B018 NUMERICAL MODELLING OF ELECTROSEISMIC SIGNALS IN FRACTURED, CONTAMINATED AQUIFER SYSTEMS

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Summary

The legacy of industrial mining has left many localized aquifer systems contaminated by highly mobile pollutants that are difficult to characterise without expensive programmes of site investigation. Although geophysical techniques have been successfully applied to many of these problems, electroseismic methods remain uncommon due to the complexity of the data interpretation. We present a modelling method that is able to simulate electroseismic wave generation from fluid-filled fractures and provide additional interpretational information on the nature of the fracture mechanisms and the properties of the fluids they contain.

Introduction

The localized contamination of aquifer systems by mining-related pollutants (such as acid mine waters, tailing dam leachates, etc), combined with the inevitable ground stability problems associated with near-surface mine-workings, pose serious environmental and health-related problems throughout the world. Many of these pollutants are highly mobile and assessing their time-varying concentrations and sub-surface distributions can be extremely difficult, particularly in complex environments. Traditionally, expensive programs of site investigation, flow modelling and direct sampling are required in order to determine the exact nature of any particular contamination problem. In the past decade, however non-invasive geophysical investigation techniques have become increasingly popular with Resistivity, Electromagnetic, Spectral Induced Polarisation (SIP) Ground Penetrating Radar (GPR) and Microseismic methods all being applied to various mining-related problems. Even though this trend continues, applications featuring Electroseismic responses are relatively uncommon despite their potential for providing additional information on the hydrogeological and geomechanical properties of the rock mass and pore fluids (Garambois and Dietrich, 2001). Unfortunately, complexities in the nature of the electroseismic sources, variations in pore fluid electro-chemistry and the modification of the EM signals as they propagate through the subsurface, make the interpretation of electroseismic data exceedingly difficult. By developing appropriate numerical forward modelling solutions these processes can be investigated in detail and the recorded data analysed with a higher degree of confidence.

Electroseismic Modelling

As a saturated rock fractures, propagating electroseismic signals are generated at the fracture faces by the physical displacement of the interstitial fluids contained within the fracture zone (Pride and Haartsen, 1996). To model this phenomenon, discrete element and finite-difference modelling techniques have been combined to provide a comprehensive modelling method that simulates both elastic and electromagnetic (EM) signal generation and wave propagation. The scheme is able to model the full three-dimensional electroseismic wave-field including converted waves, reflections, multiples and diffractions in a single computational scheme. The scheme has the advantage of being easily formulated, flexible and operates in the time-domain without the need for complex mathematical transformations. The comprehensive nature of the method permits the use of 'macroscopic' source elements to describe the natural behaviour of the rock mass and the complicated fracture geometries.

Elastic and electromagnetic wave propagation phenomena are modelled using a O(2,4) fourth-order in space, second-order in time, three-dimensional, total-field, finite-difference, time-domain (FDTD) parallel modelling technique that operates on an orthogonal, three-dimensional domain of gridded, electromagnetic and elastic 'field points'. To create realistic, practical fracture sources, a three-dimensional, discrete-element PFC3D model of the source is embedded into one of the FDTD grid sub-domains. The PFC source model has the resolution and flexibility required to describe any type of fracture mechanism and, potentially, any geometry. Individual vector velocities/displacements are recorded at the fracture face and at discrete 'source' locations within the PFC volume. As each PFC element on the fracture face is 'free' to move in directions determined by the time-varying forces acting on the particles, relative motions are created between each element. Consequently, relative fluid-solid motions are generated that, in turn, produce independently propagating EM signals (figure 1). If each inter-element volume is considered as a macroscopic region of independent, plane wave motion, then it is possible to calculate the strength of electric (E) and magnetic (H) fields generated by the relative fluid-solid flow in that particular region (Garambois and Dietrich, 2001). By de-composing each of the electric and magnetic fields into their x, y & z component parts, individual dipole fields can be transposed onto a grid of EM field recording points distributed across the source volume. At each point in time, the resultant EM field at any of the recording points will be a superposition of the individual, crack-face dipole fields. The resultant time-dependent electric and magnetic field recordings can then be used as the driving functions for electromagnetic FDTD code and the propagating electroseismic signal modelled across the whole of the sub-surface volume.

