FIRST IN SITU EXPERIMENT IN THE FRENCH UNDERGROUND LABORATORY: VERTICAL MINE-BY-TEST IN THE MAIN SHAFT

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ABSTRACT

Further to a decision by the French government in December 1998, an underground laboratory will be built in France between 2000 and 2003 in a deep argillite formation in order to study the confining properties of the argillite rock and changes caused by excavation and thermohydromechanical loading. The main shaft of the underground laboratory is 5 m in diameter and will go as deep as 508 m. The shaft will be excavated by the drill and blast method between 2001 and 2002. It will offer an excellent opportunity for studying the hydromechanical disturbance inside the rock.

An in-situ experiment, i.e. a vertical Mine-by-Test, is accordingly scheduled to trace the progress of the hydromechanical disturbance. This involves the excavation of a niche at level –445 m for drilling boreholes, the instrumentation in the boreholes, and the tracking of the disturbance before, during and after shaft excavation from –445 m to -490 m. The main objectives of this experiment are to study the disturbance induced by excavation in the rock around the shaft and to verify and validate the hydromechanical models, previously developed for argillite. These objectives are described in terms of processes to be observed and parameters to be measured with the view of comparison with numerical predictions.

INTRODUCTION

In France, following the law of 30 December 1991 (1), three potential sites were selected in 1995 for the construction of underground laboratories and subjected to a survey of viable geological formations in 1995-96: two sites with a clay host layer and one site with a granite host layer. Following these surveys, an application was filed by the French National Agency for Radioactive Waste Management (ANDRA) to the French government in 1996, for a permit to install and operate an underground laboratory at each of these sites (2). In December 1998, after numerous administrative formalities and joint discussions with the local populations and representative bodies, the French government authorized the construction of an underground laboratory in eastern France, at the boundary of the Meuse and Haute-Marne départements (Figure 1), in a layer of sedimentary argillitic rock, and also ordered a search for a new granitic site where a second underground research laboratory could be built. The decree for the application of this decision, which was published on 3 August 1999 (3), states for the Meuse/Haute-Marne laboratory that "the investigations and experiments in the underground laboratory are aimed to compile the necessary data for the design, optimization, retrievability and safety of a potential radioactive waste repository" and that the permit to operate the underground laboratory is granted up to 31 December 2006.

This paper focuses on the first in-situ experiment, which is a vertical mine-by-test in the main shaft of this underground laboratory. It points out the principle, objectives and results anticipated from this first in situ investigation, as well as the modeling approach associated with this experiment. These different aspects are discussed according to the point of view of ANDRA, who is required to define the results anticipated from the experiment with respect to the repository project.

BACKGROUND

Preparatory operations for the construction of the underground laboratory began in December 1999 after the installation of the Local Information Committee. The first underground operations will start in September 2000 with the excavation of the main shaft. The construction of the two shafts, service galleries and galleries for experimental investigations, will extend to 2003. It is currently planned to operate the laboratory up to 2006, because in 2006, ANDRA is expected to present a report on the feasibility of disposal in a deep geological formation, to the French government and Parliament.

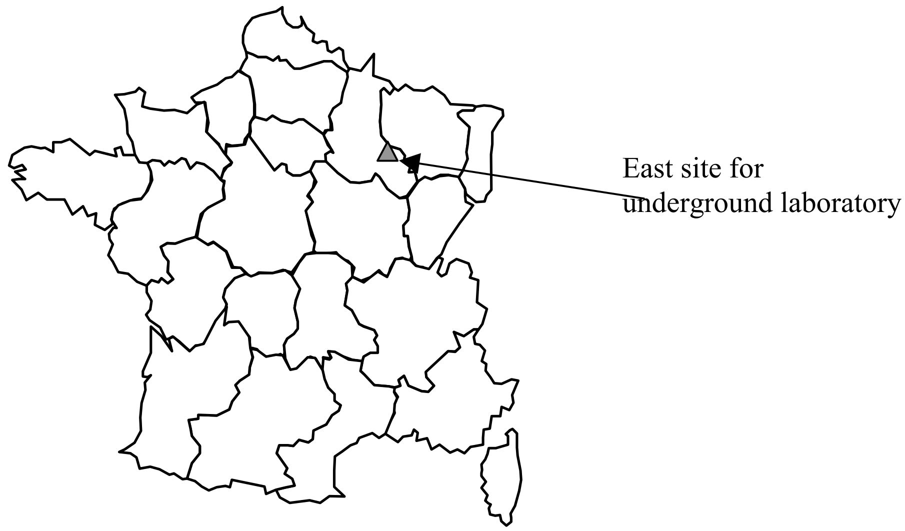

Figure 1. Map of France with location of the Meuse/Haute-Marne underground laboratory site investigated by ANDRA for underground waste disposal

To meet the objectives set by the 1991 law and clarified in the 1999 decree, a multidisciplinary geological, hydrogeological, geochemical and geomechanical research and investigation program has been initiated by ANDRA in the Callovo-Oxfordian formation of the argillites of the Meuse/Haute-Marne site.

