Ultrasonic sounding and monitoring of the excavation damaged zone in relation with drift support

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SUMMARY

Under high in situ stresses, the excavation of underground openings generally causes the creation of a disturbed (EdZ: Excavation disturbed Zone) and/or damaged (EDZ: Excavation Damaged Zone) zone, resulting from the initiation and growth of cracks and fractures and from the pre-existing stress redistribution. The EdZ or EDZ changes the mechanical and hydromechanical properties which in return, constitute a potential risk for the performance of the geologic and/or engineered structures in the context of waste underground storage. Ultrasonic experiments have been implemented to characterize the EDZ extension around drifts and its evolution in time according to the structural support type (soft or rigid) and the environmental conditions. Those studies consist of two experimental components: (1) the prior auscultation of the floor and sidewalls of the gallery by ultrasonic transmission tomography, (2) the monitoring of the time-dependant evolution of EDZ and the analysis of measurable changes in the propagation of ultrasonic waves in the medium term. A code for computing these continuous in situ velocity measurements into the elastic has been developed. Then, the five dynamic elastic constants for the assumed transverse isotropic character of the rock are derived as a function of time and the distance from the drift wall. Performed a few months after the excavation of the galleries, the tomography shows that ultrasonic velocities are higher in the orthoradial direction (both in the concrete support and rock). This velocity field highlights clearly the damaged zone and induced stress shift.

Key words: damaged zone, ultrasonic, tomography, velocity survey

INTRODUCTION

Tunnel excavation in Callovo-Oxfordian argillites produces a damaged area called EDZ (Excavation Damage Zone) which depends primarily on the physical properties and the mechanical behaviour of the host rock and the initial stress field. The nature of this area has been observed many times in underground laboratories (Maxwell and Young 1996, Balland et al. 2009). The goal is now to study its evolution over the intermediate term and more specifically about the ability of the rock to return or not towards its initial state depending on the selected support.

In this context, Andra carried out the OHZ experiment (Observation of the hydromechanical behavior and EDZ), which aims in particular to monitor the evolution of two galleries oriented in the direction of the major horizontal stress, one equipped with a soft design support (bolts, shotcrete and yieldable wedges) in the GCS drift and the other with a support of rigid design for GCR drift, same as the GCS support but with a concrete ring (**Figure 1**).

The task of INERIS in this experiment was to characterize the damage around these two galleries by ultrasonic tomography sounding and then to monitor its evolution by analyzing the propagation of ultrasonic waves in the rock. Measurements were performed in an identical configuration for both drifts. The ultimate goal was to compare the evolution of the EDZ in these two cases.

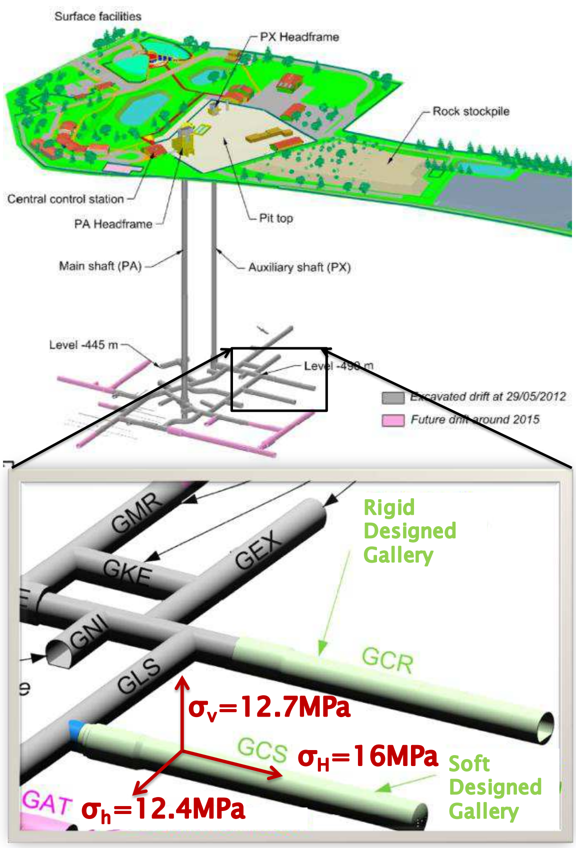

Figure 1: Plan of the underground laboratory of Meuse / Haute-Marne and experimental galleries

DEVICE AND METHOD

Two devices were selected (**Figure 2**):

• a triplet of facing horizontal drilling in the gallery side, extending to 3 m depth, with two holes 30 cm apart (about 25 cm between sensors) located in the same facies (OHZ 1841, 1842 and 1843);

• a pair of vertical boreholes in the middle of the floor of the gallery (OHZ 1844 and 1845).

