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Technical note

Modification of the discontinuous deformation analysis method and its application to seismic response analysis of large underground caverns

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ABSTRACT

Two modifications are made to enable the DDA method to be used to study the seismic dynamic response of underground caverns. The first modification involves setting viscous boundary conditions and the second involves inputting seismic waves from the bottom in stress way. The modified DDA code is verified by a two-dimensional continuous model. Moreover, for the propagation problem of an elastic P-wave travelling across a joint face, the numerical solution of the modified DDA is close to the theoretical solution. The modified DDA method is applied to study the seismic response of the underground houses of the Dagangshan hydropower station in Western China, and valuable results are obtained. At three intensity levels, whether the KOBE seismic wave or the artificial seismic wave, will bring about the damage of the surrounding rock masses of unsupported underground houses. Increasing the seismic intensity increases the destructive effect of the wave. The most unstable blocks are at the downstream side wall of the main machine building and tail surge chamber, and these blocks slide first during an earthquake. By contrast, with bolt supporting, the surrounding rock masses maintain stability. Bolt forces change dramatically during the first few seconds of the earthquake (about 6 s in the KOBE seismic wave and 10 s in the artificial seismic wave), and then remain stable. The bolts through the most unstable blocks experience the largest forces, which means the most unstable blocks are the most dangerous blocks during an earthquake.

1. Introduction

The DDA (discontinuous deformation analysis) method is a discontinuous media numerical simulation technique for use in geotechnical engineering that was originally proposed by Shi Genhua in 1988. DDA is a method similar to the finite element method, but it can calculate static and dynamic problems with large displacements for discontinuities, such as dislocations, sliding, and rotations. The DDA method includes “complete numerical implementation theory, perfect first-order displacement approximation, a strict kinetic balance, right energy consumption, and high efficiency” (Shi, 1997). Since it was proposed, the DDA method has been of interest to scholars and widely used to analyse the stability of engineered rock structures, including slopes, dams, and underground houses (MacLaughlin and Doolin (2006)).

The DEM (distinct element method) is also a typical discontinuous media numerical simulation technique. The main deference of DDA and DEM is the solving method of the kinematic equations. An explicit solution based force approach is used in DEM, while an implicit solution based energy approach is used in DDA. Cheng (1998) pointed out the force based approach in DEM suffers from the limitations that: (1) artificial springs are required to absorb the energy generated from the relaxation analysis so as to maintain equilibrium; (2) a very small time step is required for the proper solution of the problem or else numerical instability will occur due to its explicit time integration algorithm. While, the energy based DDA can overcome the two limitations of the force based DEM (Shi, 1988).

In the past, it was believed that the damage caused by earthquakes was not serious for underground facilities compared to surface structures, and minimal attention was focused on the seismic study of underground facilities until the 1990s when earthquakes occurred in Kobe (Japan, 1995), Chi-Chi (Taiwan, 1999), and Kocaeli (Turkey, 1999), destroying selected underground structures (Youssef et al., 2001). The collapse of the Daikai subway station was the first collapse of an urban underground structure due to earthquake forces rather than ground instability (Youssef et al., 2001).

DDA method is seldom used to study the seismic response of underground houses (Hsiung and Shi, 2001) but is often used to study the seismic response of slope (Irie1 et al., 2009; Wu, 2010;

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Wu and Chen, 2011; Wu et al., 2011; Cai et al., 2013; Zhang et al., 2013). There are two insufficiencies in the original DDA code. The first is the boundary condition setting. In numerical simulations of underground engineering, computing models are often cut from a semi-infinite region. For seismic dynamic analysis, the artificial boundary should be established to guarantee that the scattering wave generated in the media is not reflected at the boundary (Lysmer and Kuhlemeyer, 1969; Liao, 2002). The second insufficiency of DDA is the seismic wave input method. There are two input methods in the current DDA method. The first method is to input seismic load in all blocks without considering the wave propagation, this method is not representative of actual situations (Hatzor et al., 2004). The second method is to input seismic waves from a rigid block at its bottom, which cannot eliminate the wave reflection at the boundary (Wu, 2010; Wu and Chen, 2011).

In fact, some scholars have tried to study the wave propagation with viscous boundary in DDA method. Jiao et al. (2007) simulated the stress wave propagation in jointed rock with a viscous boundary. However, he used the blasting wave, which need not to consider the input boundary and input method. Gu and Zhao (2009), Ning et al. (2013) studied the influencing factors on the accuracy of wave propagations with the standard viscous boundary. In these studies, the computation model is just a one dimensional rock bar which not involving the wave inputting method. In this paper, with the DDA method, the viscous boundary is adopted and compared with free and fixed boundaries, the displacement and stress input methods from the bottom are discussed and compared. The stress input method and viscous boundary are verified as suitable for the seismic dynamic analysis of underground structures.

