Channel wave propagation analysis of the 3D tunnel model in isotropic viscoelastic medium

Hui Li, University of Houston, Peimin Zhu, China University of Geoscieces, Guangzhong Ji, Xi'an Branch of China Coal Research Institute*

Summary

Existence of tunnel during the coal exploration, which inevitably influences channel wave propagation in the coal bed, should be considered during the numerical simulation of channel wave. A modified mirror method is applied to simulate the coal tunnel in the horizontal/declining situation, three dimensional channel wave propagating within homogeneous isotropic viscoelastic medium containing tunnel in coal bed is simulated with an explicit, time-domain, high order staggered finite difference algorithm, and finally, we also analysis the enegry properties of channel wave.

Introduction

F.F. Evison firstly observed the phenomenon of much of seismic energy trapped inside the seam in 1955 while working in coal mine in New Zealand. Krey (1963) theoretically proved the existence of channel wave in the coal seam. Development in the subsequent 50 years has produced a powerful technique for predicting the characteristics of a particular coal seam. Compared with surrounding rocks, coal seam is a typical low velocity layer which can physically generate guide wave. Seismic wave velocities in coal beds are often less than in the wall rocks. This low-velocity zone with high-velocity walls might be expected to form a waveguide in which seismic energy, once trapped, could propagate parallel to the seam with relatively low attenuation.

Sedimentary rocks and coal beds show viscoelastic characteristic rather than elastic characteristic that generally assumed. Theoretical, numerical, laboratory, and field data indicate that seismic wave through a coal beds is significantly affected by the presence of viscoelastic property. In particular, complicated coupling mechanism of channel wave between wall rocks and coal beds varies with change of quality factors (Q), which is an important physical parameter for attenuation and dispersion of seismic wave. In turn, quality factors (Q) can be used to explain the measurements of channel wave attenuation/dispersion.

For the investigation of channel wave with numerical simulation method, finite difference, finite element etc. have been applied to simulate the seismic wave propagation in the coal seam. Based on the research of Baumargte and Krey (1961), Krey theoretically calculated the dispersion curve of channel wave. Liu (1991) mainly investigates the properties of Love channel wave while fracture existing on coal seam and surrounding rocks. Yang (2001) simulates the asymmetric 2D model of three layers including coal seam and analysis the P-SV propagation in coal tunnel. Z. Yang (2009) focused on thinner layer coal seam and calculated the dispersion curve of channel wave using numerical analysis method.

All these above work to study the property of channel wave based on 2D model which is generally not consistent with real situation. In present work, a 3D tunnel model in isotropic viscoelastic medium is developed for numerically solving viscoelastic wave equations in three dimensional spatial dimensions. Although the time-domain high-order staggered grid finite difference (FD) algorithm is more time-efficient and more precise, it is hard to handle the free fluctuation surface problem, especially on three dimension condition. By comparison and analysis the advantage and disadvantage of current free interface numerical simulation, we developed the program algorithm to simulate the tunnel on the horizontal/declining condition by modified the mirror method. Our algorithm is an adaptation of the high order staggered grid velocity-stress approach. The Perfectly Match Layer (PML) boundary condition is used to solve the finite boundary problem.

Theory and Method

Although tunnel interface is analogous to the free interface of earth surface, it is more complicated when considering the multi-interface for the 3D tunnel. Theoretically, when considering free surface boundary of horizontal interface (Z=0), the free surface boundary condition can be given

$$\tau_{zz} = 0, \tau_{xz} = 0 \qquad (1)$$

τ_{zz} is compressive stress, τ_{xz} is shear stress in the xz plane.

Generally, heterogeneous Approach, Mirror Method, and Mittet Method are three main approaches to solve the free surface boundary issues. For the free interface of tunnel surface, we will apply mirror method when the tunnel surface is horizontal, while Robertsson solution is considered on the declining and slight fluctuation situation of tunnel surface. Due to classifying too many kind of grid mode in the Robertsson method, it is impossible to implement in the 3D tunnel model. As a result, we just consider grid net located at free interface without calculating grid mode in the corner position. There might

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be more than one free surface boundary (tunnel surface) for one single grid net, so we need to set up mirror algorithm separately.

