

The volume couple as a source for micro-seismic events

Peter M. Manning*

The CREWES project, University of Calgary

pmmannin@ucalgary.ca

Summary

A case is presented that the volume couple source mechanism is a likely description of fracturing induced seismic events. Finite-difference modelling is then introduced as a valid description of the double couple by comparing its wavefield predictions to the well established theory results developed within the Aki and Richards text. The finite-difference method is then applied to the volume couple case to show the nature of the predicted wavefields. Some comparisons are then made to some published results which are consistent with the model predictions made here.

Introduction

Seismic sources within the earth are confined within a finite volume where conservation of momentum applies. This means that the sources must be modelled as couples. A complete set of simple couples may be found, for example, in Aki and Richards (1980) page 51.

The couples may be divided into two types: volume creating types as shown in Figure 1a; and shear types, both of which may create pressure and shear waves. The shear types are further restricted to also have zero angular momentum, and this can only be done by combining two sets of shear couples with opposite rotations. This combination is called the double couple, which is described in Aki and Richards (page 71f), and shown in Figure 1b.

The theory of the double couple has been successfully developed (as in Aki and Richards), and extensively applied to earthquake sources, with very satisfactory results. There is no doubt that natural sources almost always have a shearing motion, and so take the form of the double couple.

A case can be made that the double couple is not consistent with seismic sources associated with hydraulic fracturing. This is because high pressure fluid does not directly cause shear stresses, but does create volume changes by forcing cavities open. This indicates that the volume couple, as in Figure 1a, is the more likely candidate on which to base the theory of fracture induced seismic events. A case study by Jechumtalova and Eisner (2008) states this as a fact for the Canyon Sand formation of western Texas.

Method

The theory which serves as a framework for the interpretation of earthquake seismology is the double-couple source (from Figure 1b) as described in Aki and Richards (1980) page 71f. The far-field displacement from this source at a time of .056 seconds is shown in Figure 2a. The display here shows both the pressure waves (large rings), and the shear waves (small rings), although the gain required in order to make the pressure waves visible overdrives the shear wave amplitudes.

The same double-couple source may be specified to initiate a 3 dimensional finite-difference model, and then propagated through sufficient time steps to reach the same time of .056 seconds. The far-field displacement calculated by this method is shown in Figure 2b.

The finite-difference method may also be used to model the wavefields generated from a volume couple, and the vertical volume couple from Figure 1 was used to generate the

wavefields shown in Figure 3. The displacements at the surface of the same model, 80 metres above the source, and collected over time, are shown in Figures 4 and 5. These give the X and Z components of the displacements, and are meant to simulate a surface seismic recording from directly over the source to offsets of up to 150 metres. A record from the same source at 150 metres depth into a borehole string 80 metres away is shown in Figure 6.

Discussion

Inspection of Figure 2 reveals that the double-couple sourced wavefields are consistent, whether generated from pure theoretical principles (Figure 2a) or from finite-difference modelling (Figure 2b). The finite-difference version has an annealed effect which may be partially caused by numerical dispersion, but also may be seen in real seismic data generally.

According to Eisner et al (2009), it has been found that surface arrays collecting seismic data after hydraulic fracturing contained useable pressure events, but not shear events. This low shear signal amplitude was consistent enough that 3 component geophones were no longer used, in favor of simple vertical geophones. The energy distribution here could be explained by assuming that many events result from a radiation pattern as in Figure 3, with the highest amplitude pressure waves directly above, and with a notch in the shear wave pattern in the same direction. This in turn would imply that these many energy sources result from sudden volume changes between flat lying interfaces, consistent with the forcible injection of fluids into flat lying formations.

The vertical volume couple energy recorded in a nearby borehole seems to be amenable to interpretation in a straightforward way, as is shown in Figure 6.

If the vertical volume couple is indeed the style of seismic energy released after high pressure fracturing, it should be noted that the resulting shear waves do not always behave as if they originated from the same point as the pressure waves. This is indicated in Figures 4 and 5, where the shear waves do not take a simple hyperbolic shape. It appears that the shear energy is converted from non-homogeneous pressure energy which has propagated some finite distance from the event origin. Angular dependent corrections would be required to obtain accurate origin points.

Conclusions

The correspondence between the well established theoretical double-couple wavefield and the equivalent finite-difference calculated wavefield verifies the use of finite-difference methods initiated from complex sources.

The vertical volume couple is a likely description of the process which converts some of the energy stored in an earth distorted by hydraulic fracturing into seismic waves.

The vertical volume couple appears to be a more complex source than some others, because its shear energy must be converted from pressure energy at some distance from the origin.

Acknowledgements

Thanks to Gary Margrave and Ed Krebs for advice and encouragement, and the CREWES sponsors for their generous support.

