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Application of the discontinuous deformation analysis method to stress wave propagation through a one-dimensional rock mass

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ABSTRACT

The analysis of stress wave propagation through a rock mass is an important issue in rock engineering, and the discontinuous deformation analysis (DDA) method provides an effective tool to solve this problem. In this paper, based on the motion equations of block system with the Newmark integration method, the DDA method improved by the viscous boundary and the force input method is employed, and some investigations are made to extend the capability of the DDA method to address the wave propagation problem. First, for providing a quantitative method to control the damping of the DDA method, the computing methods of the damping ratio for both viscous damping and numerical damping are presented, which can effectively simulate the energy dissipation of stress wave propagation. Second, based on the one-dimensional DDA model, a further study on the size choice of a sub block for stress wave propagation is developed, which considers the homogeneous rock and the joint rock mass, and suggested values of block element ratio for both P-wave incidence and S-wave incidence are obtained by comparing with the theoretical solutions. Last, abilities of the DDA method to simulate both the no tension and slipping characteristics of a joint are validated, and the effects of the joint on wave propagation are also investigated.

1. Introduction

Generally, a natural rock mass is non-homogeneous, and full of unfavorable geological structures, such as joints and cracks.[1] These structural weak planes will greatly affect stress wave propagation, such as the seismic waves, which may cause serious casualties, enormous property losses, and further earthquake-induced disasters.[2–4] Seismic hazard investigation data[5,6] indicate that the rock mass may easily slip and collapse. Thus, it is of significance to study the stress wave propagation through a rock mass. Up to date, a variety of theoretical, experimental and numerical studies have been developed to address this problem.[7–9] Compared with theoretical and experimental studies, numerical simulation is more economical and convenient. Numerical methods can be classified into two groups, continuum-based methods and discontinuum-based methods. Considering the complexity of the rock mass, the discontinuum-based methods are more appropriate than the continuum-based methods. The distinct element method (DEM) is a typical discontinuous media numerical simulation technique, but suffers from limitations[10] due to the explicit solution based on the force approach. The discontinuous deformation analysis (DDA) method originally proposed by Shi[11] can overcome these limitations by use of the implicit solution based on the energy approach.[12]

The DDA method calculates large deformations and discontinuous problems using the time step solution, and many review articles[13–16] have proven that the DDA method can effectively deal with the dynamic problems. Stress wave propagation across the rock mass is a typical dynamic problem, and it is suitable to employ the DDA method.[17–19] Additionally, to meet the demands of specific engineering problems, researchers can expediently modify the original DDA program with an open source code.[20–22] The authors[23–25] have developed the DDA method by modifying the boundary setting and stress wave inputting. These modifications enable DDA study the stress wave propagation across the rock mass. However, further studies on some issues should still be carried out.

First is the damping problem. The original DDA program has three kinds of energy consumption, including Coulomb friction, viscous damping and numerical damping. Coulomb friction is a mature theory, which simulates the mechanical properties of a contact surface between blocks. The viscous damping described by the dynamic ratio can reflect the energy dissipation of the block

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system during the free oscillation process. The numerical damping is caused by the integration method of the DDA method, which may prevent the oscillation of penalty function to deal the contact problem. Effects of viscous damping[13] and numerical damping[26] on the DDA calculation have been done by some scholars. However, quantitative analysis of these damping is not thorough,[27] especially for the dynamic problem.[17]

Second is the choice of block size. Different from the continuous medium model, two kinds of errors will be caused by the numerical discretization model, including the low pass effect and the frequency dispersion effect.[28] For the wave propagation problem, a rough mesh size leads to poor results with significant numerical errors, and a fine mesh size leads to highly accurate results but a time-consuming calculation. Suggestions of the mesh ratio have been given by many scholars for special numerical simulation methods, such as the finite element method,[29] the discrete element method,[30] and the numerical manifold method.[9] The block size is also an important factor that influences the numerical accuracy of the DDA method. With the sub block algorithm[21] to refine the block, Gu and Zhao[31] discussed the effect of block size and recommended a block element ratio $l_r = 1/16$ for one-dimensional DDA calculation. However, the existing achievements are specifically for the P-wave incidence, and also do not consider the joint.

The joint property is the third issue. Effects of geometric properties of the joints on wave propagation have been widely studied through theoretical analysis,[32] while lack of numerical simulation, especially in the DDA method. Considering the effects of joint space and joint number, Zhang et al.[23] have analyzed the propagation laws of P-wave incidence across joints with the DDA method. However, mechanical properties of a joint are also important. At present, most of the numerical simulations focus on the joint stiffness, which assumes that the joint is linear elastic and tensile. Usually, there is not enough tensile strength of the joint surface in the normal,[33] while exists the slipping characteristics in the tangential.[34] Thus, abilities of the DDA method to simulate these properties of a joint need be examined.