Finally, with the ideas of exchanging grid net type, setting up mirror method for each single grid surface and fluctuating surface is considered by horizontal surface, we will modify traditional mirror method and simulate the 3D tunnel model with declining surface. The staggered spatial storage scheme lists as figure 1. Table 1 is the spatial distribution of seismic wave component and viscoelastic parameters.

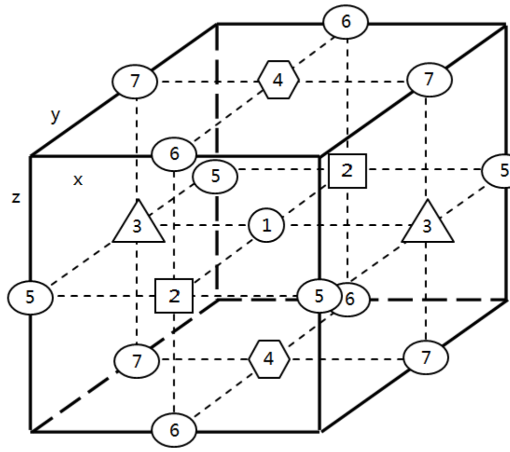

Figure 1: Staggered spatial storage scheme for the free surface boundary

σ is compressive stress, τ is shear stress, we take horizontal surface boundary as example, we assume that horizontal surface boundary is at $z = k\Delta z$, and space order is fourth, then we can obtain boundary equation of Mirror method for the tunnel bottom surface of 3D tunnel mode:

$$\begin{aligned}
&\tau_{xz}(i,j,k) = 0\\
&\tau_{yz}(i,j,k) = 0\\
&\tau_{xz}(i,j,k-1) = -\tau_{xz}(i,j,k+1)\\
&\tau_{xz}(i,j,k-2) = -\tau_{xz}(i,j,k+2)\\
&\tau_{yz}(i,j,k-1) = -\tau_{yz}(i,j,k+1)\\
&\tau_{yz}(i,j,k-2) = -\tau_{yz}(i,j,k+2)\\
&\sigma_{zz}(i,j,k-1) = -\sigma_{zz}(i,j,k)\\
&\sigma_{zz}(i,j,k-2) = -\sigma_{zz}(i,j,k+1)
\end{aligned} \tag{2}$$

Equation (1), referenced as earth surface, which is contrary with top surface of tunnel model. So we assume top surface of tunnel located in $z = k\Delta z$, then mirror equation will be changed into:

$$\begin{aligned}
&\tau_{xz}(i,j,k+1) = 0\\
&\tau_{yz}(i,j,k+1) = 0\\
&\tau_{xz}(i,j,k+2) = -\tau_{xz}(i,j,k)\\
&\tau_{yz}(i,j,k+2) = -\tau_{yz}(i,j,k)\\
&\sigma_{zz}(i,j,k+1) = -\sigma_{zz}(i,j,k)\\
&\sigma_{zz}(i,j,k+2) = -\sigma_{zz}(i,j,k-1)
\end{aligned} \tag{3}$$

Compared with equation (1), vibrating velocity ($V_z(i,j,k+1)$) of grid net of top surface of tunnel is re-calculated due to free surface boundary (Figure1, net 4), but we should set the physical parameters as zero, the physical parameters of neighboring grid net is applied when recalculates the corresponding vibrating velocity.

