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Numerical simulation and development of data inversion in borehole ultrasonic imaging

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ABSTRACT

The major function of underground nuclear waste disposal is to avoid the migration of radionucleides towards the biosphere during their active period. This function can be deteriorated by the EDZ (excavated damaged zone) around the excavation. The EDZ analysis is therefore crucial in the performance assessment of the storage. The paper deals with the determination of the EDZ around a nuclear waste storage cavity using borehole ultrasonic imaging (azimuthal tomography). Indeed, before processing experimental data obtained with this tool, it is necessary to establish that data can be satisfactorily inverted. This analysis is based on a method that is able to sound and image the rock mass velocity field. The velocity field is numerically simulated (3D geomechanical modeling) based on an assumption on the relationship between stress and velocity fields. In order to evaluate a radial velocity profile starting from inter-sensor distance and their corresponding traveltimes, different ray tracing algorithms are tested using synthetic data. These tests led to a simple and fast approach (implemented in a Mathematica package) to process a large quantity of data.
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1. Introduction

Complex mechanical phenomena related to damage occur during the excavation of deep underground galleries. In the framework of nuclear waste repositories, the knowledge of rock characteristics is important to appropriately estimate the efficiency of the storage. Damages to galleries and shafts are not easy to anticipate because of uncertainties related to the stress field, in-site rock properties and lithology effects. The monitoring of the ultrasonic wave propagation has demonstrated its capability to indirectly observe the initialisation and the extent of damage in a previously undisturbed zone (Carlson and Young, 1993, Forney, 1999; Pettitt et al., 2004). Ultrasonic waves are also strongly influenced by the stress field. So, the determination of the velocity field in the rock vicinity of an excavation provides knowledge on the rock mechanical state, especially as the ultrasonic methods are non-destructive.

The ultrasonic tomography imaging is used to characterise the velocity field. Direct wave traveltimes are measured on a sufficient number of ray paths and inverted to reconstruct the velocity field. The data inversion is based on an iterative procedure starting with an initial velocity discretized model modified to fit the observed ray traveltimes as well as the reconstruction of the best corresponding ray paths (Dines and Lytle, 1979; Peterson et al., 1985; Cote and Lagabrielle, 1986). Several types of errors appear in the application of the tomographic methods in laboratory or in situ: (1) spatial error on the positions of blasting and sensors, (2) temporal error due to detection of arrival of waves; and (3) error due to ignorance of the wave travel paths.

The restriction and the estimation of this third error source are important for the quality of the sounding and play an essential role in the assessment of the velocity uncertainties. Starting from an initial velocity model, to find the path connecting a source to a receiver, all the paths passing by this pair are explored systematically, to converge with the minimum traveltime. Specific methods have been developed to reconstruct those ray paths. The principal ones are based on iterative and convergent algorithms (Wesson, 1971; Julian and Gubbins, 1977; Um and Thurber, 1987; Gautier, 1991; Zhao, 2001).

Geotechnical applications for tomography imaging are relatively new. Bois et al. (1972) realised the first tomography inversion of crosshole data for petroleum exploration. Mason (1981) and Kormendi et al. (1986) used the algebraic reconstruction algorithm to image stress-induced velocity anomalies in an underground coal mining environment. In Hungary, Kormendi proceeded with sequential stress monitoring during a coal seam excavation. Mason and Kormendi both deduced, from computed velocity pictures around excavated galleries, a link between velocity changes and stress changes. However, they have not been able to define a direct relationship between in situ stress measurements and seismic velocities.

Ultrasonic tomographic images have also been taken around underground structures in order to explore the damaged zone

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(Maxwell and Young, 1996, Forney, 1999, Balland et al. 2009). To get a good resolution, it is however necessary to implement significant resources with a large number of sensors and boreholes. Hornby (1993) has demonstrated that it is possible to reconstruct the velocity field in a plane longitudinal to a borehole. Winkler (1996) has highlighted azimuthal velocity variations due to the stress anisotropy and the associated damages around a borehole and has developed, with Winkler and D'Angelo (2006), an ultrasonic imaging method of the wall.

In the present paper, the authors explain a method for characterising rock media through the measurement of the P-wave ultrasonic velocity field in the rock around the borehole. The principle of this method is to rebuild the velocity field around the borehole with 3 axes of freedom to cover the entire volume around the borehole. This includes distance between the pair of sensors, orientation of the device around the borehole wall and location of the device in the borehole (i.e. borehole axis). The method relies on two main hypotheses. First of all, rock volume is assumed to be without heterogeneities in the axial direction, so all velocity changes are supposed to be created only by the excavation effect and EDZ extension is assumed to be proportional to cavity radius (borehole or gallery). The second hypothesis is an arrival time between the pair of sensors that increases monotonously while the sensors distance is greater. The larger the sensors distance the larger the sounded rock velocity: proportionally, the arrival time increases less quickly than the inter-sensor distance.

