2-D finite-difference seismic modeling of an open fluid-filled fracture: comparison of thin-layer and linear-slip models

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Summary

Within the context of seismic wave propagation, fractures can be described as thin layers or linear slip interfaces. In this paper, numerical simulations of elastic wave propagation in a medium with a single fracture represented by these two models are performed by 2-D finite-difference codes: a variable grid isotropic code for the thin-layer model and a regular grid anisotropic code for the linear-slip model. Numerical results show that the agreement between these two models is excellent except for the existence of a fracture guided mode in the thin-layer model.

Introduction

The presence of fractures critically affects the permeability of rocks and therefore the character of fluid flow in hydrocarbon reservoirs. Thus, fracture detection and characterization is very important in hydrocarbon recovery. Seismic modeling of fractured media is an efficient tool for investigating the possibilities of using seismic waves to characterize the fractures.

For seismic wave propagation, fractures are often described as displacement discontinuities or linear slip interfaces (Schoenberg, 1980; Pyrak-Nolte, 1988). In the linear-slip model, it is assumed that a fracture can be represented by an interface across which the displacements caused by a seismic wave are discontinuous while the tractions remain continuous. The linear relationship between the jump in the displacement vector and the traction vector is determined by the fracture compliance tensor. Coates and Schoenberg (1995) introduced an equivalent medium theory approach for embedding a linear slip interface within an anisotropic finite-difference (FD) code.

Alternatively, an open fluid-filled fracture can be represented by a thin fluid layer following the approach of Groenenboom and Fokkema (1998). For the thin-layer model, non-uniform grid FD methods (Moczo, 1989; Jastram and Behle, 1991; Falk et al., 1996; Pitarka, 1999) can be used to smoothly vary the cell spacings from the far-field mesh to the vicinity of the fracture, thus approximating the fracture directly by a number of grid points (Groenenboom and Falk, 2000). This variable grid approach for explicit modeling of open fluid-filled fractures requires more cells than the Coates-Schoenberg approach. However, the use of the variable grid around the fracture significantly reduces the number of extra cells needed to model the fracture, compared to a uniform grid FD model.

The purpose of this study is to compare a variable grid FD method with the Coates-Schoenberg approach for a single open fluid-filled fracture seismic model to determine to what extent the thin-layer model confirms or contradicts the linear-slip model. Numerical results show an excellent agreement between these two models except for the presence of a fracture channel wave in the thin-layer model.

Methodology

Variable Grid FD Algorithm

FD seismic modeling is commonly based on uniform grids. Grid spacing is determined by the smallest length scale present in the model, usually the shortest wavelength. For discrete fracture modeling, the width or aperture of the fracture is often two or three orders smaller than the shortest seismic wavelength. This forces use of a very fine grid spacing to define the fracture, thus greatly increasing the computational load and restricting calculations to models of very small dimensions. Variable grid FD techniques (Moczo, 1989; Jastram and Behle, 1991; Falk et al., 1996; Pitarka, 1999) provide an efficient solution to this large-scale variation problem (Groenenboom and Falk, 2000).

In this paper, we use a fourth order non-uniform grid FD scheme proposed by Pitarka (1999) for solution of the 2-D velocity-stress elastic wave equation. Weights for the stretched-grid operators are pre-computed using the method of undetermined coefficients. Since the mesh is only distorted along the x and z axis, coefficients are invariant along grid lines, reducing the memory required for stencil storage. The non-uniform mesh is also staggered to increase stability and minimize numerical dispersion: a staggered scheme is crucial for handling the solid-liquid contact present in fractured media. Time derivatives are staggered across the velocity and stress variables and are approximated using an explicit second order central difference operator.

