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Genetic Full Waveform Inversion to Characterise Fractures

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Summary

Understanding the physical properties of fractures, location, orientation, and geometry is of primary importance in the comprehension of geo-resources and geo-hazards. In doing so seismic waves can be an effective tool for non-invasive investigation of fracture parameters.
We have developed a novel stochastic Full Waveform Fracture Inversion employing Genetic Algorithms (GA-FWFI) to quantify mechanical properties of fractures (fracture-specific stiffnesses) in a synthetic sample. We focus on the inversion of transmitted waves, simulating ultrasonic laboratory data, on a specimen containing 6 horizontal fractures orthogonal to the wave propagation. The inversion results show a good convergence to the solution which best fits the observed data within the maximum number of generations and number of models set.

Introduction

Fractures play an important role in mechanical and hydraulic behaviour of rock masses, being responsible for providing pathways for fluid flow and its transportation in the subsurface, as well as affecting the stability of engineered structures and excavations (Pyrak-Nolte *et al.*, 1990). Thus, an understanding of the mechanical properties of fracture zones, location, orientation, and geometry, is of primary importance in applications such as stability investigations and rock damage, CO_2 sequestration, nuclear waste monitoring and hydrocarbon recovery (Sayers, 2007).
Elastic wave measurements such as seismic, sonic or ultrasonic data can be an efficient tool for non-invasive detection and characterization of physical properties of fractures (Liu and Martinez, 2012).

Although fracture location, density and orientation are commonly extracted from seismic data, fracture-specific stiffness (the reciprocal of compliance**)** is less often determined (Worthington, 2007). Nevertheless, several authors have shown the importance of estimating mechanical properties of fractures, quantified by fracture stiffness, in order to evaluate the fluid flow through the fractures (Pyrak-Nolte and Nolte, 2016) as well as the visibility of macrofractures in seismic data (Worthington, 2007).

In this study, we have developed a method utilising a novel stochastic Full Waveform Inversion (FWI) employing Genetic Algorithms (GAs) to quantify fracture-specific stiffnesses for a set of parallel fractures in a synthetic sample. We mainly focus on the inversion of transmitted waves, mimicking ultrasonic laboratory data on a specimen, where we model numerically the laboratory experiment on laminated steel block carried out by Pyrak-Nolte *et al*., (1990) to estimate the specific stiffnesses of each fracture. In this paper, we show a 2-D synthetic example where a homogeneous and isotropic medium contains a set of 6 parallel fractures that cut the sample horizontally. All fractures are orthogonal to the wave propagation.

Numerical implementation of fractures

In theoretical studies, fractures are often modelled as aligned ellipsoidal cavities of low aspect ratio (Schoenberg and Sayers, 1995). Furthermore, assumptions are also made such as a long seismic wavelength relative to the size and spacing of fractures, low concentrations of cracks, and uniform stress state. Under these assumptions, Schoenberg and Sayers (1995) showed that seismic modelling of fractured media can be defined in terms of fracture-induced anisotropy and is well described by an equivalent elastic medium approach. This method encapsulates the behaviour of fractured rock within the elastic moduli, therefore combines the effects of fractures and the host rock into a single medium as an equivalent anisotropic solid. Despite the convenience of this approximation, it neglects the finite fracture openings, and the details of the spatial distribution of fractures: thus this approach is not able to describe correctly the behaviour of a seismic wavefield in a fractured medium (Hildyard, 2007).

For a complete description of wave-fracture interaction, it is necessary also to account for the physics of scattering at each individual discrete fracture (Liu and Martinez, 2012). This is achieved by making use of the discrete fracture representation using displacement discontinuity theory. This explicit interface approach treats fractures as a non-welded interface: across an interface, the stress field is assumed to be continuous while the particle displacements are discontinuous. The coupling between the stress and the change in the displacement across the fracture is given by the normal and shear fracture stiffness (K_n and K_s respectively) (Schoenberg, 1980).
In this research, we model the seismic wave interaction with fractures using the numerical modelling code WAVE3D (Cundall, 1992; Hildyard *et al*., 1995). This program uses the Finite Difference method and implements a discrete representation of fractures.

FWI as a global optimization approach

FWI is a model building technique that is increasingly being used in industry to yield ever more accurate quantitative models of selected subsurface parameter(s) (e.g. Virieux and Operto, 2009). In its most classical description, FWI uses a deterministic local procedure in order to minimise the difference between observed and forward-modelled data. Conceptually, FWI tries to match field data trace-by-trace and this is achieved iteratively through a succession of linearized updates to a best-guess starting model until convergence is reached (e.g. Virieux and Operto, 2009).

An alternative scheme to conventional local optimization FWI for resolving models of multi parameters may be use of a stochastic global optimization approach. Unlike the local optimization techniques which exploit only a restricted region of the model space taking into account its gradient and curvature, global methods avoid the calculation of the first- and second-order derivatives and the optimization strategy is not dependent on the initial models and they are less sensitive to local minima (Sambridge and Drijkoningen, 1992).

