



## Specialized instrumentation for hydromechanical measurements in deep argillaceous rock

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**ABSTRACT:** Within the framework of the feasibility study for a radioactive waste repository in a geological formation, the National Radioactive Waste Management Agency of France is constructing an underground research laboratory within the Callovo-Oxfordian argillite formation located in eastern France. During the sinking of the laboratory's access shaft and during excavation of the galleries, the mechanical and hydromechanical behavior of the argillite was monitored. A vertical mine-by test was carried out at depths between 460 m and 476 m in the main shaft. 12 boreholes were drilled downwards from a niche, where deformations and pore pressures were monitored. Another 11 boreholes were instrumented with mechanical and hydraulic sensors in the galleries. This paper is devoted to the instrumentation, the installation procedures and some first measurement results regarding the mechanical disturbance of the rock around the shaft.

### 1 INTRODUCTION

Investigated by the National Radioactive Waste Management Agency (Andra) within the framework of a feasibility study on a radioactive waste repository, the Meuse/Haute-Marne site is located in eastern France, some 300 km from Paris. The host formation consists of Callovo-Oxfordian argillites and is approximately 500 m deep and 130 m thick (Andra, 2005a). The Callovo-Oxfordian argillites are overlaid and underlain by relatively impermeable carbonate formations. The argillites contain an average of 40-45% clay minerals (illite, regular mixed layer R1 illite-smectite, chlorite and kaolinite in the lower part, illite and irregular mixed layer R0 illite-smectite in the upper part), 20-30% carbonate and 20-30% quartz silts (Andra 2005b). The mechanical behavior of the investigated rock is governed by the geological characteristics of the argillites. Mineralogical composition and sedimentation have led to a slightly anisotropic behavior of the argillites. The combined effect of sedimentation, compaction and diagenesis has reduced the interstitial or connected pore space. Hence, the Callovo-Oxfordian argillites in their natural state are considered a saturated porous medium with very low permeability.

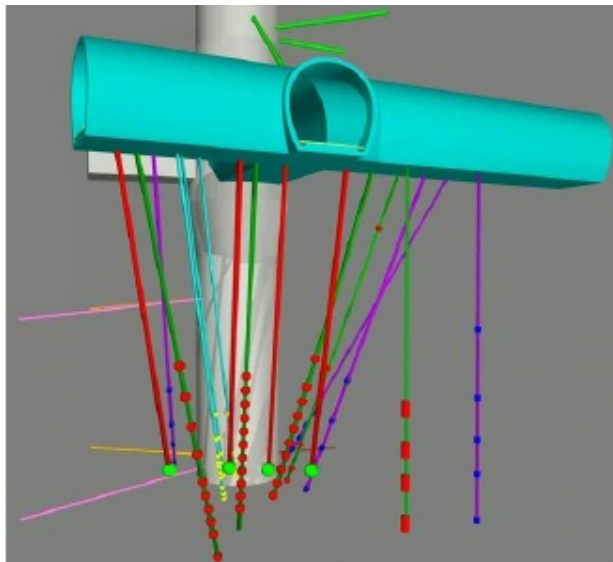
Their mechanical behavior is closely coupled with the pore pressure and the degree of saturation. From a geomechanical point of view, the host layer is subdivided into three levels with significant contrasts in mechanical behavior. In order to demonstrate the feasibility of a radioactive waste repository in the argillite formation, Andra started to construct an underground research laboratory (URL) in 2000 in the village of Bure, near the boundary of the Meuse and Haute-Marne departments.

Within the framework of the research carried out at Bure, the goal of the REP experiment was to characterize the hydromechanical behavior of the argillites during the sinking of the access shaft. Solexperts designed and installed a certain number of specific equipment for the successful completion of these measurements. The present article describes the different equipment; in particular those used for the measurement of hydrostatic pressure, and also present some of the first results.

## 2 EXPERIMENT DESIGN

The experiment was organized into four phases:

- The construction of a niche at a depth of 445 m, the starting point of the experiment.
- The instrumentation of boreholes from the niche, in order to monitor the geomechanical characteristics of the matrix. Wait for the stabilization of measurements, especially hydrostatic pressure.
- Resumption of the excavation of the shaft, monitoring the geomechanical parameters of the matrix in real time. Excavation is carried out with explosives by sections of 2 to 3.1 m.
- Instrumentation from the shaft in the excavation process.