Table1: Spatial distribution of wave component and viscoelastic parameters

Grid net	1	2	3	4	5	6	7
Parameters spatial distribution	$\sigma_{xx},\sigma_{yy},\sigma_{zz}$ r_{xx},r_{yy},r_{zz},π $\lambda,2\mu,\tau_\sigma,\tau_\varepsilon^s,\tau_\varepsilon^p$	V_x,ρ^{-1}	V_y,ρ^{-1}	V_z,ρ^{-1}	σ_{xy},μ r_{xy}	σ_{xz},μ r_{xz}	σ_{yz},μ r_{yz}

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Synthetic Data Example

The figure 3 verifies that our algorithm of tunnel model is correct, and can handle the declining tunnel model well. Here we will focus on horizontal tunnel model. Time snapshot in figure 4 illustrate channel wave propagation of 3D tunnel model in viscoelastic medium consisting of coal beds (thickness is 10m, from z=45m to z=55m). A point exploration source activated by Riker wavelet which is marked by a red star (10m,100m,50m) at coal beds in figure 2.

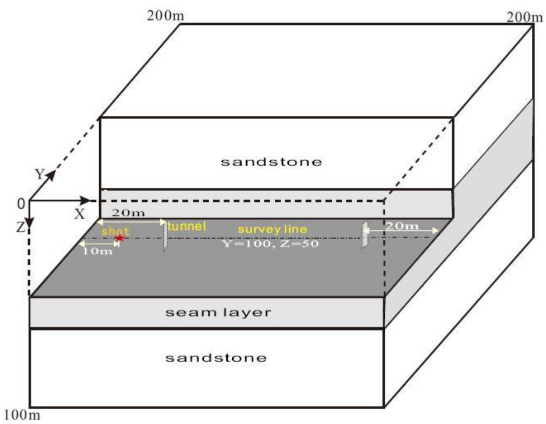

Figure 2: Schematic of systematic coal bed-wall rock geological model

Figure 2 shows the schematic of tunnel model. The size of two tunnel is 4m*160m*4m (located in the middle of coal beds), it is beyond the boundary 20m.

Table 2: Tunnel Model Simulation Parameters

Model size (m)	200*200*100
Grid net (m)	1*1*0.5
Time interval (ms)	0.1
Domain frequency(Hz)	120
Space order	6/2

Table 3: Strata Physical Parameters

P wave (m/s)	S wave (m/s)	Density (g/cm3)	Thick (m)	Lithology
2800	1618	2.2	95	Sandstone
2200	1270	1.4	10	Coal bed
2800	1618	2.2	95	Sandstone

Table 4: Quality factor distribution

Model	Qp_w	Qs_w	Qp_c	Qs_c
1	25	15	10	5
2	80	40	50	22

Table 2 is the simulation parameters of 3D tunnel model. Physical parameters and quality factors distribution are displayed in Table 3 and Table 4, respectively. In the table 3, Qp_w and Qs_w denote P wave quality factor of wall rock and S wave quality factor of wall rock, respectively. Qp_c and Qs_c denote P wave quality factor of coal and S wave quality factor of coal, respectively.

Discussion of results/Conclusions

Figure 4 shows the snapshot of Vx component (left column) and Vz component (right column) for 3D tunnel model in viscoelastic medium.

For the Vx component, compared with non-tunnel model (reference 2), the tunnel has a remarkable influence on channel wave propagation and wave energy distribution. Much more energy leaks into wall and trapped in the tunnel due to the existence of tunnel. Still less energy transmission happens as the quality factors (both wall rock and coal beds) increase.

For the Vz component, compared with non-tunnel model (reference 2), although channel wave concentrates mostly seismic wave energy, partly energy transmitting into wall rock as shear wave velocity of wall rock, but it is still observed that the existence of tunnel makes the channel wave propagation more complicated. It is maybe because tunnel lead to more wave interference pattern involved. On the contrary with Vx component, less energy leaks into wall rock as the quality factor increase.

In conclusion, we can observe that the existence of tunnel in the 3D viscoelastic model could have a remarkable influence on the channel wave propagation and wave energy distribution, it may lead to other occurrence of wave interference pattern which we have not known well yet.