Modelling Example

Figure 2 illustrates the modelled electroseismic fields emanating from a 0.4m diameter, horizontal (x-y plane) simple, strike-slip fracture source with a primary motion in the negative x direction. The matrix material is a Sherwood Sandstone of approximately 15% porosity, saturated with 'contaminated ground water' (having an electrical conductivity of 15 mS/m and a relative permittivity of 81). The results show that the presence of an asymmetrical displacement field along the fracture faces produces an independently propagating electromagnetic wave of high velocity and long wavelength. The combined effect of each macroscopic electromagnetic element is to generate an overall EM field pattern that is 'quasi-dipole' in nature (Figure 2). Similar effects have been observed at passive interfaces (e.g., bedding planes or changes in pore fluid properties) and, therefore, the EM field polarisation exhibited by the fracture source also suggests that, with the aid of suitable electroseismic instrumentation, additional information can be gained on the nature of fracture geometries through an analysis of the individual EM field components. In addition, the results indicate that the strength of EM waves is likely to be primarily governed by the surface area of the fracture, the electrical conductivity of the fluids and the pore space geometry of the rock matrix.

Conclusions

By combing discrete element and finite-difference modelling together in a comprehensive method, it is possible to simulate electroseismic signal generation and wave propagation from contaminated, fractured rock mass. Results show that the method has the potential to provide information on the electrical properties of the interstitial fluids and the geometry of the fracture system. This has obvious applications for the characterisation of contaminated aquifer systems but when considered in conjunction with multiphase fluid-flow modelling techniques, it opens up the possibility of using near-surface electroseismic techniques for the time-dependent monitoring of contaminant flow through fractured and porous media.

Acknowledgements

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References

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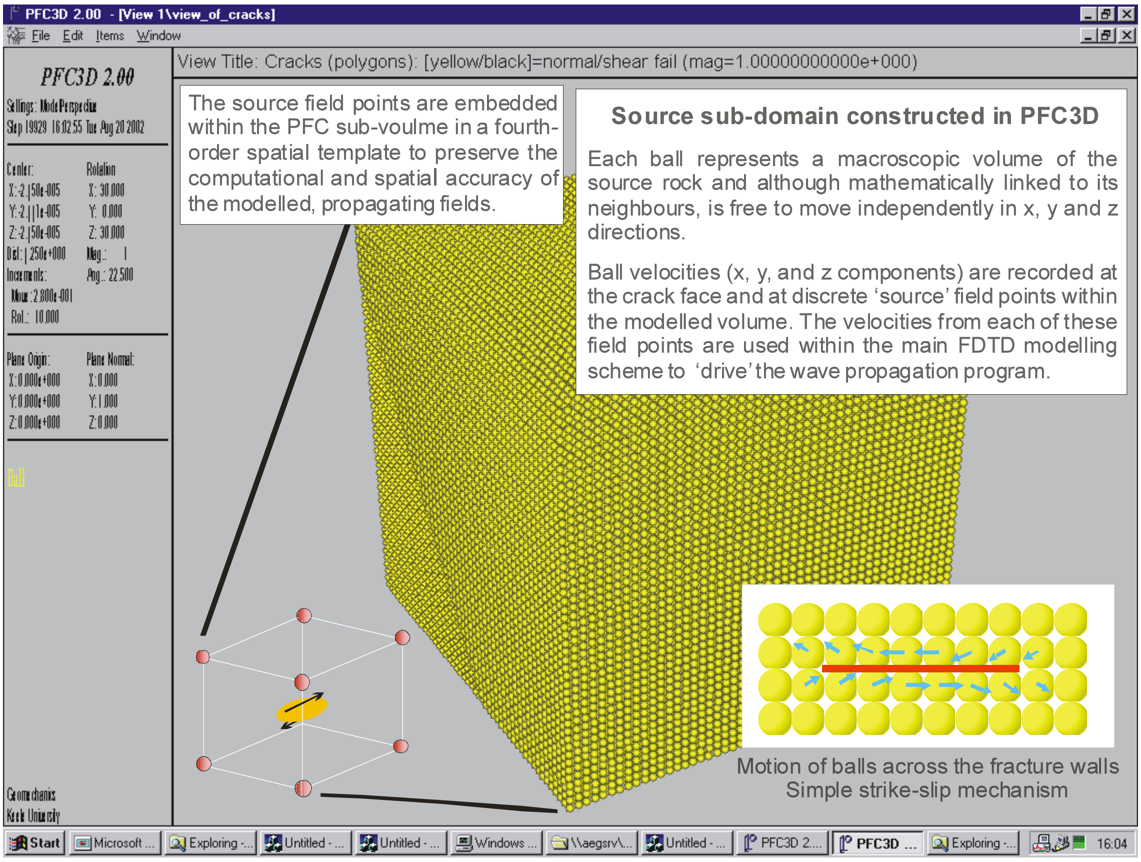
Pride, S., R. and Haartsen, M., W., 1996. Elecroseismic wave properties. Journal of the Acoustical Society of America, Vol. 100, No. 3, 1301-1315.



