Representing the seismic response of a fractured rock mass for nuclear waste repositories – effective and discrete fracture representations

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This is a fully-funded NERC-RATE studentship available to UK or EU candidates. It forms part of the consortium HYDROFRAME, studying hydro-mechanical and bio-geochemical processes in fractured rock masses in the vicinity of a geological disposal facility for radioactive waste. To apply, contact the lead supervisor (m.hildyard@leeds.ac.uk).

Project Summary:

Internationally, it is generally agreed that each country is responsible for storing its own nuclear waste and that the safest long term solutions are deep geological disposal in carefully engineered repositories. The geological barrier is intended as a secondary barrier to the engineered barrier and must maintain a very low permeability to fluids over the life of the repository if it is to ensure that no groundwater contamination can occur. Natural and stress- or temperature-induced fracturing will provide fluid pathways which increase the permeability of the rockmass and hence threaten the effectiveness of the geological barrier. We need to avoid or minimise such fracturing and be confident in our knowledge of the long term evolution of the fracturing. A key component of this is that we need the ability to confidently identify and properly quantify fracture systems. This is essential both for appropriately locating a repository, as well as for testing and understanding the evolution of fracturing.

Seismic and ultrasonic measurements provide information on fracturing through either the passive recording of acoustic emissions and microseismic waveforms generated during fracture formation, or through the changes to waveforms generated from either active or passive seismic sources due to interaction of the seismic waves with fractures. The changes caused by fracturing can be observed as changes in velocity, attenuation, or shear-wave splitting, but examining the full waveforms show that far more detailed mechanical knowledge of the fracturing is present and can be obtained (e.g. Hildyard, 2007). The key problem with detection and characterisation of fractures from seismic waves is ambiguity. Changes in seismic signals have multiple explanations. Low frequency seismic effects due to fracture size, fracture stiffness and fracture density are all inter-related, while attenuation and dispersion are caused both by scattering and damping mechanisms. This non-uniqueness leads to uncertainties affecting all parts of the evaluation process ultimately limiting the certainty of decisions made on it.

We need to be able to test our levels of detection and our capacity to quantify the mechanical nature of an underlying fracture system through seismic or ultrasonic methods. An obvious way of doing this is through numerical models where we can define a priori the underlying fracture state and then model the resulting changes to seismic waveforms. In addition to knowledge of the fracture systems we can also interrogate the model in manners not feasible in current acquisitions (for example in increased frequency bands, denser arrays, spatial waveforms) which can identify how acquisitions can be improved. Two types of forward models can be used to generate seismic waveforms in fractured rock. When fracturing is widespread and seismic wavelengths are much longer than the fracture lengths, the rock mass can be assumed to behave with effective elastic properties derived from a combination of the compliance in the rockmass
and compliance due to the fractures. Many of the seismic inversion techniques assume waveforms result from an effective medium representation of fracturing. Alternatively we can model fractures discretely as discontinuities with their own individual mechanical properties. This has a closer link to the physical behaviour of fractures but is far more computationally demanding. The increased computational effort may mean that we cannot represent a fracture zone with fractures at a small enough scale or with the same geometrical complexity that is evident in real fracture systems.

This project will study both discrete and effective representations of fracturing, and establish under what conditions each is most appropriate. The measure of this will be how well the models capture real effects on waveforms which can be measured and interpreted. This research will ultimately inform important decision making in the UK (and international) nuclear industry of how best to model fractures seismically such that they can evaluate and improve the effectiveness of in detecting and characterising fracturing. The research will also have impact in many other engineering applications where characterising fracturing is crucial due to the effect of fractures on the stability and permeability of rock, including mining, petroleum, and CO2 storage.

**Training:** The successful applicant will receive training in seismology, fracture mechanics, and numerical modelling. They will have access to and will be trained to use industry-leading software as a foundation of their research, and will learn to use university and national HPC computing facilities. They will present research at consortium meetings and meet other consortium members from University of Leeds, Imperial College, University of Birmingham, NERC and the NDA, and will have the opportunity to attend summer schools offered through the RATE programme. The student will be guided in the preparation and presentation of their research to academic, industry and policy audiences. Presentations at high-profile international conferences will be expected. Upon completion, the student will be well prepared for a career in industry or academia, with transferable skills allowing the student to independently contribute to the science and application of science in areas as diverse as nuclear repositories, CO2 sequestration, reservoir monitoring, and earthquake seismology.

**Funding:** The project is a fully-funded NERC-RATE studentship available to UK/EU candidates and forming part of the RATE HYDROFRAME consortium. The funding will pay tuition fees, a tax-free stipend, research training and support grant, for up to 3.5 years. For queries or to apply, contact the lead supervisor (m.hildyard@leeds.ac.uk).

**Contribution to NERC HYDROFRAME consortium:** This PhD studentship contributes to the consortium project HYDROFRAME, which is studying hydromechanical and biogeochemical processes in fractured rock masses in the vicinity of a geological disposal facility for radioactive waste. It will complement Work Package 3, “Seismic forward modelling of fracture response to inform survey design for repositories”. This work package uses extensive numerical modelling to examine the key seismic attributes for identifying fracture properties (e.g. fracture density, orientation and stiffness) that play a critical role in repository performance. The numerical results will be used to design optimal seismic acquisition parameters to enhance seismic observation of large-scale and sub-seismic scale fracture systems that will enable quantification of storage risks associated with potential fracture reactivation and/or contamination of groundwater.

**Candidate:** Candidates should have a background in either geophysics, seismology, applied mathematics, physics, or engineering.
Further Details: One method for modelling the seismic and geomechanical behaviour of fractured rock is to use an equivalent medium representation of the underlying fracture network (e.g. Sayers and Schoenberg, 1995; Zhang et al, 2009). While much has been achieved with these methods, there are limitations such as the applicable frequency range, the types of fracture properties which can be studied, and non-uniform influences, for example due to the stress field. The alternative is to model fracture networks explicitly with discrete fractures, wherein actual boundary conditions are used to encapsulate individual fracture behaviour. This approach readily allows the models to capture complex behaviour such as the influence of stress state (Fig 1, Hildyard, 2007), as well as specific fracture properties such as fracture size, filling and stiffness. In this case, rather than being prescribed, the gross behaviour becomes an emergent property of the combination of individual fractures (Fig 2). Fracture networks with tens of thousands of explicit fractures have been modelled using these methods, successfully encapsulating various emergent properties of these fracture networks (Fig 3, Pettitt et al., 2005; Hildyard and Young, 2002; Hildyard, 2007).

Representing discrete fractures is however numerically intensive if realistic fracture networks are to be studied. The purpose of this project therefore is to establish the most suitable representations of fracture networks for describing seismic and geomechanical behaviour for nuclear waste repositories. In particular, it will explore and determine under what conditions effective medium representations encapsulate sufficient detail of the effective behaviour of the fracture networks. It will do this through comparison of models with explicit fractures with their effective medium representations. The project will primarily use the finite difference code WAVE3D, and will use 3DEC (Itasca) to study more complex and realistic geometries of fracture networks. Ultimately, this work will inform the design of acquisition strategies that enhance observations of seismic attributes sensitive to fracture systems.
References


3DEC (http://www.itascacg.com/software/3dec )