Spatial discretization (h) and temporal increments Δt are chosen to minimize dispersion and maintain stability during the computation. In particular, the inequalities

$$h_{max} < \frac{V_{min}}{5\, f_{max}} \tag{1}$$

$$\Delta t < \frac{0.606\, h_{min}}{V_{max}}, \tag{2}$$

are enforced, where h_{min} and h_{max} are minimum and maximum grid spacings, f_{max} is the maximum frequency of the propagating signal, and V_{min} and V_{max} are the lowest and highest velocities, respectively.

Coates-Schoenberg Approach

To incorporate a linear slip fracture into a FD code, Coates and Schoenberg (1995) introduced an equivalent medium approach. In this approach, all FD grid cells containing a fracture are replaced by grid cells with equivalent anisotropic properties that describe the fracture and host compliances.

The variables required for the equivalent medium calculation in each FD cell are Lamé constants λ and μ of the background medium, the length of the fracture L (in 2-D) in each cell, its orientation, and the normal and shear fracture compliances Z_n and Z_t.

For a vertical fracture with its normal in the 1-direction, the 4 independent anisotropic elastic constant for a 2-D model in the 1-3 plane are (Nihei et al., 2001) :

$$C_{ij}^{cell} =$$

$$\begin{bmatrix} (\lambda+2\mu)(1-\delta_N) & \lambda(1-\delta_N) & 0 \\ \lambda(1-\delta_N) & (\lambda+2\mu)(1-r^2\delta_N) & 0 \\ 0 & 0 & \mu(1-\delta_T) \end{bmatrix}, \quad (3)$$

where

$r = \nu/(1-\nu)$,

$\delta_N = Z_N(\lambda+2\mu)/[L+Z_N(\lambda+2\mu)]$,

$\delta_T = Z_T\mu/(L+Z_T\mu)$.

and ν is the background Poisson's ratio. The equivalent medium described by Equation 3 is transversely isotropic with a horizontal axis of symmetry (HTI media). If the fracture is at an angle to the FD grid, a coordinate transformation must be applied to Equation 3.

After the equivalent medium properties of each cell are calculated, the standard FD scheme for anisotropic media can be applied. The code we used is a staggered grid FD scheme with fourth order spatial differencing and second order temporal differencing.

Numerical Examples

Both the variable grid FD method and the Coates-Schoenberg approach are used to model wave propagation in a medium with an open water-filled fracture to examine the extent to which the thin-layer model confirms or contradicts the linear-slip model.

Figure 1 shows the model. A vertical water-filled fracture with 4mm thickness is embedded in a homogeneous elastic medium. A monopole source (S), located at (12.78m, 12m), has a Ricker pulse with central frequency of 3000Hz. A receiver (R) is located at (10.2m , 18m). For variable grid FD modeling, the horizontal grid spacing smoothly increases from 1mm to 6cm over a transition region 11.7cm wide in the vicinity of the fracture. The vertical spacing is 6cm throughout the grid. For the Coates-Schoenberg approach, a constant FD grid spacing of 6cm is used in both x and z direction. The calculation of effective medium properties of the cells containing the fracture is based on the transverse fracture compliance $Z_T = \infty$, and the normal fracture compliance $Z_N = 0.004m/2.25\ GPa$. The parameters of the background medium are $C_{11} = C_{33} = 43.92\ GPa, C_{13} = 7.62\ GPa, C_{55} = 18.15\ GPa$, $\nu = 0.148$ calculated from V_p, V_s and ρ.