GA inversion

Genetic algorithms (GAs) are a subclass of evolutionary algorithms that mimic evolutionary processes and the natural selection of its biological counterpart (Holland, 1975). The GA framework consists of a variety of evolutionary operators (*i.e.* selection, crossover, mutation, and elitism) which operate in order to select the best candidate solutions, interpreted as individuals of a population, and through the evolution process find the optimum individual that best fits the recorded data.

We have developed a novel stochastic Full Waveform Fracture Inversion employing Genetic Algorithms (GA-FWFI) to quantify the mechanical properties of fractures which embodies WAVE to model the seismic data:

i) In the first step, an initial population of individuals (each individual is defined as a finite set of fracture parameters) is randomly generated within a defined search area;
ii) For each individual, a forward model is solved through WAVE and a misfit function is computed to quantify the discrepancy between the observed and modelled data using a L2 norm;
iii) From the actual population, the most successful individuals, according to the misfit function, are selected employing the 'tournament selection technique';
iv) Selected models are paired to create new individuals (also called offspring) and a random number of offspring is mutated to generate the new population in the following generation.
v) Steps ii)-iv) are repeated until the convergence is reached.

Synthetic sample with 6 horizontal fractures

We consider a synthetic square sample with a side length of 9 cm containing 6 fractures (Figure 1a). The fractures cut the sample horizontally from one side to the other. They are located from 2.88cm to 6.53 cm from the top of the specimen with a fracture spacing of 0.73 cm. The host medium is isotropic and homogeneous, and represents the laminated steel block in the experiment carried out by Pyrak-Nolte *et al*. (1990). The material density is 7750 Kg/m^3 with P-wave and S-wave velocity of 6023 m/s and 3254 m/s respectively. The normal fracture stiffness (K_n) values are bounded between $0.9{\cdot}10^{14}$ and $5{\cdot}10^{14}$ Pa/m while the shear fracture stiffness (K_s) values between $0.9{\cdot}10^{13}$ and $1.5{\cdot}10^{14}$ Pa/m, consistent with the values defined in Worthington and Lubbe (2007).
The acquisition geometry is illustrated in Figure 1a, which is composed of one single P-wave source on the top of the block and a line of 241 receivers on the bottom. The source wavelet is a Ricker with a peak frequency of 0.83 Mhz. The observed data related to the block in Figure 1a is shown in Figure 1b.

We then perform a global inversion to estimate 12 fracture parameters simultaneously - one normal and one shear fracture stiffness for each fracture - making use only of the transmitted energy.
The position and size of fractures, the material properties and the source function are fixed in the inversion process. The search space for the model parameters K_n and K_s is defined within the following bounds: $K_n \in [9{\cdot}10^{12}, 5{\cdot}10^{15}]$ Pa/m while $K_s \in [9{\cdot}10^{11}, 1.5{\cdot}10^{15}]$ Pa/m (Figure 2b).
The inversion process exploits a population of 200 individuals that evolve for at most 100 generations. To select the best individuals for each generation, we use a tournament size of 3 (3 individuals compete with each other to select the best of them), a mutation ratio of 0.1 (10% of the entire population is

randomly muted), and an elitism operator of 0.1 (10% of the best individuals of the previous generation are copied, unchanged, in the next generation).

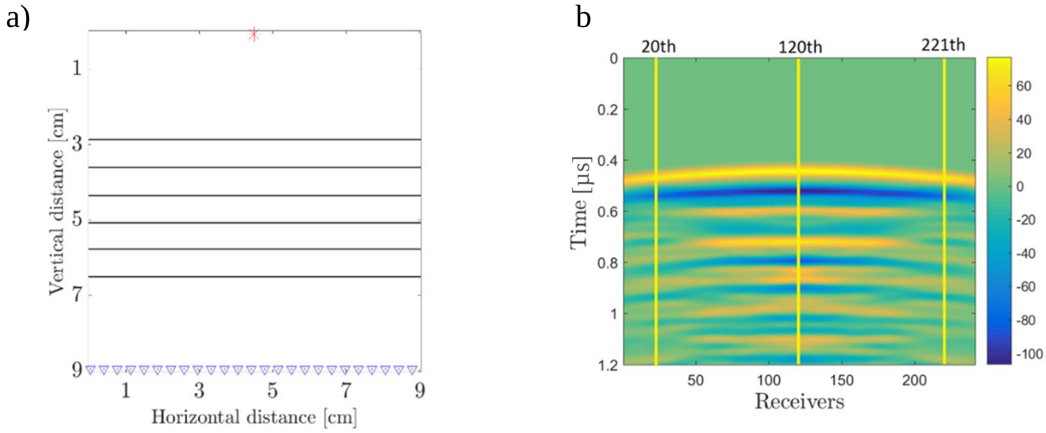

Figure 1 *a) Synthetic square sample with 6 horizontal fractures used in the experiment. Red star indicates the source location and blue triangles the receivers' locations. b) Observed velocity data modelled using the properties defined in the text for the sample in a). The yellow lines are the traces used to compute the residuals in the Figure 3.*

