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Multi-hole seismic modeling in 3-D space and cross-hole seismic tomography analysis for boulder detection

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ABSTRACT

A boulder stone, a common geological feature in south China, is referred to the remnant of a granite body which has been unevenly weathered. Undetected boulders could adversely impact the schedule and safety of subway construction when using tunnel boring machine (TBM) method. Therefore, boulder detection has always been a key issue demanded to be solved before the construction. Nowadays, cross-hole seismic tomography is a high resolution technique capable of boulder detection, however, the method can only solve for velocity in a 2-D slice between two wells, and the size and central position of the boulder are generally difficult to be accurately obtained. In this paper, the authors conduct a multi-hole wave field simulation and characteristic analysis of a boulder model based on the 3-D elastic wave staggered-grid finite difference theory, and also a 2-D imaging analysis based on first arrival travel time. The results indicate that (1) full wave field records could be obtained from multi-hole seismic wave simulations. Simulation results describe that the seismic wave propagation pattern in cross-hole high-velocity spherical geological bodies is more detailed and can serve as a basis for the wave field analysis. (2) When a cross-hole seismic section cuts through the boulder, the proposed method provides satisfactory cross-hole tomography results; however, when the section is closely positioned to the boulder, such high-velocity object in the 3-D space would impact on the surrounding wave field. The received diffracted wave interferes with the primary wave and in consequence the picked first arrival travel time is not derived from the profile, which results in a false appearance of high-velocity geology features. Finally, the results of 2-D analysis in 3-D modeling space are comparatively analyzed with the physical model test vis-a-vis the effect of high velocity body on the seismic tomographic measurements.

1. Introduction

In recent years, subway system has undergone rapid expansion in major cities of China. During urban subway construction, tunnel boring machine (TBM) method, due to its advantages, has played an increasingly significant role. Unknown boulders (e.g., the remnant of a granite body which has been unevenly weathered), as a common geological feature in south China, could bring adverse obstacles and risks to subway construction, such as difficulty in controlling TBM, cutter head to be frequently stuck, distortion, or rapidly worn out, and even collapse of the tunnel face, resulting in enormous losses of life and property (Babendererde et al., 2004). Therefore, detecting the status and grain size of boulder beforehand is a key part of the exploration.

Contrasting physical properties of boulder make it easy to be separated from surrounding rocks or soil (residual soil, fully or intense weathered rock, etc.), and this is the basis of detecting boulder using geophysical techniques including the cross-hole resistivity method (Li et al., 2015), the cross-hole seismic tomography (Guo et al., 2015), the micro-tremor profiling method (Xu et al., 2012) and so on. By comparing with the drilling results, cross-hole seismic tomography is found to be an effective way to locate boulder, and it has gained wide interest in practice.

Since cross-hole seismic methods were in 1972 (Bois et al., 1972), many studies had been developed since then, for example, detection and monitoring of oil and gas reservoir(Beydoun et al., 1989; Ahmadi et al., 2013), mining exploration (Wong, 2000), geotechnical and engineering (Angioni et al., 2003; Rumpf and Tronicke, 2014), hydrological prospecting (Hyndman et al., 2000; Bergman et al., 2004) and civil engineering geological investigation (Rechtien et al., 1995; Jackson and McCann, 1997; Shustak et al., 2015). In additional, nonlinear inversion method (Plessix, 2000; Tronicke et al., 2012), joint inversion method (Nath et al., 1999; Göktürkler, 2011; Paasche and Tronicke, 2014) and interpretation and evaluation of results (Hansen et al., 2014; Fechner

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et al., 2014, 2015) were proposed to improve imaging accuracy and reliability. In most crosshole applications, the 2-D assumption is acceptable in terms of information content, provided the medium properties only change in 2-D and no out-of-plane arrivals are present in the data. Auer et al. (2013) assess the validity of the widely used 3-D to 2-D data transformation derived from asymptotic ray theory. However, the conversion of the real data sets from 3-D to 2-D, may influence the inversion results. Therefore, 3-D numerical domains are preferable.

In terms of seismic cross-hole wave field numerical simulation, Wu and Harris (2004) developed a 2-D variable-grid finite difference method to perform relevant wave field simulations and analyzed on guided waves that propagate along boreholes. Song and Pei (2006) studied the characteristics and propagating patterns of cross-hole seismic viscoelastic wave field using a numerical simulation method. In addition, some researchers also conducted 3-D finite difference modeling of seismic waves in borehole environment (Yoon and McMechan, 1992; Cheng et al., 1995; Mallan et al., 2011). Most of the existing works reviewed above involve simulations based on 2-D space or borehole 3-D geological model, while effects of medium inhomogeneity bodies positioned far away from boreholes in 3-D spaces on cross-hole sections were barely considered. Mufti (1995) investigated cross-hole seismic response of a number of simple 3-D reservoirs by finite-difference models based on the acoustic wave equation. In his work, it was indicated that a 2-D inversion algorithm will lead to incorrect results in that the corresponding 2-D cross-hole imaging analysis was missing. At the same time, the results of Washbourne et al. (2002) showed that some 3-D aspects of real cross-hole surveys, including well deviations and out of cross-hole plane structure, were ignored in 2-D models. For boulder detection in civil engineering, cross-hole tomography method can only provide 2-D velocity structure model between the two wells, however, the size and central position of the boulder usually are difficult to be accurately defined (Liu et al., 2015).

