Fracture spacing effects on seismic anisotropy and scattering: A 3D numerical simulation study on Discrete Fracture Models

Yungui Xu[1,2], Mark Chapman[1,2], Xiang-Yang Li[1,2] and I.G.Main[2]

[1] *British Geological Survey, Murchison House, West Mains Road, Edinburgh EH9 3LA, UK. Email:yunabc@bgs.ac.uk*
[2] *Geoscience School, University of Edinburgh, Grant Institute, West Mains Road, Edinburgh EH9 3JW, UK*

Summary

We model 3D seismic wave propagation in media with vertical isometric fractures using the standard O(2,8) time-space staggered grid Finite Difference technique. This high order FD method has particular utility when modelling small fractures in 3D. Compared with the 2D case, full 3D simulation provides significantly more information with which to characterize fractures or fracture network properties. The representation of a compliant discrete fracture with vanishing thickness in FD grids is done by applying the known Coates-Schoenberg scheme. We have built a group of 3D models among which all the model parameters remain the same except the fracture spacing. The calculated seismic response in the plane perpendicular to the vertical fracture plane shows the following. First, P-wave seismic anisotropy increases systematically as fracture spacing decreases. If the ratio of the fracture spacing to applied wavelength is more than 1/4, the reflection curves related to the fracture spacing can be clearly observed, and their properties used to infer fracture spacing. Scattering energy weakens and forms systematically different patterns in the different coodinate planes, as fracture spacing increases.

Introduction

Seismic modeling in fractured media provides geophysicists an effective tool for characterizing fractured reservoirs. A fracture or fault is often modelled as an interface across which there is a linear relationship between displacement discontinuity and tractions which remain continuous (Schoenberg and Sayers, 1995). Based on this model, Coates and Schoenberg (1995) describes how to simulate wave propagation through Finite-Difference grid in fractured media, which allows seismic modeling in fractured media up to a new level. Since then many seismic modeling studies are performed to investigate the effects of fracture size and spatial orientation on wave propagation (Vlastos etc., 2003, 2007; Mark E. Willis etc., 2006; Ying Rao etc., 2009). However, most of these seismic modeling approaches (except Mark E. Willis etc., 2006) are carried on in 2D space. In 2D space modeling, if the symmetry of the fracture system is lower than that of orthorhombic medium, the modeling procedure with the standard elastic wave equation neglects the wavefield along the Y-axis; moreover, simulation of azimuthal seismic analysis cannot be performed in 2D case. In this study, we try to simulate wavefront in a group of 3D models with vertical parallel fractures, and to examine the effects of different fracture spacing on seismic anisotropy and scattering energy. We develop the code of the 3D standard O(2,8)-accuracy time-space staggered grid Finite Difference(FD) to model wave propagation in fractured media. And we conclude by model comparison that there is a direct link between seismic anisotropy of P-wave and fracture spacing, and also different spacing models show different scattered energy patterns.

Finite Difference implementation for fractured media with the Coates-Schoenberg Scheme

Theoretically, single fracture or fault is often assumed to have negligible thickness compared with the length of the seismic waves. Traction is continuous across the interface but the small displacement field is not (Coates and Schoenberg, 1995). With these two assumptions, the effective medium theory predicts that, the overall compliance in the fractured medium can be expressed as the sum of the compliance in the host medium and the extra compliance related to the fracture, as expressed in Equation (1) (Schoenberg and Sayers, 1995). In fracture modeling with FD scheme, a FD cell may contain one or more fractures and we call the cell as a fracture cell. Elastic constants for the fracture cell are related to the FD cell size and the elastic constants of each individual fracture within the cell (Coates and Schoenberg, 1995). In this study in order to simplify the representation, we regard fracture spacing as the distance from one set of vertical fracture cells to the adjacent set of vertical fracture cells.

$$s_{ij} = s_{ij}^b + s_{ij}^f \qquad (1)$$

Where s_{ij}, s_{ij}^b and s_{ij}^f are the compliances of the fractured medium, the host medium and the fracture region respectively. The compliance s_{ij}^f is related to, for an instance in the case of vertical fracture model, the two compliance components Z_N and Z_T, which are the normal fracture compliance component and the tangential fracture compliance component respectively. The two components depend on the interior conditions and infill within the fracture.