References

- Aki, K., and Richards, P. G., 1980, Quantitative Seismology: W.H. Freeman and Co., first edn.
- Eisner, L., Duncan, P. M., Heigl, W. M., Keller, W. R., 2009, Uncertainties in passive seismic monitoring: The Leading Edge, 28, 648-655.
- Jechumtalova, Z. and Eisner, L., 2008, Seismic source mechanism inversion from a linear array of receivers reveals non-double-couple seismic events induced by hydraulic fracturing in sedimentary formation: Tectonophysics, 460, 124-133.

Figures

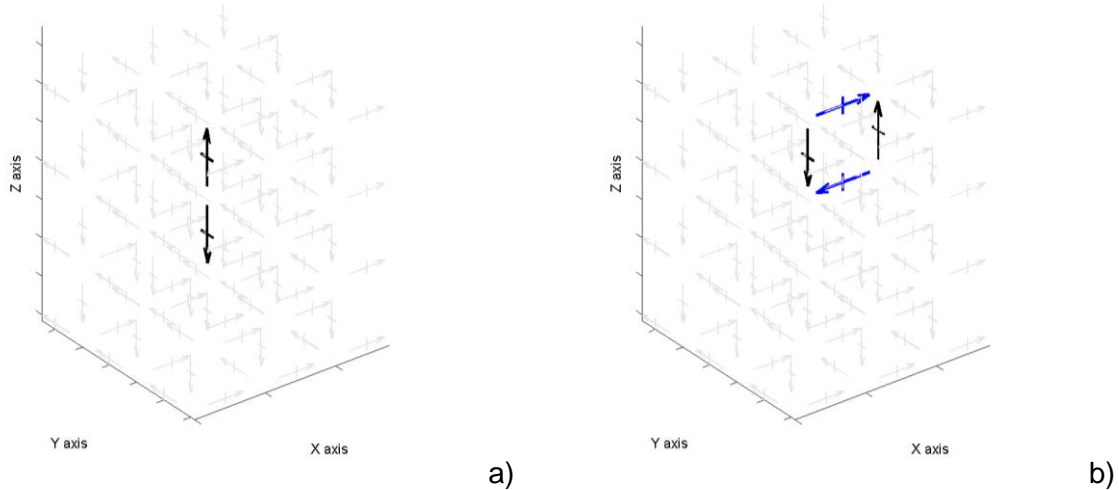


FIG. 1. Two proposed sources of energy for the initiation of seismic waves. The vertical volume couple is shown in a) and the xz plane double-couple is shown in b).

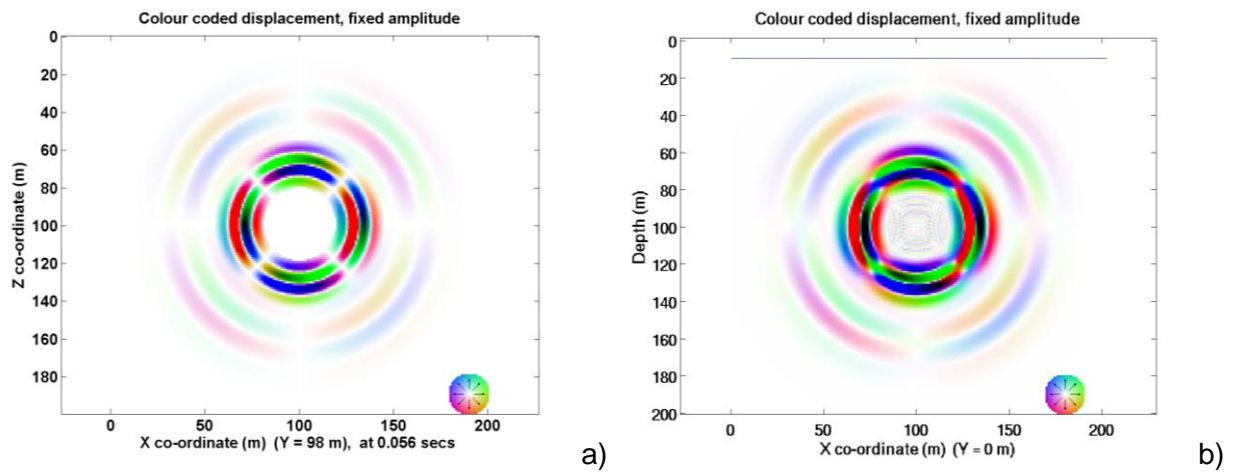


FIG. 2. The zero-phase wavefield after propagating for 0.056 seconds from an initializing double-couple. In a) the wavefield was calculated with the equation from Aki and Richards; in b) as propagated by a 3D finite-difference program.