With these modifications, the DDA method is used to study the seismic response of underground houses of the Dagangshan hydropower station in Western China, and valuable results were obtained. At three intensity levels, whether the KOBE seismic wave or the artificial seismic wave, will bring about the damage of the surrounding rock masses of unsupported underground houses. The most unstable blocks are on the downstream side wall of the main house and the tail surge chamber, and these blocks slide first. In contrast, with supporting bolts, the surrounding rock masses remain stable.

It is worth noting that many scholars especially Zhao's group have successfully studied the propogation characteristics of stress wave across jointed or fractured rock mass with DEM, particularly using UDEC/3DEC (Zhao et al., 1999, 2012, 2006, 2008; Zhu et al., 2011; Chen and Zhao, 1998; Deng et al., 2012; Sitharam and Resmi (2013)). But for the seismic dynamic analysis of large underground rock engineering, in order to satisfy the complexity and specificity of the engineering, and to improve the computing efficiency (by using a larger time step), it would be better to use the modified DDA code, as presented in this paper.

2. Modification of the DDA method

2.1. Viscous boundary setting

In the numerical analysis of underground engineering, a computing model is often selected from a semi-infinite region, and the boundary conditions are important. The current DDA code contains free and fixed boundary conditions. For problems without wave propagation, these two boundary conditions are adequate for numerical simulation. However, for seismic response analysis, these conditions are not adequate because there is a reflection effect of the seismic wave on the free or fixed boundary. Viscous boundary conditions, which can absorb energy, are often used in seismic response analysis and are introduced as part of the DDA method in this paper.

This approach to simulate viscous boundary involves determining a damper in the normal and tangent directions of the boundary blocks. Dampers provide normal and tangential stresses in contrast with the block velocity. The damper stresses can be expressed as

$$f_n = -\rho c_p v_n \tag{1}$$

$$f_s = -\rho c_s v_s \tag{2}$$

where ρ is block medium density, c_p and c_s are the propagational velocities of the P- and S-waves in the medium and v_n and v_s are the normal and tangential velocities of the boundary block movement.

According to wave propagation theory, c_p and c_s can be determined with the following equations, respectively.

$$c_p = \sqrt{\frac{E(1-v)}{\rho(1+v)(1-2v)}} \tag{3}$$

$$c_s = \sqrt{\frac{E}{2\rho(1+v)}} \tag{4}$$

where E, v, ρ are the Young's modulus, Poisson's ratio, and medium density.

Generally, the seismic record is not given in velocity time history. The direct integration method and difference method are applied to transform the acceleration or displacement time history into velocity time history, the whole transformation process is shown in Fig. 1. In order to ensure the consistency of the integral, the constant acceleration integration of Newmark method is used like DDA method. Drift may appear in the integration process, the traditional baseline correction method is adopted to solve this problem.

A rock column model is used to study the effects of different boundaries on stress wave propagation. As shown in Fig. 2, a rock column is 300 m $*$ 2 m, and the block element size is 2 m $*$ 5 m. The accuracy of the wave propagation highly depends on block size in DDA. Gu and Zhao (2009) proposed that a block element size should be about 1/16 of the shortest wavelength. In this paper, all the block elements in the DDA model are about 1/15 to 1/20 of the shortest wavelength. The mechanical parameters of the rock include a Young's modulus of 20 GPa, Poisson's ratio of 0.25, and density of 2650 kg/m^3. Gravity is not considered. For simulating continuous media, the joint parameters are set to large enough values to ensure the medium continuity. The sinusoidal stress P-wave, with a stress peak of 50 kPa and a time period of 0.025 s, is inserted from the bottom of the model. The top of the model includes free, fixed and viscous boundaries.

Two measurement points, A and B, are located at the bottom and middle of the model, respectively. Fig. 3 shows the stress waveform record at points A and B with different boundary conditions. Point A records the input wave, and point B records the wave propagated from A and reflected from C. One-dimensional stress wave theory illustrates that at a free boundary, the wave will be reflected and the compression and tensile waves will alter each other, that at a fixed boundary, the wave will be reflected without changing its characteristics, and that at a viscous boundary, the wave will be absorbed. Fig. 3 shows that DDA simulation results are consistent with this theory.

2.2. Seismic wave input method

In the original DDA code, a seismic wave is transformed into stress and applied to each block in the system. This method does not adequately simulate wave propagation. In fact, seismic waves should be inserted at the bottom of the model. There are two