Therefore, to analyze the reasons of the inaccurate interpretation, it is essential to study characteristics of seismic wave-field in a 3-D space. In existing works, the boulder's 3-D wave field analysis of its response characteristics and how the boulder affects the results of cross-hole seismic tomography in a 3-D space have not been systematically studied. In this study, the 3-D aspects of this problem and their effects on result reliability are investigated. Firstly, basic theory of 3-D elastic wave and inversion of first arrival travel times are introduced. Then, cross-hole seismic numerical simulations and response characteristics of two boulder models are studied in 3-D space. In addition, a 2-D imaging analysis based on first arrival time is also conducted. Finally, the results of 2-D analysis in 3-D modeling space are comparatively analyzed with the physical model test.

2. Methodology

2.1. Numerical simulation theory for elastic waves

For an isotropic medium, the 3-D elastic wave equation can be represented as a first-order hyperbolic equation of velocity v and stress τ, and formulated as formula (1) and formula (2) under Cartesian coordinates (Graves, 1996).

$$\begin{cases} \rho\dfrac{\partial v_x}{\partial t} = \dfrac{\partial \tau_{xx}}{\partial x} + \dfrac{\partial \tau_{xy}}{\partial y} + \dfrac{\partial \tau_{xz}}{\partial z} \\ \rho\dfrac{\partial v_y}{\partial t} = \dfrac{\partial \tau_{xy}}{\partial x} + \dfrac{\partial \tau_{yy}}{\partial y} + \dfrac{\partial \tau_{yz}}{\partial z} \\ \rho\dfrac{\partial v_z}{\partial t} = \dfrac{\partial \tau_{xz}}{\partial x} + \dfrac{\partial \tau_{yz}}{\partial y} + \dfrac{\partial \tau_{zz}}{\partial z} \end{cases} \tag{1}$$

$$\begin{cases} \dfrac{\partial \tau_{xx}}{\partial t} = (\lambda+2\mu)\dfrac{\partial v_x}{\partial x} + \lambda\left(\dfrac{\partial v_y}{\partial y} + \dfrac{\partial v_z}{\partial z}\right) \\ \dfrac{\partial \tau_{yy}}{\partial t} = (\lambda+2\mu)\dfrac{\partial v_y}{\partial y} + \lambda\left(\dfrac{\partial v_x}{\partial x} + \dfrac{\partial v_z}{\partial z}\right) \\ \dfrac{\partial \tau_{zz}}{\partial t} = (\lambda+2\mu)\dfrac{\partial v_z}{\partial z} + \lambda\left(\dfrac{\partial v_y}{\partial y} + \dfrac{\partial v_x}{\partial x}\right) \\ \dfrac{\partial \tau_{xy}}{\partial t} = \mu\left(\dfrac{\partial v_x}{\partial y} + \dfrac{\partial v_y}{\partial x}\right) \\ \dfrac{\partial \tau_{yz}}{\partial t} = \mu\left(\dfrac{\partial v_y}{\partial z} + \dfrac{\partial v_z}{\partial y}\right) \\ \dfrac{\partial \tau_{xz}}{\partial t} = \mu\left(\dfrac{\partial v_z}{\partial x} + \dfrac{\partial v_x}{\partial z}\right) \end{cases} \tag{2}$$

In the formulas, v_x, v_y, and v_z are velocity components for three directions; τ_{xx}, τ_{yy}, τ_{zz}, τ_{xy}, τ_{xz}, and τ_{yz} are stress components; ρ is density; and λ and μ are Lame coefficients. In this paper, we use the staggered-grid finite-difference with second-order accuracy in the time domain and fourth-order accuracy in space for the numerical simulation (Virieux, 1986; Levander, 1988). In addition, the convolutional perfectly matched layer (CPML, Komatitsch and Martin, 2007) boundary condition is applied to absorb the artificial reflection waves.

2.2. Tomography theory

Seismic first arrival travel time tomography can be described as a mean of solving velocity distributions whereby the first arrival travel time is given (Dines and Lytle, 1979), and the relation can be expressed as

$$T = \int_r S dl, \tag{3}$$

where T is the seismic wave travel time, r is the ray path, and S denotes the slowness (the reciprocal of seismic wave velocity). Formula (3) can be also expressed as follows using matrix

$$T = AS \tag{4}$$

where A denotes the coefficient matrix for recording information on the seismic wave propagating path, A is a large sparse matrix, some numerical approximate solution algorithm can be used to solve the equation. In this paper, the Simultaneous Iterative Reconstruction Technique (SIRT, Krajewski et al., 1989) is applied. In addition, the Back Projection technique (BPT, Herman, 2009) algorithm is used to reconstruct the initial model, to accelerate convergence.

3. Model and survey layout

To precisely determine and analyze the nature of cross-hole seismic wave propagation, a geological model having boulder is shown in Fig. 1. Model I is a simple model with a high-velocity sphere placed inside homogeneous medium in order to simulate the boulder in the quaternary weathered layer as shown in Fig. 1(a), while model II is relatively more complex, with a boulder located in a three-layered medium and the interface depths are 10 m and 30 m as shown in Fig. 1(b).

Sphere center of two models are both at (8.5 m, 10.0 m, -20.0 m) with the same radius as 1.5 m. Size of two models are both 20.0 m × 15.0 m × 40.0 m, grid spaces are measured as 0.2 m × 0.2 m × 0.2 m, and physical property parameters are listed in Table 1. In Table 1, V_p and V_s are P- and S-wave velocities in m/s respectively, and rho is density in kg/m^3.

In the model, four wells (Well-0, Well-1, Well-2 and Well-3) are laid at (0.0 m, 3.0 m), (15.0 m, 0.0 m), (15.0 m, 15.0 m), and (15.0 m, 20.0 m) respectively, with a well depth of 40 m. Shot point intervals and geophone intervals are 1.0 m, and excitation and record processes are