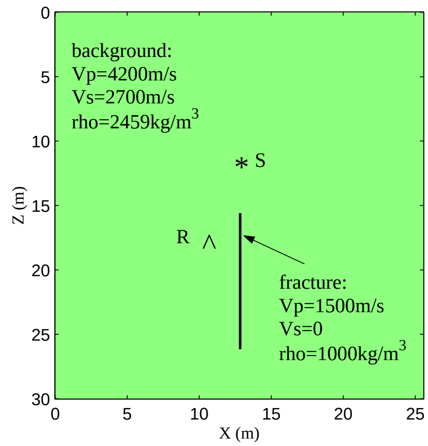

Fig. 1: A vertical fracture model

The snapshots of horizontal and vertical particle velocity components of the thin-layer model and the linear-slip model are shown in Figure 2. In order to make the faint fracture tip diffracted waves visible, the gain was chosen such that amplitudes were clipped at 1 percent of the maximum value. It can be seen that the body wave (P) and the head wave (H) are in good agreement. Fracture tip diffracted waves (PdP, PdS) are similar but with small differences in the amplitudes. The incomparable event is the guided wave (G) along the fracture which is present in the snapshots of the thin-layer model (obvious on V_x snapshot but too weak to be seen on V_z snapshot), but is absent in the snapshots of the linear-slip model. This guided wave is the slow channel wave described by Groenenboom and Fokkema (1998).

Figure 3a and 3b show the horizontal and vertical particle velocity component seismograms at receiver R of the thin-layer model and the linear-slip model. The fit between the two models is excellent since the wavefield is dominated by the body wave. We plot the seismograms of the scattered wavefield generated by the fracture, i.e., the difference between the wavefield in the presence and the absence of the fracture (Figure 4). Small amplitude differences in the P to P and P to S fracture tip diffracted waves can be seen. These results suggest that both models generate similar diffracted wavefields from the fracture tip.

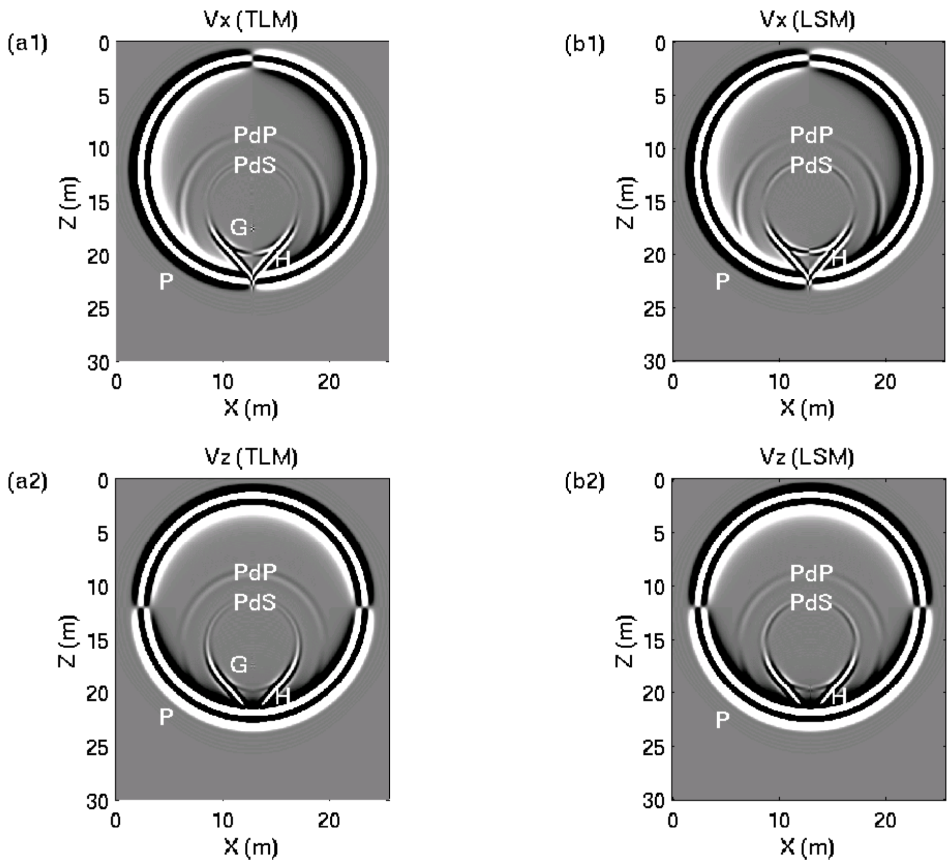

Fig. 2: Snapshots of Vx and Vz component at 2.05ms: (a1) and (a2) are the results of the thin-layer model (TLM); (b1) and (b2) are the results of the linear-slip model (LSM). P, H, and G are direct P-wave, head wave, and fracture guided wave; PdP and PdS are P to P and P to S diffracted waves, respectively.