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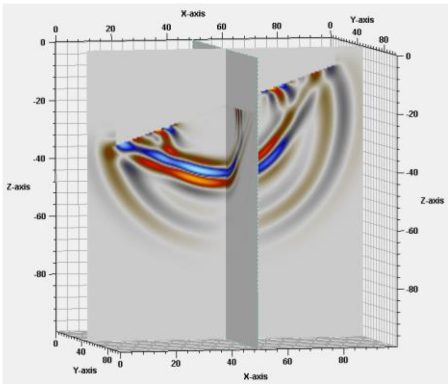
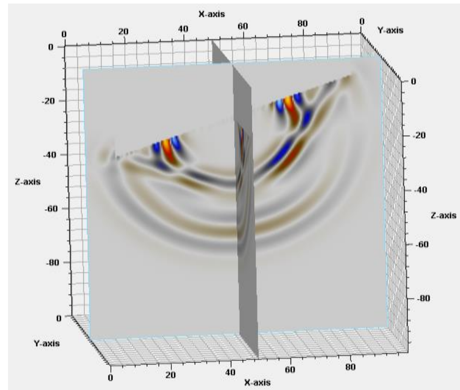
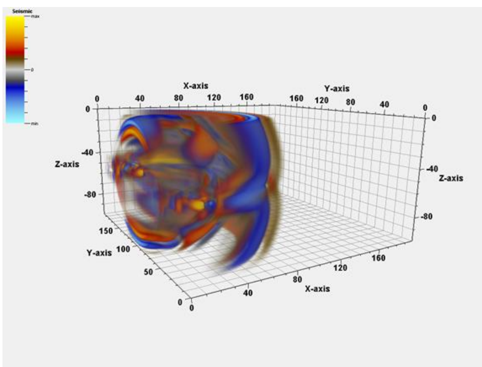


Vx 40ms

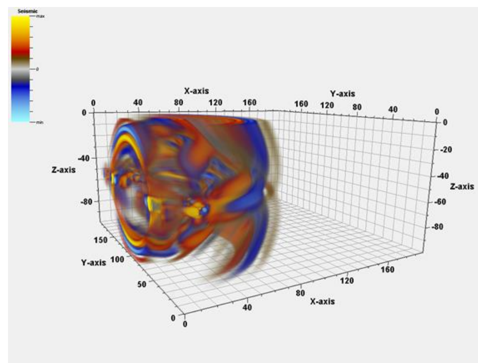


Vz 40ms

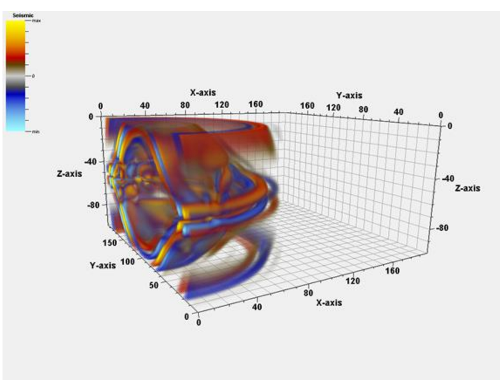
Figure 3: Snapshot of declining tunnel model



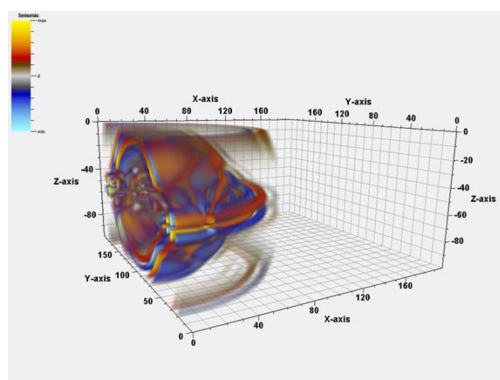
Model 1: Vx 45ms



Model 2: Vx 45ms



Model 1: Vz 45ms



Model 2: Vz 45ms

Figure 4: Tunnel model snapshot in viscoelastic medium.

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EDITED REFERENCES

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