**Fig. 1: Layout of the REP experiment**

### 3 EQUIPMENT

Hydrostatic pressure and permeability measurements in clay formations with low permeability at depths of 500 m require the implementation of equipment capable of assuring the fastest possible return in pressure, long-term stability, and of being resistant to strong pressures (up to 100 bar). The carrying out of the experiment during the construction phase, with production deadlines for excavation, also presupposes the use of robust and reliable equipment.

#### 3.1 Hydrostatic pressure measurements in the matrix

Hydrostatic pressure measurements are carried out with the aid of a specific multi-packer system called the PP system (Pore Pressure System).

The system allows the definition of up to 5 measurement intervals in the same borehole. Each 20 cm interval has two stainless steel lines connected to a control panel placed on the surface. A pressure sensor mounted on one of the line allows the continuous monitoring of variations in pressure, while the other line allows the running of hydraulic tests (pulse, injection, production). The volume of the chamber is reduced to the maximum in order to assure the rapid stabilization of pressure. Each interval is insulated with the aid of a section of resin in the annulus of the borehole. The resin assures great, long-term stability as well as very low system compressibility. The resin is put in place after isolated the measurement interval with a mechanical packer.

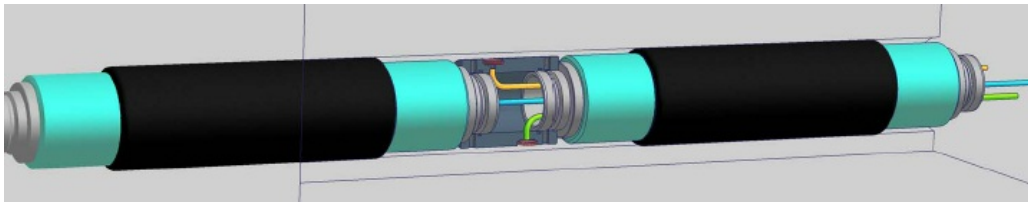


**Fig. 2: PP system**

Three core boreholes, 25 m in length and 101 mm in diameter, are drilled from the niche. In each borehole, a PP packer system defines 5 measurement chambers, distributed around the shaft at a distance of between 1.08 m and 4.88 m from the theoretical walls and at a depth of 460 m and 476 m. The chambers of borehole REP2101 are located in the direction of the maximum stress in relation to the shaft, while those of borehole REP2102 are located in the direction of the minimum stress. The chambers of borehole REP2103 are oriented principally in the direction of the major stress in relation to the shaft, except one, which is located closer to the direction of the minor stress. A fourth borehole, REP2104, located in an area that is little influenced by shaft at 13.8m from the wall, acts as a reference measurement for pressure and permeability.

### 3.2 Permeability measurements around the shaft

In order to study the impact of excavation and the variations in permeability due to the development of the EDZ, permeability tests are carried out during excavation. These measurements complement the permeability measurements carried out before and after the excavation in the multi-packer system PP (cf. the preceding chapter). In the course of excavation, the permeability measurements are carried out in proximity to the wall, thus it is necessary to use intervals that are close to one another and adjustable. For that reason Solexperts designed the MMPS system (Mini-Multi-Packer-System), which allows the definition of 5 to 6 chambers 10 cm to 20 cm in length. Each chamber is isolated by a packer inflated with water. The volume of the chambers is reduced in order to assure the rapid stabilization of pressure, and the rigid packers limit the compressibility of the system. Two stainless steel lines allow continuous monitoring of pressure and the running of pneumatic and hydraulic tests. The system is designed with easily interchangeable parts.



**Fig. 3: MMPS System**

During the excavation of the shafts, two sections were studied at depths of 467 m and 479 m. In each case, hydraulic tests were conducted in a horizontal radial borehole 56 mm in diameter and 6 m in length drilled from the bottom of the shaft. An MMPS system defining five chambers centered 0.35 m - 0.85 m - 1.35 m - 2.85 m - 5.85 m from the wall was used for these two boreholes. After drilling the borehole, the system is installed, the packers are inflated and then the gas and water tests are carried out. At the end of the tests the system is removed. A PP-type system with a chamber is then implemented for long-term monitoring of hydrostatic pressure. The MMPS system is then used again for the next boreholes. The MMPS system and an appropriate procedure test allow short deadlines to be met for making the shaft available for experiments.



