM, it is assumed that the motions of the particles are satisfied with Newton's second law, and the calculation cycle of 4D-LSM is shown in Fig. 1(a). When the relative particle displacement is obtained initially or from the last time step, the contact bonds between the particles with a specific constitutive law can be used to calculate the new contact force and detect any breakage. The force between two particles obey Hooke's law and an elasto-brittle constitutive model (see Fig. 1(b)) is used. The interaction force between two particles is given as is

$$F_{ij} = ku_n\mathbf{n}_{ij} \tag{2}$$

where $\boldsymbol{F}_{ij}$ is the force from particle i to particle j, k is the stiffness of the spring, $\mathbf{n}_{ij}$ is the normal vector from particle i to particle j and u_n is the deformation of the spring. The spring deformation u_n can be calculated with the following expression:

$$u_n = |\mathbf{x_j}-\mathbf{x_i}|-|\mathbf{x_j^0}-\mathbf{x_i^0}| \tag{3}$$

where $\mathbf{x}$ is the current position of the mass point, $\mathbf{x^0}$ is the corresponding initial position, and $|\cdot|$ refers to get the norm of a vector. The spring normal $\mathbf{n}_{ij}$ can be further calculated with the following expression:

$$\mathbf{n_{ij}} = \frac{\mathbf{x_j}-\mathbf{x_i}}{|\mathbf{x_j}-\mathbf{x_i}|} \tag{4}$$

For elastic problems, there are only two parameters, i.e. k^{3D} and λ^{4D}, are needed in 4D-LSM, and these mesoscopic elastic parameters can be calculated by macroscopic elastic parameters, i.e. E and ν, through the