The final objective of this research is to determine the damaged zone characteristics of a borehole to estimate those of the galleries or shafts with similar configurations. Here we assume the behaviour of a borehole is similar to the behaviour of larger excavations with respect to the extent of damaged zone, location and orientation.

The aim of tomography sounding is to provide an overall visualisation of the spatial and intensity distribution of the damaged zone around an excavation (gallery, borehole, shaft, etc.). The frequential domain of the mechanical waves was selected to be as high as possible because the damage phenomenon has to be represented in a small scale phenomenon (since the wave propagation is sensitive to heterogeneities whereof the scale is similar to the wave length). Thus, tomography needs to be in the ultrasonic domain and the sensors must be piezoelectric transducers. It is proposed to use a purely mechanical source with small wave length in order to reach the specific scale of damaged heterogeneities.

In the Underground Research Laboratory (URL) of Meuse/Haute-Marne located at Bure, ANDRA (the French National Agency on Nuclear Waste) carried out a gallery excavation evaluation at a depth of −490 m, which is the main level under experimentation. Requested by ANDRA, geophysical investigations have been performed by INERIS researchers, who have implemented an ultrasonic tomography experimental program. The excavated damaged zone around a nuclear waste storage cavity is to be examined using borehole ultrasonic imaging. It is necessary to establish that useful data are likely to be recorded with this tool (Balland and Renaud, 2009) and that the data can be satisfactorily inverted. The first aspect of this program focuses around a vertical single borehole at the roof of URL gallery.

This paper presents the design engineering, and the feasibility and dimensioning study of the ultrasonic tomography experimentation. It mainly deals with the following topics:

- the estimation of the velocity field starting using both a mechanical modelling of the environment around the borehole and laboratory test results;
- the optimisation of the measurement devices based on the specificity of the argillaceous rocks, the field experience feedback, and methodologies for inversion of the ultrasonic data.

2. Velocity field estimation around the gallery

2.1. Method

As the velocity field around an excavation in Callovo-Oxfordian argillaceous rock is not yet known, an empirical approach is proposed in this paper, based on modelling after extrapolating the results of experiments on samples in a controlled laboratory condition. Laboratory tests are performed to measure the mechanical parameters and P-wave velocities under applied and controlled stresses. The main idea is to obtain a relationship between velocity and a mechanical characteristic. It is then possible to represent an empirical estimate of the velocity field around the excavation in order to study and to optimise the measurement device on site.

The most direct way to link the velocity field to a mechanical characteristic is to establish a relationship between measured velocities and the strain tensor (because the strain variations are more significant than the variations of stresses in the vicinity of the failure peak). However, in the post-failure phase, the precise measurement of the strains by gauges is no longer possible (gauges being broken, nevertheless, LVDT sensors placed directly on the servo-controlled machine make strain monitoring possible), whereas the stress measurement (via the applied forces) is always operational. The relationship between strain and P-wave velocity highlighted during the tests on argillaceous rock is more dispersive than for the stresses and P-wave velocities. This is why an empirical relation between the stress tensor and P-wave velocities has been employed. This type of relation was clearly highlighted in the literature (Nur and Simmons, 1969; Lockner et al., 1977).

However it should be noticed that the empirical relationship between velocity and stress variations relies only on very little experimental data, which is not enough to define a true model of velocity variations around the excavation. Moreover, these data on samples were obtained during triaxial compression tests, i.e. under conditions of loading not exactly representing the stress state expected around the excavation. In fact, the rock can be subjected to other stress paths (lateral extension for example). Thus, the numerical model presented in this paper gives a reasonable estimate of the amplitude of the expected velocity variations, which cannot be representative of the velocity distribution around the excavation. This is, however, sufficient in the light of our main objective: to assess damage extent (proportional to velocity variations) around a structure in a nuclear waste disposal context.

2.2. Numerical model

A vertical borehole is supposed to be located at a gallery roof (at the main laboratory level: −490 m). A first numerical model (including meshing of gallery and borehole, Fig. 1) showed that the gallery excavation effect (with respect to stress, strain and thus velocity) is negligible after a distance of 6 m from the road head. This is why the bottom of the measurement device will have to be placed at more than 6 m (vertical distance) from the gallery roof (Fig. 1). The borehole has a radius of 38 mm. The vertical stress at this depth is estimated at 12 MPa and is supposed to be a principal stress. The initial stress state is homogeneous (no variation due to gravity). According to Ben Slimane (2002), K_H (ratio between the major horizontal stress and the vertical stress) varies between 1.2 and 1.4. The models consider a maximum ratio of 1.4 (the most unfavourable case).

The selected elastoplastic model is noted EPE (Souley et al., 2003), where the damage is modelled through a positive work hardening and the post-rupture failure behaviour by a negative work hardening. The failure criteria and damage initiation criterion are based on the modified Hoek–Brown criterion (Su, 2002).

In the view of a significant damage extension around the modelled borehole, the selected parameters are the average values corresponding to the model residual strength.

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