**Photo 1: MMPS Installation in a borehole**

### **3.3 Deformation measurements**

#### *3.3.1 Measurements in the rock around the shaft*

The deformation measurements of the matrix are carried out with two ten-point extensometers and a permanent ten-point inclinometer chain, installed before excavation in the inclined boreholes drilled from the niche.

The 24.55 m and 29.11 m length extensometers measure the deformations between 10 evenly distributed anchors and a measurement head placed in the niche. The first anchor of the 24.55 m extensometer is 0.48 m away from the shaft and the tenth is 11.08 m apart.

The inclinometer chain, specifically developed for this purpose, comprises 1 m components for a borehole inclined at 18°. The inferior measurement point is located at a distance of 0.5 m away from the shaft. The chain's design assures the complete continuity of measurements between each component thanks to a particular ball joint comprising a support point for two consecutive components.

#### *3.3.2 Extrusion measurements*

A vertical borehole 34 m in length located in the shaft axis is equipped with a Sliding Micrometer tube. Manual measurements, carried out after each excavation phase, provide a complete profile of the axial deformations (extrusion) of the massif, precise to 3 micrometers per meter measured. The damage to the measuring tubes caused by the blasts disrupted some measurements.

## 4 RESULTS

The deformation measurements of the REP2202 extensometer are reported in Figure 4. The measurements, stabilized before the resumption of excavation, show a compression phase before the passage of the tunnel front, connected to the extrusion of the massif, followed by an extension due to shaft convergence after the passage of the tunnel front. The maximum measured compression between anchors 1-10 is 3 mm just after the passage of the tunnel front. With each blast, an instantaneous displacement is measured over the extensometer. During mucking, the recorded displacements are lower in amplitude. When the shaft reached a depth of 480.3 m, increments of instantaneous displacements start very low, but an increase varying between 0.5 mm and 0.8 mm was observed between 15 July and 1 September 2005. The displacements measured during that period are not induced by the shaft sinking itself, but rather to shaft convergence (creep behavior). Armand et al (2006b) show that a 3D elastic model taking into account an in situ stress anisotropy of 1.3, well predicts the deformation in the direction of the major horizontal stress during the excavation. However, the displacement magnitude is well predicted until the end of June where displacement is mainly due to creep.

The pressure measurements were practically stabilized before the resumption of excavation. Each blast induced an immediate variation in pressure in the intervals, in which the amplitude varies according to the distance to the shaft. In the case of borehole REP2101 (Figure 5) a fall in pressure was observed after each blast, while borehole REP2102 (Figure 6) shows suppressions as long as the tunnel front was located in front of the chamber. After the passing of the tunnel front the pressure falls in all the chambers. This behavior is consistent with a poroelastic model of shaft excavation in a state of anisotropic stress (Armand et al 2006b). The strongest suppressions were in effect observed in the chambers closest to the direction of minimum horizontal stress, while the greatest falls in pressure were observed in those closest to the maximum horizontal stress.

The extrusion measurements (Figure 7) completed progressively after each excavation phase, show an excavation influence distance of 6 m to 9 m in the shaft axis with a maximum extrusion amplitude of 4 mm. A contraction of several millimeters was also observed on the first meter of the gallery bottom, connected to the compression caused by the blasts.

A series of hydraulic pulse tests were conducted in hydraulic chambers first in the REP boreholes and then after shaft sinking in the same boreholes with the additional radial borehole at a depth of 467 m, in order to account for disturbances induced by excavation. Figure 5 shows the evolution of the estimated permeability to water with error ranges, measured before and after excavation in the near field of the shaft. The permeabilities measured with the MMPS system during excavation are consistent with those measured with the PP system. It shows that permeability increases after excavation up to one order of magnitude near the wall. This increase progressively diminishes with distance from the wall.