We use the Finite Difference algorithm with the standard O(2,8) time-space staggered grid for 3D fracture modeling, which requires at least 15 parameters at each FD cell (5 independent stiffness constants, 1 density, 6 stress components and 3 velocity components). Vlastos etc. (2003, 2007) uses the Pseudo Spectral (PS) algorithm to simulate wave propagation in 2D fracture medium. However, with present computer technology the PS method is not suitable for 3D fracture modeling due to its high consumption of computer memory and CPU resource for 3D FFT. In addition, normally fracture modeling requires relatively small cell size, which results in even more hardware requirements with the PS method where the size of the whole model remains spatially same. On the contrary, the FD method only uses the local values to calculate the next time-step value with the central difference scheme. If the FD cell becomes small the computation also increases, but not as much as that in the PS method. One of the weakness of the FD method is that in the case of vertical fracturing, the density ρ, the stiffness constants c_{44}, c_{55} and c_{66}, need to be interpolated at the central difference location, which increases computation errors.

Models with Vertical Discrete Fractures

To investigate the effect of different fracture spacings on the wavefront, a group of models were designed. Each model consists of an isotropic host medium and an array of vertical fracture cells which are embedded into the host medium. All the parameters of the models are the same except the fracture spacing. The model size is 450 x 450 x 450 with a cell size of 10m x 10m x10m. The thickness of fracture cell is 1 cell length, i.e., 10 meters. The host medium parameters are the P-wave velocity V_p=3300m/s, the S-wave velocity V_s=2000m/s and the density ρ=2200kgm^{-3}, and we assume that the two fracture compliances are $Z_N = Z_T = 5.6x10^{-10}$ GPa^{-1} (all of the medium parameters are set the same as those in Vlastos, 2003). The density of the fracture region remains the same as the host medium. We use a 20Hz Ricker wavelet (the P-wave wavelength is 165 meters in the host medium) as source wavelet for simulation. The fracture spacing changes from 160m, 120m, 80m, 40m, 20m to 10m(the last three cases are shown in Figure 1b, 1c and 1d). For comparison, two other special models are constructed, the host background isotropic medium only without fracturing (Figure 1a), and the model with fractures in every cells (the seismic behaviour in this case is identical to that of HTI medium due to the same stiffness matrix form as HTI medium, Figure 1e). Therefore, the ratios of fracture spacing to the wavelet length for P-wave propagation are 1/16, 2/16, 4/16, 8/16, 12/16 and 16/16 (∞ and 0 for the two special cases). This design can examine the scattering effects and wavefield characteristics for the specific ratio range. An explosive source is located in the centre of each model.

Numerical Simulation

The snapshots of the resulting wavefront are taken at 600 ms (Figure 2). We find the changes in the subplots of Figure 2 show characteristic behaviours. First, let us examine the subplots in the X-Z plane (Figure 2a1-2h1). Apparently the P-wave wavefront looks like a series of ellipses. The 'ellipticity' of the P-Wave wavefront increases gradually with the decrease of the fracture spacing, and reach to the maximum when the spacing is 0m. We can use the short-axis/long-axis ratio of the ellipse to measure the variation of the strength of the P-wave seismic anisotropy with the fracture spacing (as shown in Figure 3). The reason for such a variation is that the two extra compliances do not affect the P-wave velocity in the direction of fracture strike, but reduce the velocity perpendicular to the strike, and this velocity becomes slower with the decrease of fracture spacing, which means seismic anisotropy becomes stronger with the decrease of fracture spacing. P-wave wavefront is a circle in Figure 2a1 and no seismic anisotropy shows here as expected. On the contrary, when the spacing is 0m, the model is a homogeneous HTI model and seismic anisotropy reaches the strongest (Figure 2h). From Figure 2b1 to Figure 2g1 we can see that the vertical fractures trap a lot of scattering energy among them, and the pattern of scattering energy is linked to the ratio of fracture spacing to the wavelet length. As we can see from Figure 2b1 to Figure 2d1, P-wave reflections from the fracture form a series of clear curves on the vertical direction, and the curve spacing reflect the fracture spacing and become closer with the decrease of the fracture spacing, which means seismic response can distinguish the different fracture spacing within the range (160m, 120m, and 80m, and the ratios are 1, 3/4, and 1/2), but it cannot distinguish for the case of fracture spacing 40m, 20m and 10m (the ratios are 1/4, 1/8, and 1/16), which basically agrees with the geophysical understanding that seismic wave can distinguish the object with the range of more than 1/4 wavelength. In these cases scattered energy is very clear in the middle zone of the models. For the case of the fracture spacing 20m and 10m (the ratios are 1/8, and 1/16), the reflections interfere and mix heavily with each other, and the resulting seismic responses exhibit the features that are much closer to that in general homogeneous HTI medium. The S-wave wavefront forms similar circles inside of the P-wave, and the S-wave energy submerges in the P-wave and the converted wave in the case of Figure 2b1-e1.