Based on the above analysis, the three proposed issues, including damping, block size and joint property, are discussed in detail to simulate stress wave propagation across the rock mass more applicable using the DDA method.

2. A brief of the DDA method

2.1. Motion equations of block system with the Newmark integration method

The governing equations of the block system are expressed as[26]:

$$[M]\{\ddot{D}\} + [C]\{\dot{D}\} + [K]\{D\} = \{F\} \tag{1}$$

where $\{\ddot{D}\}$, $\{\dot{D}\}$ and $\{D\}$ denote the acceleration vector, the velocity vector and the displacement vector, respectively; $[M]$, $[C]$, $[K]$ and $\{F\}$ denote the mass matrix, the damping matrix, the stiffness matrix and the load vector, respectively.

Solving Eq. (1) with the direct integration method and introducing the relationships of the Newmark assumption:

$$\{D\}_{n+1} = \{D\}_n + \Delta t\{\dot{D}\}_n + \frac{\Delta t^2}{2}\left[(1-2\beta)\{\ddot{D}\}_n + 2\beta\{\ddot{D}\}_{n+1}\right] \tag{2}$$

$$\{\dot{D}\}_{n+1} = \{\dot{D}\}_n + \Delta t\left[(1-\gamma)\{\ddot{D}\}_n + \gamma\{\ddot{D}\}_{n+1}\right] \tag{3}$$

where n and $n+1$ are the DDA calculation time steps, β and γ are the parameters of Newmark integration method, and Δt is the interval time step.

Next, substituting Eqs. (2) and (3) into (1), the governing equations of the block system at time step of $n+1$ can be expressed as:

$$[\hat{K}]\{D\}_{n+1} = \{\hat{F}\}_{n+1} \tag{4}$$

where

$$[\hat{K}] = [K] + \frac{1}{\beta\Delta t^2}[M] + \frac{\gamma}{\beta\Delta t}[C]$$

$$\{\hat{F}\}_{n+1} = \{F\}_{n+1} + [M]\left[\frac{1}{\beta\Delta t^2}\{D\}_n + \frac{1}{\beta\Delta t}\{\dot{D}\}_n + \left(\frac{1}{2\beta} - 1\right)\{\ddot{D}\}_n\right] + [C]\left[\frac{\gamma}{\beta\Delta t}\{D\}_n + \left(\frac{\gamma}{\beta} - 1\right)\{\dot{D}\}_n + \left(\frac{\gamma}{2\beta} - 1\right)\Delta t\{\ddot{D}\}_n\right]$$

2.2. DDA method for wave propagation

To absorb the energy at the artificial boundary, the viscous boundary condition is introduced in the DDA method.[35,36] The approach employed to simulate a viscous boundary involves determining dampers in the normal and tangent directions of the boundary blocks. The dampers provide normal and tangential stresses that contrast with the block velocities. The damper stresses are expressed as:

$$\sigma_n = -\rho c_p v_n \tag{5}$$

$$\tau_s = -\rho c_s v_s \tag{6}$$

where v_n and v_s are the normal velocity and tangential velocity, respectively, of the block boundary movement; ρ is the block medium density; and c_p and c_s are the propagation velocities of P-wave and S-wave, respectively, in the medium.

Using the principle of minimum potential energy, the contributions of the viscous boundary to the DDA equations are obtained:

$$\frac{2\rho l[T_i]^T[W][T_i]}{\Delta t} \rightarrow [K_{ii}]$$

$$\rho l[T_i]^T[W][T_i]\{\Delta\dot{D}_i\} \rightarrow \{F_i\} \tag{7}$$

where l is the length of the block boundary; $[T_i]$ is the shape function matrix[11]; $[W]$ is the wave velocity matrix, $[W] = \begin{bmatrix} c_p n_x^2 + c_s n_y^2 & (c_s - c_p)n_x n_y \\ (c_s - c_p)n_x n_y & c_p n_y^2 + c_s n_x^2 \end{bmatrix}$; n_x and n_y are the direction cosines of the block boundary; $\{\Delta\dot{D}_i\}$ denotes the velocity vector of the block.

Relative to previous studies,[31] the viscous boundary implemented by this paper is more efficient and has a high absorption precision.[25] Based on the viscous boundary, a force input method is used for inputting the incident wave.[23] The normal and tangential components of the velocity time history of the incident wave are transformed to the corresponding stress components:

$$\sigma_n = 2\rho c_p v_n' \tag{8}$$

$$\tau_s = 2\rho c_s v_s' \tag{9}$$

where v_n' and v_s' are the normal and tangential components, respectively, of the velocity time history.