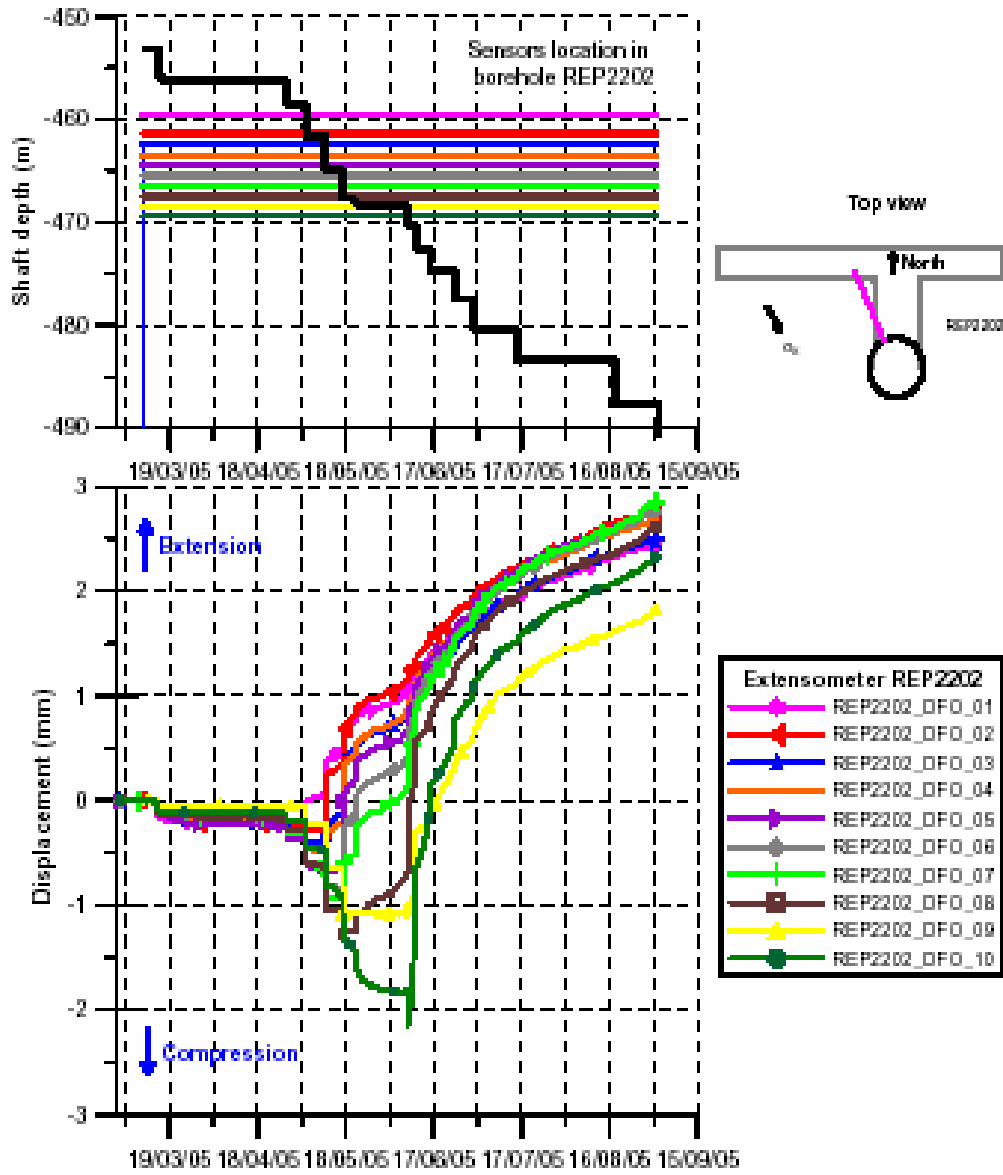


Fig. 4: Measured displacement in REP2202

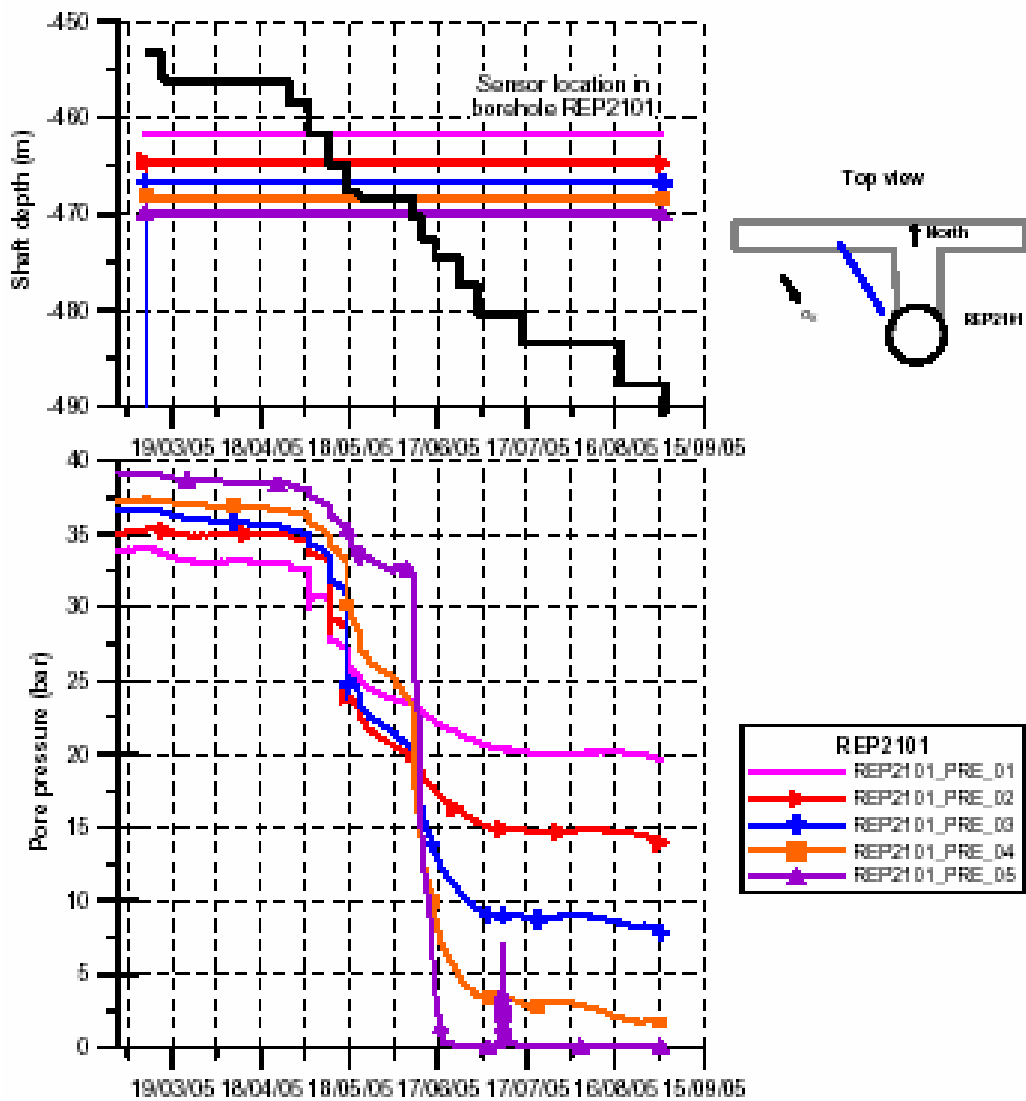


Fig. 5: Evolution of pore pressure in REP2101



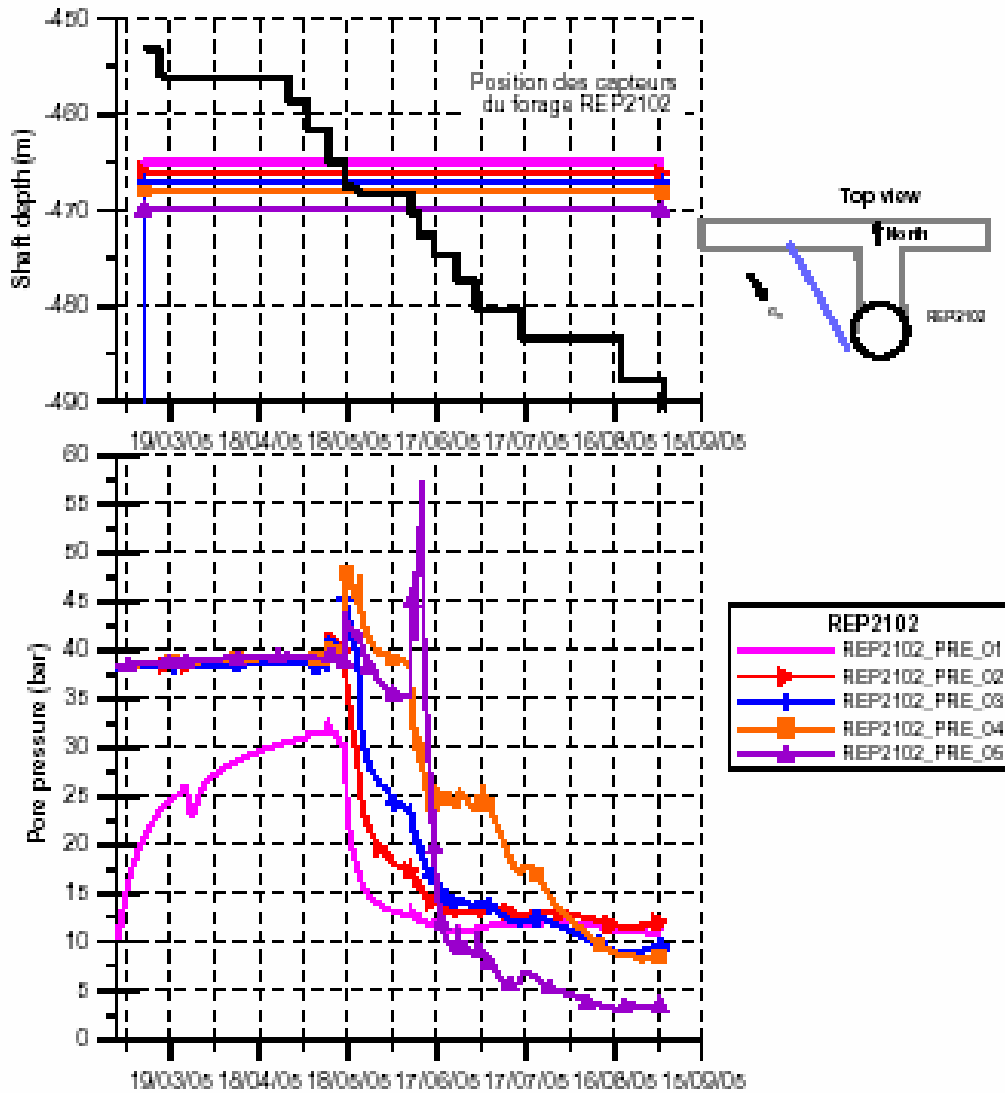


Fig. 6: Evolution of pore pressure in REP2102

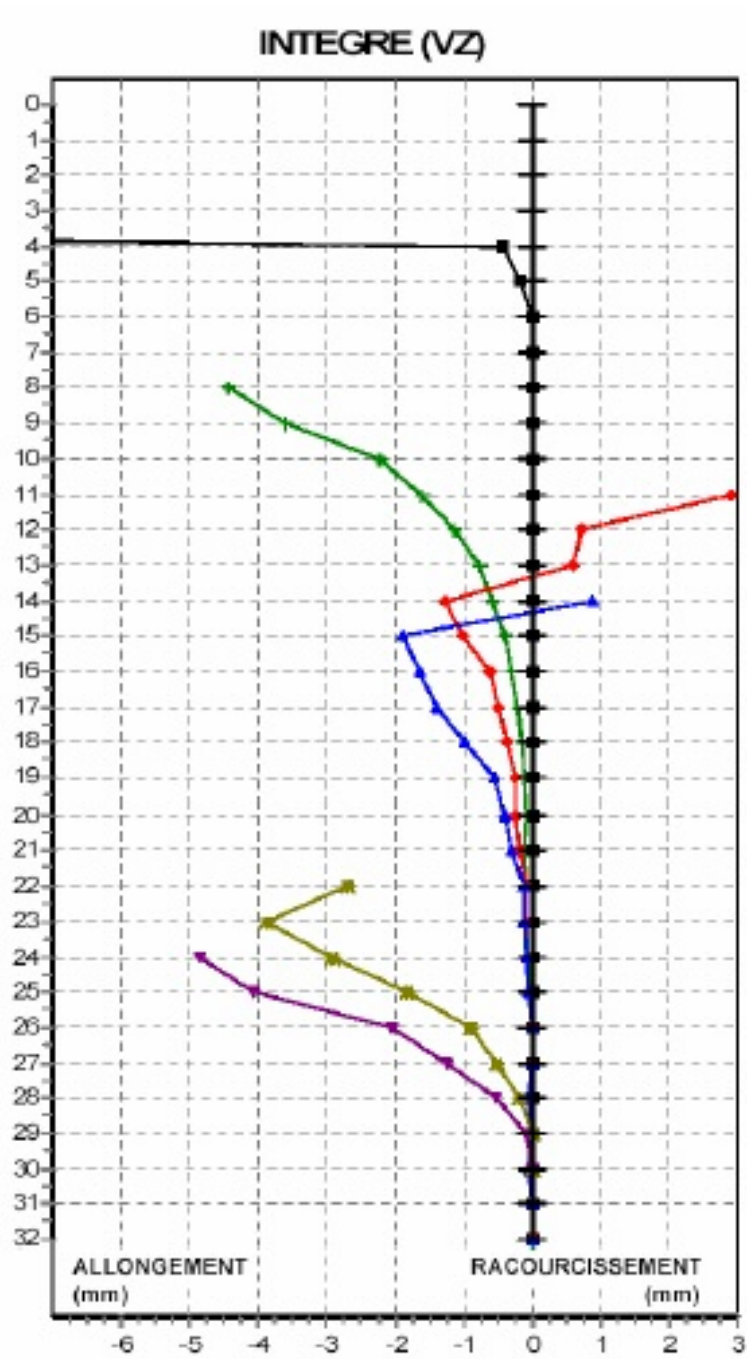
