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Two-dimensional pre-stack reverse time imaging based on tunnel space ☆

Fei Cheng [a], Jiangping Liu [a,*], Niannian Qu [b], Mao Mao [a], Liming Zhou [c]

[a] Subsurface Imaging and Sensing Laboratory, Institute of Geophysics and Geomatics, China University of Geosciences, 388 Rumo Rd., Wuhan, Hubei, 430074, China
[b] Guizhou Geology Survey, Guiyang, Guizhou, 550004, China
[c] Changjiang River Scientific Research Institute, Wuhan, Hubei, 430010, China

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ABSTRACT

In order to increase the safety and efficiency in tunnel constructions, there is a need to carry out an effective and precise tunnel prediction method to detect unexpected lithological and structural heterogeneities ahead of tunnel face. Seismic prediction is considered as one correct and efficient method. The assumption, which differs from the reality, taken in most of the current tunnel seismic imaging methods is that the tunnel space is a homogeneous medium with surrounded layers with the same elastic characters. In this paper, taking into account the actual situation of tunnel space, we propose some new tunnel geological models that are closer to the reality using the first-order coupled elastic equations of particle velocity and stress, and high order staggered grid finite-difference algorithm to fulfill numerical simulation of seismic full-wave fields in tunnel space. Then for these synthetic simulated records, we utilize reverse time migration operator based on non-conversion wave equation with decoupled P- and S-waves, and excitation time imaging condition to achieve reliable two dimensional (2D) reverse time migration imaging (RTM) based on tunnel space effectively. Results demonstrate that (1) it is able to achieve synthetic simulation and reverse time migration imaging correctly by using a staggered grid finite-difference (FD) algorithm with second-order accuracy in time and fourth-order accuracy in space, and reverse time operator based on non-conversion wave equation with decoupled P- and S-waves; (2) tunnel-based reverse time migration imaging can effectively suppress mirror artifact occurring in conventional imaging approaches; and (3) as the dip angle of lithological interface decreases, the energy of P wave imaging increases while the energy of S wave imaging decreases when shooting and receiving at the same side of interface, while when the dip angle of interface is 90°, common-source gather with shots near the tunnel face is beneficial to the imaging of P wave.

1. Introduction

Infrastructure construction in urban areas and larger traffic development projects often involve tunnel excavation. Tunnel is an underground work with many unknown geological conditions such as fracture zones, faults, caves and aquifers in front of it. Failing to recognize and predict these geological conditions ahead of the tunnel front represents dangers ranging from construction progress delay and instrument damage to tremendous casualties. Therefore, using advanced technology to predict these lithological and structural heterogeneities ahead of a tunnel front is of major importance before excavating tunnels. Surface measurements can provide general geological information of the ground, but the data resolution is not sufficient to identify lithological boundaries or other geological features hampering failure-free tunnel construction. Advance borehole drilling is relatively more accurate than surface measurements, but is also normally restricted to a limited prediction distance which will significantly delay the construction progress. Hence, to increase the safety and efficiency of tunnel constructions, geophysical exploration ahead of a tunnel has become a valuable tool.

Nondestructive geophysical methods are efficient techniques investigating and predicting lithological and structural heterogeneities for distances up to several hundred meters from the tunnel wall. Among all these methods, seismic imaging is the most effective one because of its relatively deep penetration range and high spatial resolution. Different tunnel seismic prediction systems have been applied since the early 1990s in tunneling projects worldwide. The Tunnel Seismic Prediction (TSP) software developed by AMT, Switzerland (Dickmann and Sander, 1996, Bohlen et al., 2007), identifies reflections from front of the tunnel face in the recordings by their traveltime curves and their intersection with the tunnel axis derived from depth migration images. Zeng (Zeng, 1994) proposed the negative apparent velocity method which uses apparent velocity gradient of direct wave and

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* Corresponding author. Tel.: +86 27 67883525.
E-mail address: liujp_geop@126.com (J. Liu).