The geomechanical research program has two main scientific objectives:

- a safety objective which is to assess the impact of the mechanical and hydromechanical disturbances induced by excavation and by operations, and the impact of thermal disturbances due to exothermic waste, during the different phases of the life of the repository, on the confinement properties (permeability, porosity) and on the transfer pathways,
- a geotechnical objective which is to evaluate the stability of the underground works making up the repository: shafts, access galleries, handling galleries and disposal cavities, during construction and operation and during the different phases of the closure of the repository.

Within the framework of this geomechanical research program, the first in situ full-scale experiment in the host formation represents a key step of this program. Because it is the first one, it is of special importance for the orientation of the research program which hitherto has been based on small scale studies on samples and on modelings conducted with predictive models and boundary conditions not actually verified or not validated in situ. This experiment also called E-REP, aims at tracking the mechanical response of the argillites to the excavation of the access shaft of the underground laboratory.

Excavation of the main shaft will permit the first observations of the argillites in the wall of an underground structure and, above all, in the core of the rock, and the E-REP experiment will supply quantified data on the mechanical behavior of the rock as well as a first verification of the available models (conceptual models, constitutive models, numerical models). It will help to determine whether to include or ignore the different currently identified processes and mechanisms (such as hydromechanical coupling, cracking) and the potential need to integrate processes heretofore considered negligible (for example, the effect of rock desaturation, mechanical effect of temporary support structures).

DESCRIPTION OF THE EXPERIMENT

The E-REP experiment calls for the observation and measurement of the characteristic quantities of the hydromechanical behavior of the argillites around a section of the access shaft during its excavation.

Brief Description of the Host Rock

The host rock in which the underground laboratory will be built consists of a clayey rock called argillites of the Callovo-Oxfordian. The argillaceous formation lies at a depth of 400 m and is about 130-m thick. The mineralogy content of Callovo-Oxfordian argillite includes 40% clay, 20-30% carbonates and 20-30% quartz and feldspar. From the geological standpoint, the upper part of the Callovo-Oxfordian formation, which will be investigated during the construction of the laboratory, can be divided into 3 units: carbonate siltite, silty marls and bioclastic argillite.

The argillite studied is a typical hard claystone and a plastic porous material. Its mechanical behavior is coupled with pore pressure: a first evaluation of the hydromechanical coupling parameter, Biot's coefficient, was obtained by oedometric tests and the coefficient was found to decrease with increasing axial stress. The measured onset of swelling is very low, and the swelling amplitude small. The initial permeability of the argillite is less than 10^{-20} m^2, low enough for the dissipation of the pore pressure induced by mechanical disturbance to take much longer than the mechanical loading.

Damage characterized by crack initiation was also observed and criteria have been proposed and characterized for damage onset and failure. Decreases in Young's modulus as a function of damage were measured by local strain measurements.

Preliminary tests in special conditions approaching the in-situ stress path for the argillite also suggest that this rock exhibits relatively substantial time dependent behavior, the rate of which increases with rising temperature.

Based on the mechanical characterization of argillaceous rock samples, it has thus been demonstrated that the Callovo-Oxfordian argillite exhibits typical poro-elasto-visco-plastic behavior, and that anisotropy of mechanical, thermal and hydraulic properties is not significant at this scale.

Brief Description of the Excavation of the Main Shaft

The access shaft, which is 508-m deep, has a lined inside diameter of 5 m, with a gross diameter of 5.9 m in the host rock between 420 and 508 m depth. In this shaft, at the -445 m level, excavation of the shaft will be halted to excavate a horizontal experimental niche 20 to 40-m long.

The technique selected for sinking the shaft is the conventional drill and blast method, except on a 10-m section located just under the niche, which the builder plans to excavate mechanically. In fact, he plans to change the excavation method on resumption of shaft sinking after excavating the niche to avoid damaging the landing of the niche (access structure specific to the intersection of a shaft and a gallery) during the first blastings. The planned excavation rate is about 2 m/day and the unsupported excavated section will be a maximum of 2.4-m high. A bolt/grating support is planned as soon as the scientific observations of the wall are terminated. The installation distance of the final lining of formwork concrete is about three blast lengths, or about 6 to 8 m behind the front. These indicative figures will be clarified on completion of the design studies conducted by the builder, which are currently under way.