Sensors chosen are best suited to clays encountered. P-wave sensors of R6 type (Mistras) have a 60 kHz bandwidth centred response chosen as compromise between the Fresnel zone (corresponding to the influence zone of the wave train) and attenuation of high frequencies in argillites. For S-waves, the sensor of SH6 type has been specifically developed to produce a pulse in the same P-wave frequency scale. The acquisition system (Pettitt et al. 2005) consists of three main components:

• the data acquisition unit trigering and recording on ;
• the sensor interface unit, which manages the multiplexing and sensors alternatively used as emitters or receivers;

The acquisition system enables particularly the transmission and recording of the waves in the active mode.

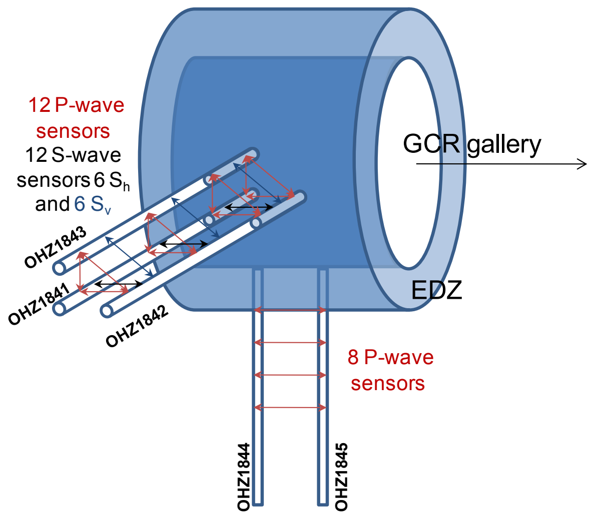

Figure 2: Ultrasonic device installed around the galleries.

RESULTS

Velocity field anisotropy

Figure 3 and **Figure 4** present four stereonets computed from all velocity measurements for the three tomography planes in the GCR drift sidewall. Each stereonet corresponds to areas of interest selected the tomographic images: the ring of cast concrete, shotcrete, damaged rock (EDZ) and finally the undisturbed rock.

In the undisturbed rock (Figure 4), the velocity field shows mainly transverse isotropy as expected for the argillites (Ghorbani et al. 2009), the axis of isotropy (or main direction of the lowest P-wave velocity) does not seem vertical. It rather dips northeast-east in the direction of the minor horizontal stress (N65°). Stereonet also shows anisotropy in the horizontal plane with the main directions of velocity close to those of the stress field, what might emphasize the impact of the stress field. The same anisotropy scheme, but amplified, is observed in the EDZ. In that case, the velocity field is mainly disturbed by preferential fracturing at gallery side along the axis of the major horizontal stress, as was observed on the boreholes cores. It might also be influenced by stress redistribution around the drift.

The velocity stereogram in shotcrete (**Figure 3**) is rather heterogeneous and therefore does not show well defined anisotropy. On the contrary, the concrete ring shows a marked anisotropy in the direction of the gallery itself i.e. in the direction of the major horizontal stress. The highest velocities are measured on the tangential raypaths to the gallery. The question is therefore whether this velocity anisotropy of the concrete ring is intrinsic (structure, installation, sealing ...) or due to mechanical loading.

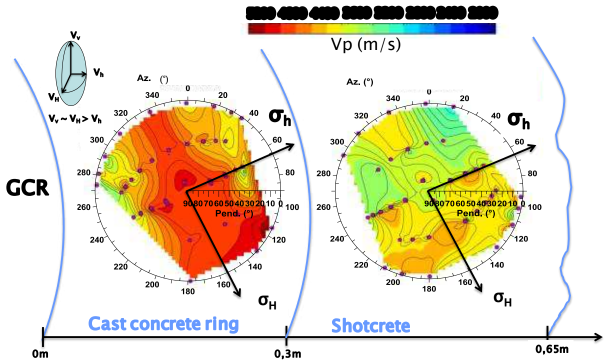

Figure 3: Stereonet in support.