Then let us to examine the Y-Z plane (Figure 2 a2-h2, column 2&4). Note that the vertical reflections in the Y-Z plane interfere with each other to form a series of complex concentric circles (as shown in

Figure 2 b2-g2), which cannot be observed in 2D simulation. We think that the number of the concentric circles changes with the snap time and their energy becomes weaker from Figure 2 b2 to Figure 2 g2, which means that energy reflection and scattering is also linked to the fracture spacing.

Conclusions

We have conducted a 3D numerical study of the effect of fracture spacing on P- and S-waves. In this study, the Coastes-Schoenberg scheme is applied to generate the equivalent medium parameters. We use the Finite Difference algorithm with the standard O(2,8) time-space staggered grid for 3D fracture modeling, which enables us to simulate the 3D seismic response highly accurately with a reasonable amount of computation. Our results indicate that the P-wave seismic anisotropy increases with the decrease of the vertical fracture spacing, and P-wave wavefronts show characteristic elliptical variations. The reflection curves from the fracture spacing can be clearly observed in X-Z planes and we believe that the spacing of the reflection curves can distinguish the different fracture spacing if the ratio of the spacing to the wavelength is more than 1/4. We find that, scattering energy turns weaker with the decrease of the fracture spacing in both the vertical and horizontal planes, and particularly, the scattering energy forms different patterns of complex concentric circles, which cannot be simulated with 2D modelling. We believe that the pattern of P-wave seismic anisotropy and scattering energy can be used to characterize the fracture spacing of fractured reservoirs.

Acknowledgements

This research is supported by the sponsors of the Edinburgh Anisotropy Project. This work is published with the approval of the Executive Director of the British Geological Survey and all the EAP Sponsors.

References

Coates, R.T., and Schoenberg, M., 1995, Finite-difference modeling of faults and fractures: Geophysics, 60, 1514–1526.
Rao, Y., and Y., Wang, 2009, Fracture effects in seismic attenuation images reconstructed by waveform tomography: Geophysics, 74, R25-R34.
Schoenberg, M. and Sayers, C.M., 1995, Seismic anisotropy of fractured rock: Geophysics, 60, 204–211.
Vlastos, S., E.Liu, I.G.Main, and X.Y.Li, 2003, Numerical simulation of wave propagation in media with discrete distributions of fractures : Effects of fracture sizes and spatial distribution: Geophysical Journal International, 152, 649–668.
Vlastos, S., E.Liu, I.G.Main, and C.Narteau, 2007, Numerical simulation of wave propagation in 2-D fractured media Scattering attenuation at different stages of the growth of a fracture population: Geophysical Journal International, 171, 865–880.
Willis, M.E., Willis, Daniel R.Burns, Rama Rao, Burke Minsley, M.Nafi Toksoz, and Laura Vetri, 2006, Spatial orientation and distribution of reservoir fractures from scattered seismic energy: Geophysics, 71, P.O43-O51

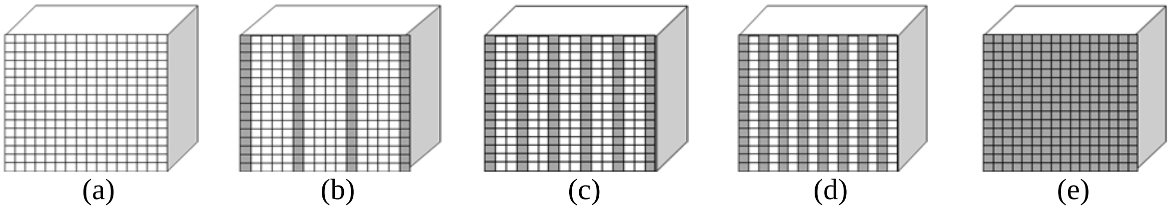

***Figure 1**. Models above illustrate isotropic host media interleaved with vertical isometric fractures. White cells represent the host medium and dark cells represent the vertical fracture. Fracture thickness is 10 meters in all models. The fracture spacing is constant in each model but different among the models: (a) Isotropic model; Model with fracture spacing (b) 40m, (c) 20m, (d) 10m, (e) 0m(HTI).*