Location of the Experiment

The E-REP experiment is positioned between the levels of -445 m, corresponding to the level of the experimental niche in the upper part of the host layer, and -490 m, corresponding to the main level of the laboratory galleries (Figure 2).

The shaft section involved in the actual E-REP experiment, i.e., the section monitored for measuring the hydromechanical disturbances induced by shaft excavation, has been selected so that the influence of the existing or planned structures will be as low as possible: that is 15 m below the niche and 13 m above the top of the main galleries. These distances approximately correspond to two shaft diameters, which is normally considered in geotechnics as characteristic of the zone of the influence of the excavation front of an underground structure. As follows, the instrumented shaft section extends from -460 m to -473 m.

The E-REP section lies completely within a relatively uniform zone of the Callovo-Oxfordian formation. This zone displays a mineralogy intermediate between that of the upper portion of the layer, which is strongly carbonate, in which the niche is excavated, and that of the median portion of the layer with high argilosity, in which the galleries of the main level of the underground laboratory are excavated. Given this location and the advance schedule of the operations, excavation of the instrumented shaft section is planned in June 2002.

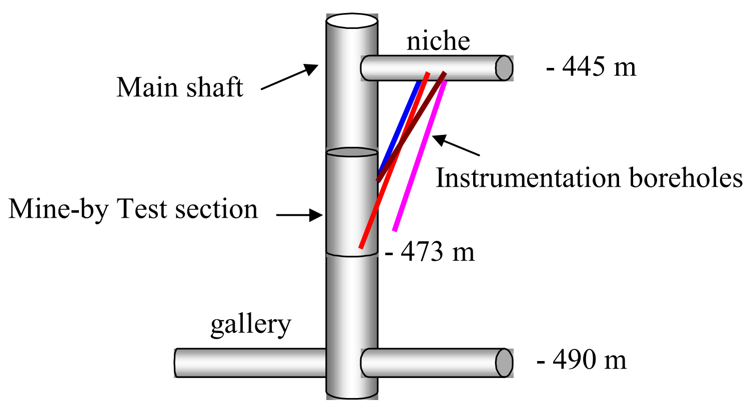

Figure 2 : Schematic of the vertical mine-by-test in the access shaft of the Meuse/Haute-Marne underground laboratory

The Experiment

Starting from the experimental niche (Figure 2), instrumentation boreholes of the E-REP experiment will be drilled, in order to install the sensors and measurement systems in the experimental zone before shaft excavation resumes. These instrumentation boreholes are directed towards a level lying between -465 m and -470 m at different radial distances from the axis of the shaft and in different directions selected according to the main horizontal stress directions. Thus, on resumption of shaft excavation, the instruments previously placed in these boreholes will monitor in real time the effects of the approach and the passage of the excavation front and the related time-dependent effects. The measurements provided by these instruments will then be used to estimate the variations in strains, stresses, pore pressure and permeability in the rock formation. After the passage of the excavation front, other observations and measurements of rock behavior (cracking, deformation and sonic properties) will also be made from the wall shaft or from radial boreholes, and stress and/or strain gauges will be installed in the liner.

For modeling the excavation of the shaft, it is necessary to know the initial state of the rock as accurately as possible before the excavation of the shaft, and especially the pore pressure. To establish this initial state of the rock, a stabilization phase is needed for all the sensors after they are installed in the boreholes drilled from the niche, and in particular for those instruments which measure the pore pressure. Therefore, to minimize the delay to the construction of the shaft, pore pressure gauges will be installed first.

OBJECTIVES OF THE EXPERIMENT

In view of the current knowledge and uncertainties surrounding the hydromechanical behavior of the host rock, the general objective set by the decree of August 1999, and the fact that this is the first in situ investigation, the E-REP experiment is designed to meet the following three major objectives:

1. Observe the response of the argillites to the construction in a real situation. This means observing the behavior of the argillites with respect to the excavation and lining of the shaft. For example, cracking type and mode, rock stiffness and ductility, effect of local heterogeneities, anisotropy and initial stresses on the response of the argillites and nature of rock-support interactions and alterability in air will be observed.
2. Characterize the extent and amplitude of the hydromechanical disturbances induced by the excavation of the shaft by blasting: changes in deformations during, after excavation and delayed, desaturation, increase in permeability, changes in pore pressure, degradation of mechanical properties in a zone of limited extension around the shaft.
3. Verify conceptual models and test the capacity of the related constitutive models and numerical models, under construction, to predict the hydromechanical behavior of the argillites around an underground structure, by comparing the modeling results and the E-REP in situ measurements.

Processes to be Observed and Quantities to be Measured

Table I summarizes the processes to be observed and the quantities to be measured to meet the three major objectives identified above.