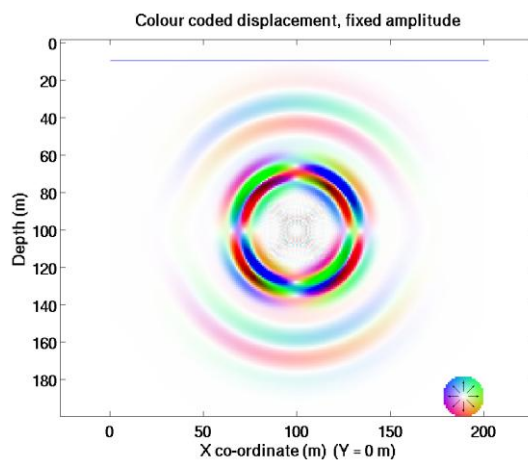


FIG. 3. The finite-difference wavefield initialized from the source in Figure 1a). This response is symmetric about the axis of the source

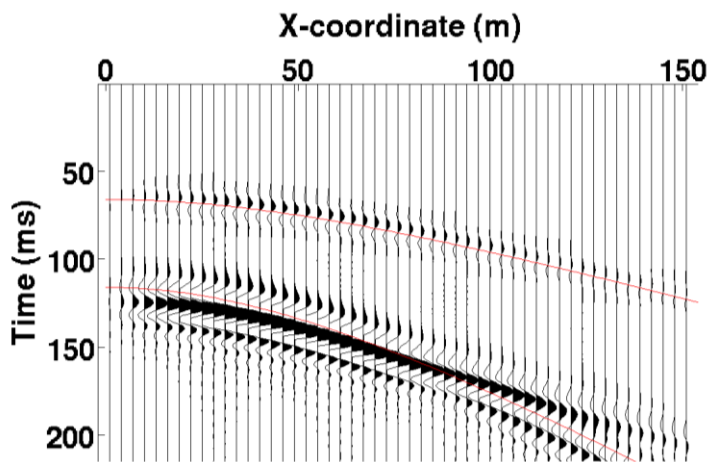


FIG. 4. Record from horizontal geophones at the surface. The Z volume couple is at 80 metres. The red lines show the moveout curves to the centre of the wavelets, which should appear at trace inflection points. At top is the pressure event, at bottom is the shear event.

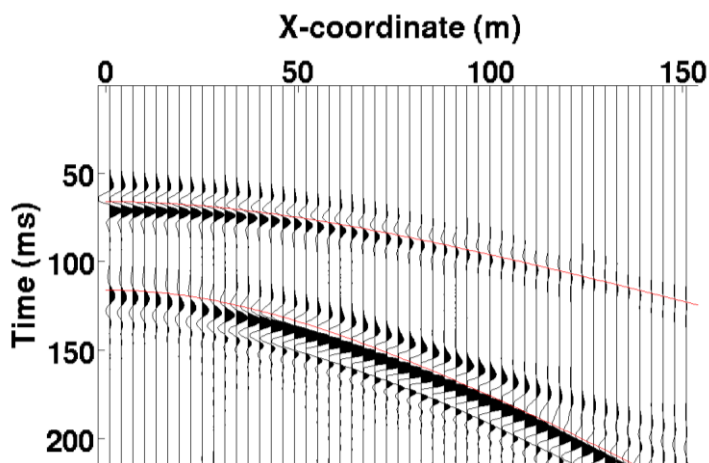


FIG. 5. The vertical geophone record equivalent to Figure 4.

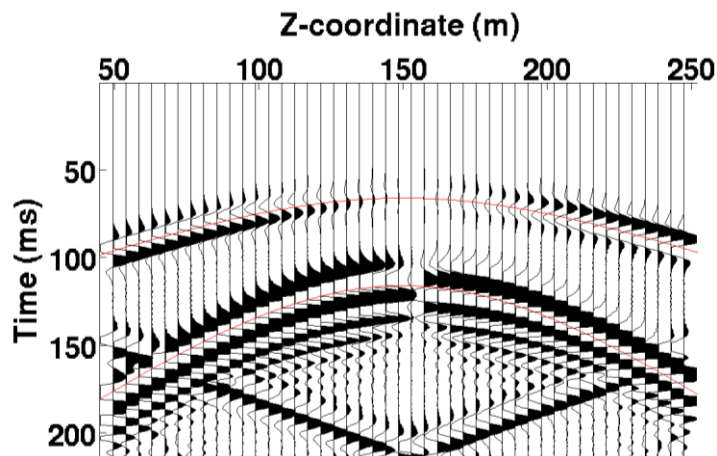


FIG. 6. Record from vertical geophones in a vertical borehole. The Z volume couple is at 150 metres depth and 80 metres away. The crossing events are reflections from boundaries.