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reflected wave to predict faults ahead of tunnel face. OYO, Japan, put forward a method named HSP (Horizontal Seismic Profiling) by using a source and receiver geometry as in a surface refraction seismic survey (Inazaki et al., 1999). NSA Engineering in the United States developed the True Ref1ection Tomography (TRT) technology which uses multi-point shooting and receiving observation system to identify the rock mass conditions ahead of tunnel excavation. The spatial distribution of receivers and sources contributes to obtain sufficient spatial wave field information (Neil et al., 1999). In 1999, a seismic exploration system called the Integrated Seismic Imaging System (ISIS) has been developed to obtain the knowledge of the upcoming rock conditions during tunneling at the GFZ, Germany (Borm et al., 2001, 2003). In this system, TBM is used to generate wave field and three-component geophones situated on the side wall are used to register records. Throughout the previous research the ignorance of tunnel space does not correspond to reality obviously.

In recent researches about tunnel prediction using seismic records, Bohlen (Bohlen et al., 2007) and Stefan (Stefan et al., 2010, 2011) considered the impacts of tunnel space and used surface wave along with converted S wave to predict geological structures ahead of tunnel. They discussed the conversion mechanism between these two kinds of waves as well. Petronio (Petronio et al., 2007) used the Tunnel-Seismic While-Drilling (TSWD) method to predict geologic interfaces ahead of a tunnel front. In the research area of seismic imaging for tunnel excavation, Rechlin (Rechlin et al., 2009) implemented Kirchhoff migration for TSWD data. Lüth (Lüth et al., 2008) applied "Kirchhoff Pre-Stack Depth Migration" (KPSDM) to tunnel predication. Furthermore, Tzavaras (Tzavaras et al., 2012) applied "Kirchhoff Pre-Stack Depth Migration" (KPSDM), "Fresnel Volume Migration" (FVM), and "Reflection-Image-Spectroscopy" (RIS) to tunnel predication, respectively. However, only a few researches are related to using reverse time migration to tunnel predication. It is known that restricted survey layout and rock mass location affect resolution to different extents. Therefore, it is necessary to consider the influence of tunnel space and select an accurate imaging method to do the prediction of geological conditions in front of the tunnel.

In this paper, we present a new tunnel seismic prediction method. Taking into account the tunnel space, we build tunnel geological models that are closer to the reality by using a staggered grid finite-difference (FD) algorithm with second-order accuracy in time and fourth-order accuracy in space to realize numerical simulation of seismic full-wave field based on tunnel space (Liu et al., 2012). Then for these simulated records from different models, we utilize non-conversion wave equation with decoupled P- and S-waves to achieve reliable reverse time migration imaging in tunnel space effectively. At last, we verify and demonstrate the effectiveness of this method in field tunnel data.

2. Methodology

2.1. Elastic wave pre-stack reverse time migration

In wave field extrapolation, incidence of seismic wave to the interface reproduces converted wave. This converted wave leads to disturbed wave in the imaging process because it does not meet the imaging condition. Therefore it is necessary to develop a non-conversion wave equation and decouple elastic wave field to guarantee that P wave and S wave propagate independently. In 2009, Zhang (2009) put forward the non-conversion wave equation with decoupled P- and S-waves. When propagating in inhomogeneous medium in which ρ and μ are constant while λ is variable, the completely decoupled S and P waves propagate independently and no converted wave is reproduced. Therefore assuming that ρ and μ are constant, we could obtain the non-conversion elastic displacement equation as follows (Eq. (1))

$$\begin{cases} \partial^2 u_x/\partial t^2 = \partial/\partial x\left(V_p^2(\partial u_x/\partial x+\partial u_z/\partial z)\right)+\partial/\partial z\left(V_s^2(\partial u_x/\partial z-\partial u_z/\partial x)\right) \\ \partial^2 u_z/\partial t^2 = \partial/\partial z\left(V_p^2(\partial u_x/\partial x+\partial u_z/\partial z)\right)+\partial/\partial x\left(V_s^2(\partial u_x/\partial x-\partial u_z/\partial z)\right) \end{cases}, \quad (1)$$

