Journal of Rock Mechanics and Geotechnical Engineering 6 (2014) 348–355

Contents lists available at ScienceDirect

Journal of Rock Mechanics and Geotechnical Engineering

journal homepage: www.rockgeotech.org

Full length article

Modeling stress wave propagation in rocks by distinct lattice spring model

Gaofeng Zhao*

Centre for Infrastructure Engineering and Safety, School of Civil and Environmental Engineering, The University of New South Wales, Sydney, NSW 2052, Australia

A R T I C L E I N F O

Article history:
Received 26 November 2013
Received in revised form
23 March 2014
Accepted 24 April 2014
Available online 24 June 2014

Keywords:
Distinct lattice spring model
Rock
Stress wave
Verification

A B S T R A C T

In this paper, the ability of the distinct lattice spring model (DLSM) for modeling stress wave propagation in rocks was fully investigated. The influence of particle size on simulation of different types of stress waves (e.g. one-dimensional (1D) P-wave, 1D S-wave and two-dimensional (2D) cylindrical wave) was studied through comparing results predicted by the DLSM with different mesh ratios (*lr*) and those obtained from the corresponding analytical solutions. Suggested values of *lr* were obtained for modeling these stress waves accurately. Moreover, the weak material layer method and virtual joint plane method were used to model P-wave and S-wave propagating through a single discontinuity. The results were compared with the classical analytical solutions, indicating that the virtual joint plane method can give better results and is recommended. Finally, some remarks of the DLSM on modeling of stress wave propagation in rocks were provided.

1. Introduction

Stress wave propagation in rocks is one of the most important issues in rock dynamics, e.g. the damage criteria of rock structures under dynamic loads are generally regulated according to threshold values of wave amplitudes: peak displacement, peak particle velocity or peak acceleration. Prediction of stress wave propagation in rocks is also the fundamental requirement in the study of mechanism of seismic events in earthquake. Up to now, a variety of theoretical, experimental and numerical studies have been conducted. For example, Schoenberg (1980) and Pyrak-Nolte et al. (1990) developed analytical solutions to predict the incident wave through a single dry or fully liquid-filled fracture using the displacement discontinuous models. Later, these equations were validated by laboratory experiments carried out by Myer et al. (1985) and Suárez-Rivera (1992), respectively. The analytical solutions to interface wave propagation alongside a single failure have been studied by Gu (1994) and Gu et al. (1995), which were also successfully validated by laboratory measurements. Stress wave propagation through a single discontinuity is simple and straightforward. However, stress wave propagation within a medium with multiple joints (a typical situation of rock mass in nature) is much more complex due to multiple reflections between separate failures. For this kind of situation, analytical solutions can only be derived under idealized conditions; examples can be found in Cai and Zhao (2000), Zhao et al. (2008) and Li et al. (2010).

To overcome the limitation of analytical method, more and more numerical methods have been applied for the analysis of stress wave propagation in rocks, e.g. the finite element method (FEM) (e.g. Moran, 1987), finite difference method (FDM) (e.g. Reeshidev and Mrinal, 2008), boundary element method (BEM) (e.g. Demirel and Wang, 1987), discrete element method (DEM) (e.g. Resende et al., 2010), discontinuous deformation analysis (DDA) (Jiao et al., 2007), discontinuous Galerkin method (DGM) (e.g. Park and Tassoulas, 2002), and numerical manifold method (Fan et al., 2013; Zhao et al., 2014). Lattice spring model (LSM) can be viewed as a numerical model based on the concept of bottom-up and one-dimensional (1D) modeling concept (Wang, 2008; Rinaldi, 2013). The LSM was originally developed by Hrennikoff (1941) to solve elasticity problems. However, due to computational limitations and the development of FEM, this method was underdeveloped. In recent years, many researchers have renewed their interests in this method due to its advantage in modeling solids fracturing. The LSMs are also adopted for stress wave propagation in rocks, e.g. O'Brien (2008) developed a visco-elastic LSM for seismic wave propagation, and Takekawa et al. (2013) proposed

* Tel.: +61 2 9385 5022; fax: +61 2 9385 6139.
E-mail address: gaofeng.zhao@unsw.edu.au.
Peer review under responsibility of Institute of Rock and Soil Mechanics, Chinese Academy of Sciences.

Production and hosting by Elsevier

1674-7755
http://dx.doi.org/10.1016/j.jrmge.2014.03.008

a similar model for stress wave propagation in solid. However, most of these models only considered the rocks as continuous media without addressing the joints/discontinuities.

In this work, the application of distinct lattice spring model (DLSM) (Zhao, 2010; Zhao et al., 2011) to stress wave propagation through rocks is discussed. The main contributions of the DLSM are: (1) the restriction on the Poisson's ratio in classical LSM was removed through a technique to evaluate spring deformation using the local strain technique rather than the particle displacements directly; (2) a close relationship among the spring parameters and the macro-elastic constants, Young's modulus and Poisson's ratio is established; and (3) the lattice structures can be both regular and irregular. A few examples of the DLSM on modeling of stress wave propagation through a continuous rock bar were described in Zhao et al. (2011). Verification of DLSM on modeling 1D P-wave propagation through rock masses was studied by Zhu et al. (2011). In this context, a more comprehensive investigation on the ability of the DLSM to model stress wave propagation through rocks is presented, e.g. both 1D P-wave, 1D S-wave and two-dimensional (2D) cylindrical wave will be covered.