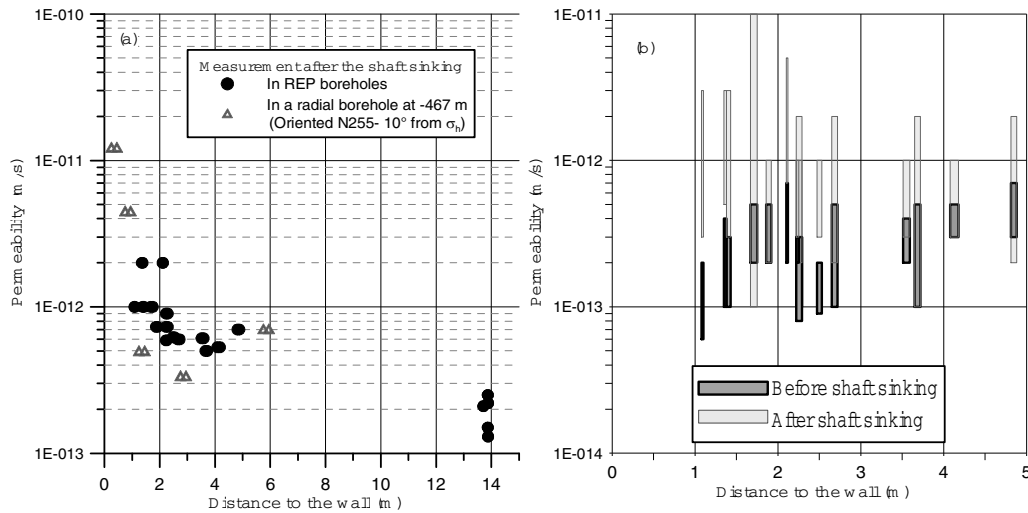


Fig. 7: Extrusion measurements in shaft axis



**Fig. 8: Permeability measurements**

## 5 CONCLUSION

The set of sensors installed in the framework of the REP experiment allowed us to get a large number of measurements regarding the behavior of argillites during the boring of a shaft. The PP type Multi-packer system was specifically adapted for the precise measuring of pressure variations in low permeability terrain (on the order of  $10^{-14}$  m/s). These systems also proved their great reliability in difficult conditions.

The first results confirm a strong hydromechanical coupling, characterized by hydrostatic suppressions and subpressures generated by the boring of the shaft in a field of anisotropic stress.

These results are currently the object of modeling in the framework of the European research program, Modex-Rep.

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