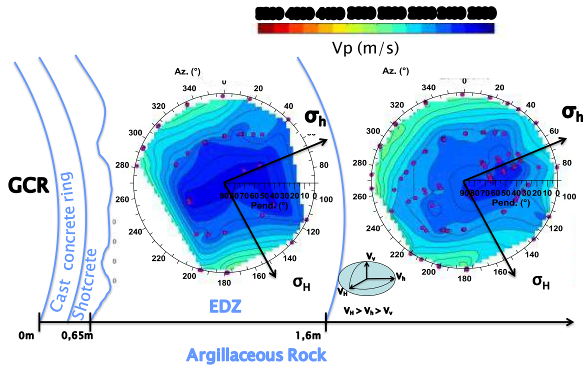

Figure 4: Stereonet in rock.

Tomography

The acquisition of the tomographic data (**Figure 5**) has been carried out both through the concrete (65 cm thick) and the rock. P-wave velocities, calculated from the arrival time, vary from 2000 to 5000 m/s. However, these velocities are well differentiated between concrete and rock. In argillites, they vary in a range comparable to previous experiments (2000 to 3500 m/s). The concrete itself is differentiated by the ultrasonic velocities ranging from 3500 m/s and 4500 m/s in the shotcrete and around 5000 m/s in the concrete ring. These first images of the velocity field clearly show the contrast between the rock and the two types of concrete.

The tomographic images were then corrected for anisotropy calculated in each plan except for the horizontal plane where no natural anisotropy is expected in the argillites. Anisotropy correction takes into account only the anisotropy found in the rock. This correction was also applied to the concrete (the device does not allow to discriminate the anisotropy in different areas). The velocity scale was adjusted to reflect only the velocity range observed in the rocks (1600-3500 m/s). The image is saturated in concrete areas because the velocity is over this scale. The purpose of these images is mainly to identify the velocity variations in the rock. The 3 tomographic panels show lower velocities in the rock near the shotcrete. In the first 30 cm of rock (0.6 m to 0.9 m depth from the face of the gallery), the velocities are very low (less than 2000 m/s) and then gradually increase up to 1.2 m deep (0,6 m in the rock). This area may be associated with the EDZ generated during excavation of the gallery. Another area between 1.6 and 1.9 m (1 to 1,3 m in the rock) deep with low velocities can also be identified. This anomaly is especially well marked in the horizontal plane between 1.7 and 1.8 m depth. This anomaly can be associated with an isolated crack observed before the experiment in three horizontal boreholes.

Inversion of wave velocities data in GCR drift

A code for the inversion of these continuous in situ measurements of five elastic wave velocities (i.e. $V_P(0°)$, $V_{Sh}(0°)$, $V_P(90°)$, $V_{Sv}(\theta)$ and $V_P(\theta)$, where θ is off-axis) has been developed with the help of *Mathematica* software. Then, the five dynamic elastic constants for the transverse isotropic character of the argillites (assumed in this paper) are derived as a function of time and the distance from the gallery wall. From these elastic constants, some indicators of damage rate were proposed with respect to the space and the time. Finally, in addition to the experimental data analyses, synthetic data (generated from the given elastic constants and velocities derived from the theoretical formulation) as well as data from literature (measurements of ultrasonic velocities in the laboratory on samples) allowed us to successfully evaluate the consistency of the results obtained with this program.
Indeed, the measures of wave velocities performed on samples (resulting from cores drilled in the vicinity of the experiment area) in laboratory showed that the average values of modules perpendicular (E1) and parallel (E2) to the stratification and the shear modulus in the anisotropic plane (G12) are respectively 7, 10 and 4.5 GPa. The inversion of the first measures of velocities recorded in situ give the values of 4, 8 and 3.8 GPa for E1, E2 and G12 near the wall (at the distance of 0,5 m from the gallery wall). They are 7, 12 and 4.4 GPa at 3 m of the wall (in the undamaged domain). The next stage will consist in analyzing all the in situ measures with respect to the space around the gallery and the time.

CONCLUSIONS

Ultrasonic tomography measurements were performed successfully in argillites around a rigid support drift. Tomographic measurements highlight the damaged zone of the rock on gallery side. The lower velocities may be due to fracturing or preferential opening of fractures parallel to the gallery, in agreement with visual observations on drilling core. Finally P and S wave velocities was traced back to the stiffness matrix versus depths, in the rock. However impact of the anisotropy in stiffness computation must be verified because the method is based on the hypothesis that the rock presents a purely transverse anisotropy and we highlight that is not entirely true.