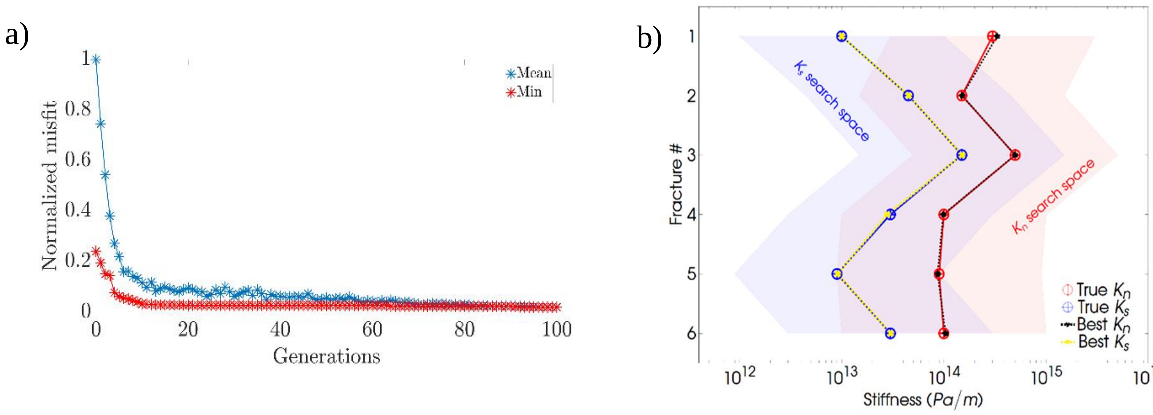

Figure 2 *a) The evolution of the normalized data misfit. b) Graphical representation of the comparison between the True and the Best model parameters of fractures. The shaded areas are the search spaces for Kn (red) and Ks (blue).*

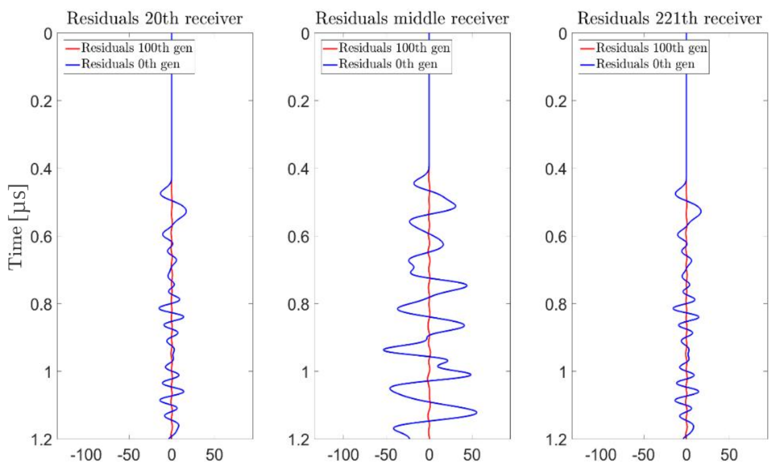

Figure 3 *The residual data related to the 20th, 120th, and 221th trace (from Figure 1b) of the worst model in the first generation (blue) and the best model in the 100th generation (red). The amplitude of the blue line is the same order of magnitude of observed data (Figure 1b).*

The evolution of normalized misfit is shown in Figure 2a. It illustrates that the convergence to the best solution is reached after 80-90 generations where the misfit hits values less than 10^{-3} with respect to the initial misfit value. The parameters obtained from the inversion and the true values used for generating the observed data are very close each other (Figure 2b) (errors less than 5% with respect to the true values). Figure 3 compares the residual data of the worst model in the first generation and the best model in the 100th generation, showing that the data have been fitted across the whole range of offsets.

Conclusions

We present a novel stochastic FWFI employing Genetic Algorithms to estimate some mechanical properties of fractures such as normal and shear fracture stiffness from a synthetic data in a simulated laboratory experiment. To account for the physics of scattering at individual discrete fracture we model the seismic data using a discrete fracture representation through the program WAVE. The inversion results show a good convergence to the best solution within the maximum number of generations set. Thus, the methods shows potential and robustness in estimating the fracture parameters from recorded seismic data with respect to the number of model parameters tested. Further development of the GA-FWFI code will be done to extend the inversion to other fracture parameters such as fracture orientation, position, fracture density. Furthermore, more tests need to be done to show the robustness to the noise in order to apply this methodology to real laboratory datasets.

Acknowledgments

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