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The source field points are embedded within the PFC sub-voulme in a fourth-order spatial template to preserve the computational and spatial accuracy of the modelled, propagating fields.

Source sub-domain constructed in PFC3D

Each ball represents a macroscopic volume of the source rock and although mathematically linked to its neighbours, is free to move independently in x, y and z directions.

Ball velocities (x, y, and z components) are recorded at the crack face and at discrete 'source' field points within the modelled volume. The velocities from each of these field points are used within the main FDTD modelling scheme to 'drive' the wave propagation program.

Motion of balls across the fracture walls
Simple strike-slip mechanism

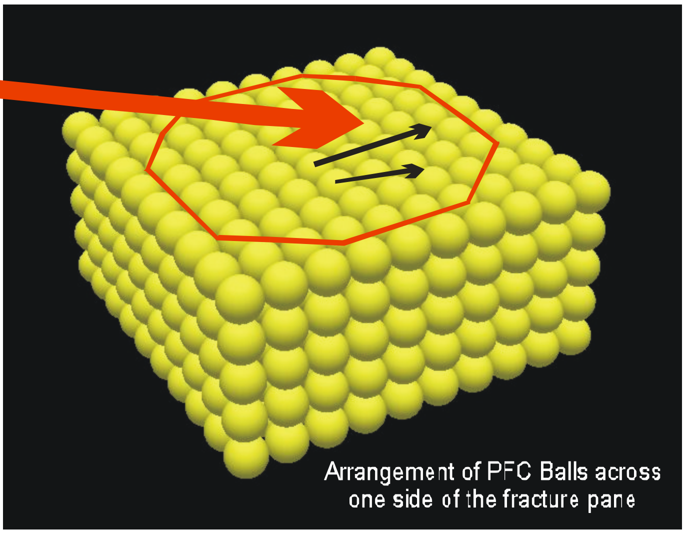
PFC source sub-volume embedded into the FDTD model

Arrangement of PFC balls across the fracture face. Displacement of each ball is determined by the forces acting within the source volume.

Variations in each of the ball's displacement/velocity generates relative solid-fluid motions between each ball.

These relative motions are converted into independent electric and magnetic dipole moments.

The resultant fields are then transposed to the EM field recording points distributed around the source volume.



Arrangement of PFC Balls across one side of the fracture pane

Figure 1. Generation of the electro-seismic source signals from the discrete-element PFC3D model. Each element (or PFC 'ball') represents a macroscopic volume of the rock mass.