More generally, ultrasonic tools and methods associated with the inversion of the velocity field is an interesting approach to investigate the performance of the rock face and the support of the deep mining structures (drift or shaft). It can provide both diagnosis and monitoring of the EDZ. It can then help to detect unexpected breakage or damage of the structure support and then prevent associated risks

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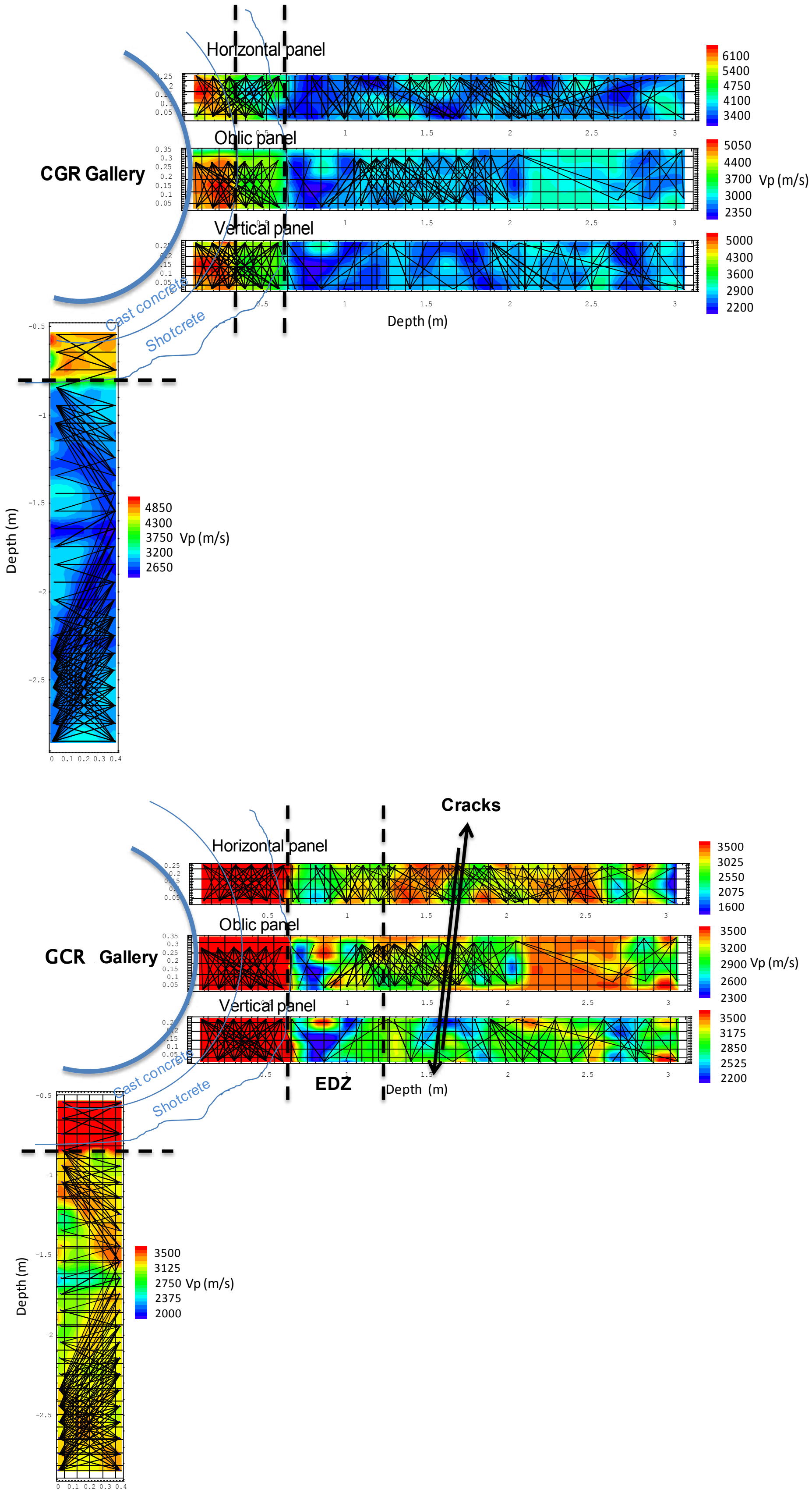

Figure 5: Tomographic panels around the rigid supported gallery with two different Vp scales.