2. Stress wave propagation by the DLSM

2.1. The model

In DLSM, the material is represented as particles bonded together by springs (see Fig. 1). The equation of motion for the system is described as

$$[\boldsymbol{K}]\boldsymbol{u} + [\boldsymbol{C}]\dot{\boldsymbol{u}} + [\boldsymbol{M}]\ddot{\boldsymbol{u}} = \boldsymbol{F}(t) \tag{1}$$

where $\boldsymbol{u}$ is the vector of particle displacement, $[\boldsymbol{K}]$ is the stiffness matrix, $[\boldsymbol{M}]$ is the diagonal mass matrix, $[\boldsymbol{C}]$ is the damping matrix, and $\boldsymbol{F}(t)$ is the vector of external force. In DLSM, Eq. (1) was solved using the Newton's Second Law. Details can be found in Zhao (2010) and Zhao et al. (2011).

The input elastic parameters in DLSM are the Young's modulus and the Poisson's ratio. During calculation, the spring parameters are calculated from the following equations:

$$k_{\mathrm{n}} = \frac{3}{2\alpha^{3\mathrm{D}}}\left(\frac{E_i}{1-2\nu_i} + \frac{E_j}{1-2\nu_j}\right) \tag{2}$$

$$k_{\mathrm{s}} = \frac{3}{2\alpha^{3\mathrm{D}}}\left[\frac{(1-4\nu_i)E_i}{(1+\nu_i)(1-2\nu_i)} + \frac{(1-4\nu_j)E_j}{(1+\nu_j)(1-2\nu_j)}\right] \tag{3}$$

where k_{n} and k_{s} are the normal and shear spring stiffness, respectively; E_i and E_j are the Young's moduli of the linked particles, respectively; ν_i and ν_j are the corresponding Poisson's ratios; and $\alpha^{3\mathrm{D}}$ is a microstructure geometry coefficient of the lattice model expressed as

$$\alpha^{3\mathrm{D}} = \frac{\sum l_i^2}{V} \tag{4}$$

where l_i is the length of the ith bond, and V is the volume of the model.

2.2. Viscous boundary condition

Stress wave propagation in a computational model with finite boundary causes the wave to be reflected and blended with the initial input. It is very difficult to analyze the mixed results. To solve this problem, a non-reflection boundary was implemented into DLSM to simulate the computational model without finite boundaries. The viscous non-reflection boundary condition in DLSM is shown in Fig. 2. Three dashpots were placed at particles on the artificial boundary plane to minimize the reflected wave. Details on the implementation can be found in Zhao (2010).

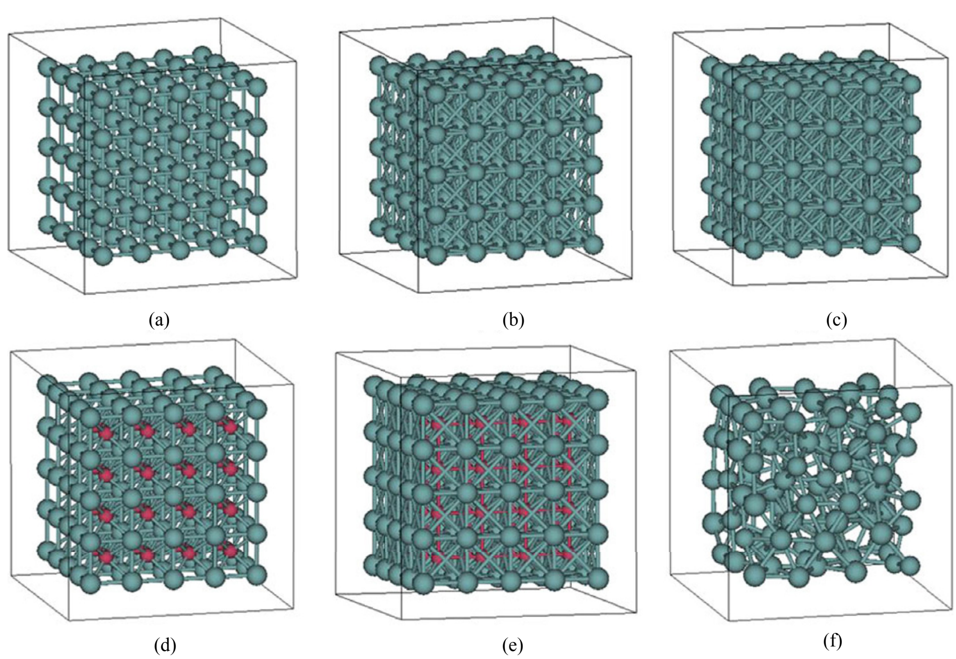

Fig. 1. Lattice structures in DLSM (Zhao et al., 2011). (a) Simple cubic lattice, (b) Simple cubic II lattice, (c) Simple cubic III lattice, (d) BCC lattice, (e) FCC lattice, and (f) Random lattice.