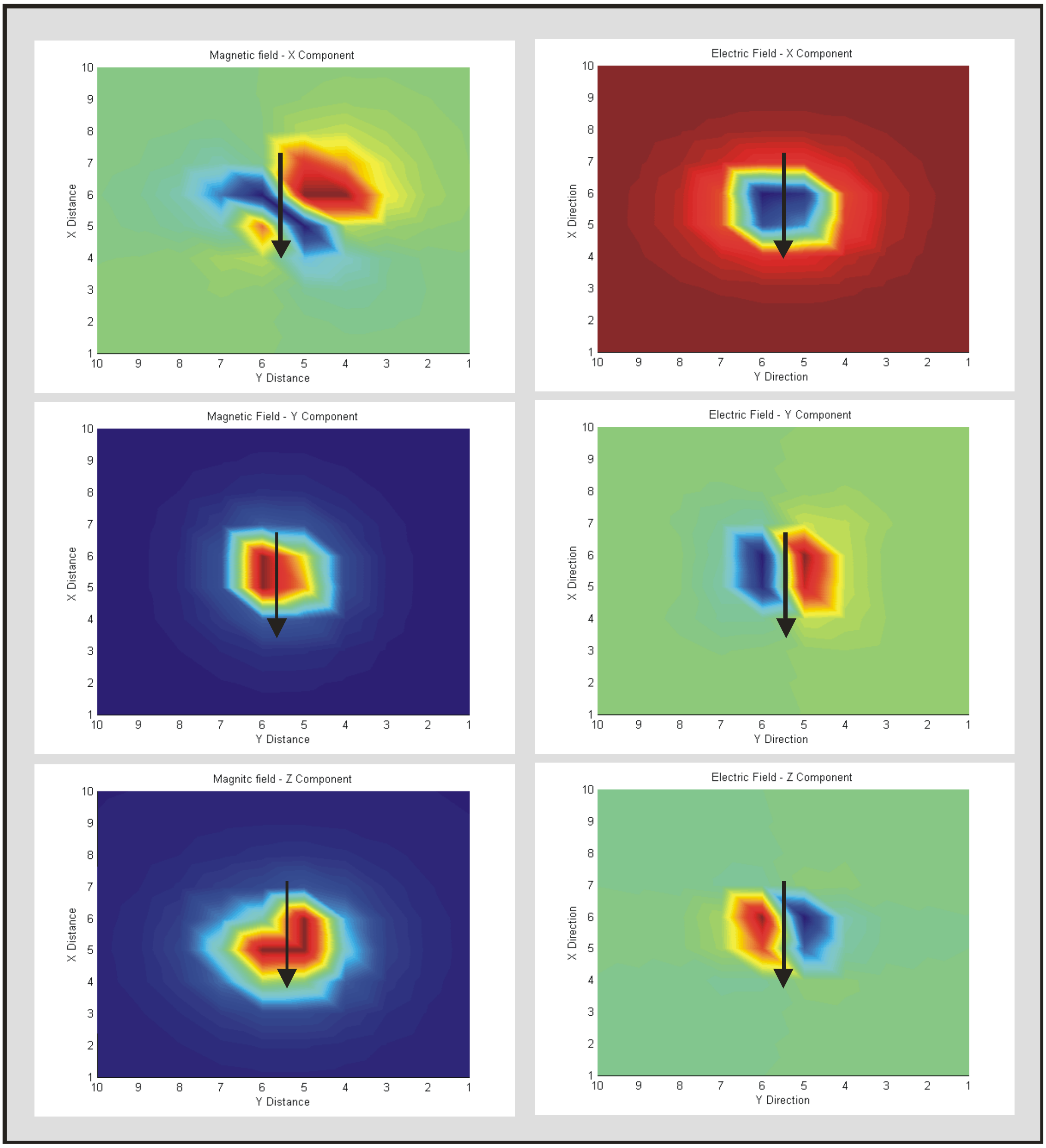


Figure 2. Modelled 'electroseismic' fields emanating from a 0.4m diameter, horizontal (x-y plane) simple, strike-slip fracture source. Individual images illustrate the distribution of the Electric (E) and Magnetic (H) field vector components in the x-y plane at a height of 1m above the fracture (Arrow represents the primary motion of the strike slip fracture). Note the quasi-dipole distribution of the fields.