where u_x and u_z denote x component and z component, respectively, while V_p and V_s are the velocity of P and S waves, respectively. With introducing:

$$\begin{cases} \tau_p = V_p^2(\partial u_x/\partial x+\partial u_z/\partial z) \\ \tau_{sx} = V_s^2(\partial u_x/\partial z-\partial u_z/\partial x) \\ \tau_{sz} = V_s^2(\partial u_z/\partial x-\partial u_x/\partial z) \end{cases}, \quad (2)$$

Taking the derivative of time on both hand sides of the equations, the order of Eq. (1) can be reduced to obtain generalized first order stress and velocity non-conversion wave equation (Eq. (3))

$$\begin{cases} \partial v_x/\partial t = \partial\tau_p/\partial x+\partial\tau_{sx}/\partial z \\ \partial v_z/\partial t = \partial\tau_p/\partial z+\partial\tau_{sz}/\partial x \\ \partial\tau_p/\partial t = V_p^2(\partial v_x/\partial x+\partial v_z/\partial z) \\ \partial\tau_{sx}/\partial t = V_s^2(\partial v_x/\partial z-\partial v_z/\partial x) \\ \partial\tau_{sz}/\partial t = V_s^2(\partial v_z/\partial x-\partial v_x/\partial z) \end{cases}, \quad (3)$$

v_x and v_z are mixed wave field including both P wave and S wave. We need to decouple the wave field to obtain independent P and S waves for reverse time migration. Setting $v_x = v_{px} + v_{sx}, v_z = v_{pz} + v_{sz}$ and substituting them into Eq. (3), we calculate the first order equation with decoupled P and S waves (Eq. (4))

$$\begin{cases} \partial v_{px}/\partial t = \partial\tau_p/\partial x \\ \partial v_{pz}/\partial t = \partial\tau_p/\partial z \\ \partial v_{sx}/\partial t = \partial\tau_{sx}/\partial z \\ \partial v_{sz}/\partial t = \partial\tau_{sz}/\partial x \\ \partial\tau_p/\partial t = V_p^2(\partial v_x/\partial x+\partial v_z/\partial z) \\ \partial\tau_{sx}/\partial t = V_s^2(\partial v_x/\partial z-\partial v_z/\partial x) \\ \partial\tau_{sz}/\partial t = V_s^2(\partial v_z/\partial x-\partial v_x/\partial z) \end{cases}, \quad (4)$$

De-propagation process, an extrapolation of the recorder wave field (seismogram), which is prescribed in the reverse order at the receiver location, includes calculating imaging time for each grid point and applying imaging condition to extrapolated wave field in every extrapolation. Reverse time extrapolation is an initial boundary value problem based on the velocity–stress equation (Eq. (4)). It begins from the maximum recorded time of the (x, z) plane and takes seismic record $f(x, z = 0, t)$ as the boundary condition to calculate back through the time axis.

2.2. Imaging condition

We use the dynamic programming traveltime computation method proposed by Schneider (Schneider et al., 1992) to calculate imaging time. This method will accurately determine the first arrival traveltime through arbitrary, discrete, and discontinuous velocity distributions. It is more stable, needs less calculation time, and is not going to cause any shaded region.

We use excitation time image condition as shown in Eq. (5)

$$\left\{ I(x,z) = \sum_{t=0}^{T} R(x,z,T-t)f(x,z,T-t)f(x,z,t) = \begin{cases} 1 & x=x', z=z', t=t_d(x',z') \\ 0 & other \end{cases} \right., \quad (5)$$

where T is the maximum recorded time of wave field record. The corresponding wave field is picked up from reverse time extrapolation wave field $R(x, z, t)$ according to excitation time $t_d(x', z')$.

2.3. Boundary condition

Absorbing boundary condition around the boundary of models in the de-propagation process is employed in our models (Cerjan et al.,