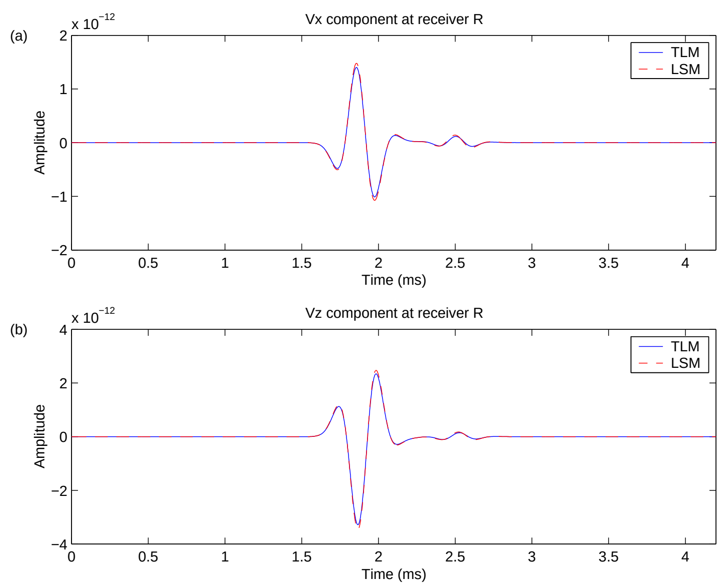

Fig. 3: Seismograms of fractured medium at receiver R in figure 1: (a)horizontal particle velocity; (b)vertical particle velocity.

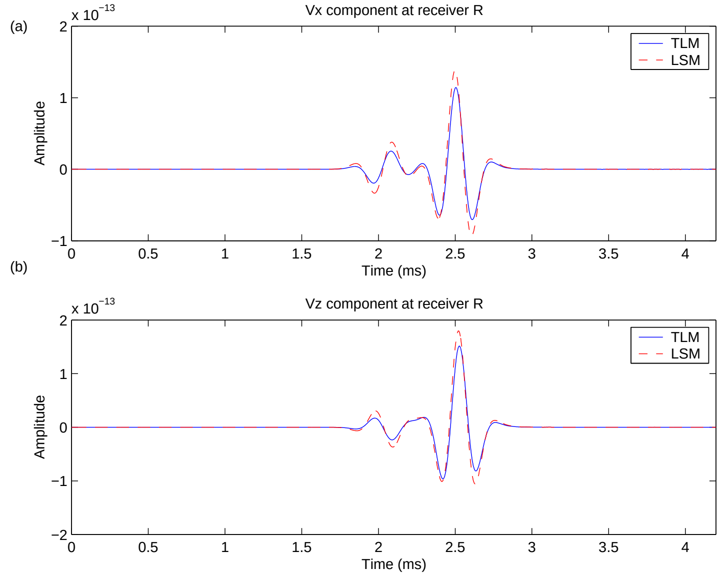

Fig. 4: Seismograms of scattered wavefield (the difference between the wavefield in the presence and the absence of the fracture) at receiver R in figure 1: (a)horizontal particle velocity; (b)vertical particle velocity.

Conclusions

In this paper, a comparison is made between a single fracture modeled by a variable grid elastic FD code (thin-layer model) and a regular grid anisotropic FD code (linear-slip model). Numerical results generated by these two models show an excellent agreement except for the existence of the fracture channel wave in the thin-layer model. Future work is planned to combine the variable grid FD technique and the equivalent medium representation of fractures to model single-well and VSP field data obtained from a fractured sandstone reservoir.

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