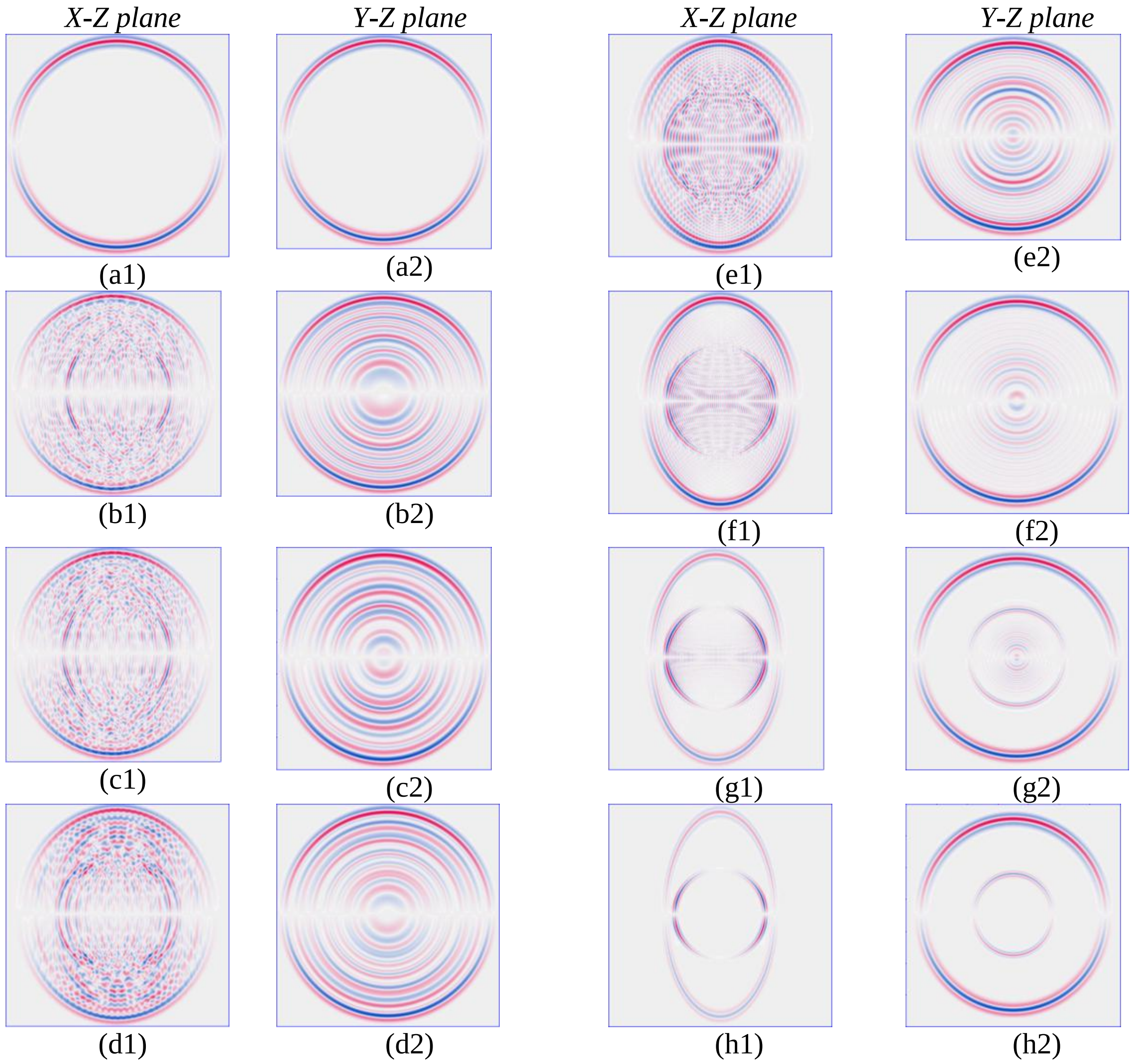

Figure 2. *Snaps of the Z-component wavefront are taken cross the centre of the models at the time of 600ms in X-Z (columns 1 and 3) and Y-Z planes (colums 2 and 4). Wavefront snapshots for (a) the isotropic model; models with fracture spacing (b) 160m, (c) 120m, (d) 80m, (e) 40m, (f) 20m, (g) 10m, and (h) 0m(HTI).*

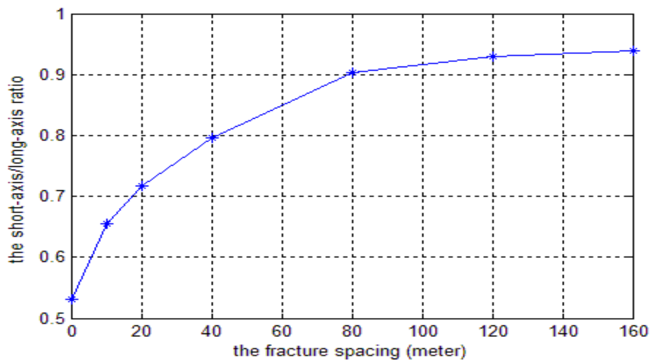

Figure 3. *The variation of the ratio of short to long axis of the P-wave wavefront ellipse in Figure 2 with the fracture spacing. The lower of the ratio, and the stronger of P-wave anisotropy. The ratio zero means the strongest anisotropy (HTI medium), and when the spacing goes to the infinity, the ratio approaches 1.0(isotropic medium).*