Even though the analysis of the delayed behavior of the argillites is not one of the major objectives of the experiment, information about this time-dependent behavior of the rock will nonetheless be available via strain (and stress) measurements in the liner, which will be acquired regularly during the construction and operation of the underground laboratory. In fact, the time-dependent behavior of the rock around a gallery causes a convergence of the gallery if it is not lined (creep type conditions) or an increase in the radial stress if a rigid liner has been installed (relaxation type conditions). With respect to the shaft, the installation of the liner will block the deformations in the wall and the time-dependent behavior of the rock will only be observable via stress measurements in the liner. These measurements, taken over a number of years, will supplement the currently available data obtained exclusively from tests on small scale samples lasting only a few weeks or months.

PHENOMENOLOGICAL MODELING ASSOCIATED WITH THE EXPERIMENT

While the E-REP experiment is being prepared and conducted, mechanical and hydromechanical phenomenological models of the experiment will be constructed in order to:

- Test, improve and validate the predictive models that are available or being constructed in geomechanics, which will be used to design a repository; and
- Identify the experimental data acquired in situ which can be compared with the results of the phenomenological models.

The conceptual model of the host rock and the associated numerical models will be steadily improved throughout the construction of the underground laboratory, as each experiment supplies supporting data or improvements. In fact, constitutive and numerical models will be continually improved and possibly complexified gradually by the progressive integration of the results of the in situ experiments into the numerical models. Thus, for each experiment, the following approach is pursued for the modeling:

- Predictive modeling of the experiment, conducted blind, with the models available before the experiment, which will integrate the maximum information from the previous experiments,
- Analysis of the differences between models and in situ measurements and/or observations,
- Adjustment (readjustment of parameters) and improvement (integration of one or more previously ignored factors) of the models to reduce the identified discrepancies,
- New comparison between adjusted models and in situ measurements to select the best model(s) to reproduce the observed behavior of the argillites.

Ultimately, the capacity of a model will be judged not only on the qualitative and quantitative agreement of the results, but, above all, on the reasons underlying this agreement (for example, representation of elementary processes, ability to reproduce the response in elementary loading paths, parameter adjustment approach, etc). These reasons will instill confidence in the capacity of the model to predict the behavior of the rock in similar but nonetheless different conditions (for example, the shaft or the disposal galleries).

Approach to Predictive and Ex Post Facto Models of the Experiment

The approach to the foregoing modelings will be applied to the E-REP experiment as follows:

- ➢ *Before the experiment* is conducted, blind predictive modeling will be performed by several research teams: teams which have already developed constitutive and numerical models for ANDRA in connection with the repository project in the argillites, and international research teams which will use the models they have developed independently of ANDRA's project. These two categories of models and their results will be compared during international benchmarks. The predictive numerical models of E-REP experiment will rely on the advance phasing of the operations supplied by the constructor (first blind modeling).
- ➢ *During the experiment*, i.e. during the installation of the sensors from the niche and during excavation of the shaft, a second blind predictive modeling exercise will be conducted, as soon as the precise phasing is known for the excavation of the inspected shaft section and the precise location of the measurement cells. At this time, the partners will, in their models, integrate these actual experimental conditions as well as data acquired in the course of complementary investigations and interpreted later, such as the initial in situ stresses measured before shaft excavation. By contrast, the parameters of the constitutive models used in the first blind modeling (before the experiment) will not be modified and the first results of the in situ measurements will not be transmitted to the modeling staff.

- *After the experiment*, model/measurement comparison for each predictive model will serve to identify the differences in values and the cause of these differences including the phasing of operations or certain physical mechanisms not fully accounted for in the model, boundary conditions containing strong uncertainties and 3-D effects. Depending on the source of the discrepancies, a number of alternatives for improving the modelings will emerge: integration of an additional mechanism in the constitutive model, readjustment of the model parameters, adjustment of boundary conditions, better representation of the phasing of the operations and/or the geometry of the structures. On completion of this comparison phase, some models will be abandoned because the means of improvement are unfeasible or correspond to other predictive models already constructed and more susceptible to improvement. To verify the relevance of the model improvement methods, determined at the end of the previous phase, the E-REP experiment will be modeled a final time, with the adjusted models. A new comparison of adjusted modeling results with in situ measurements will help to identify the best models for reproducing the hydromechanical behavior of the argillites around a cavity.

Contribution of the Experiment for the Evaluation and Improvement of Predictive Models of the Repository

The assessment of the safety and time evolution of an underground repository entails the use of predictive models. The confidence in these models entails a good knowledge of their pertinence and of their capacity. Therefore, a comparison of the prediction of the behavior of the rock supplied by the models with the actual behavior observed in situ is important. Model/in situ measurement comparisons will be made at two levels:

1. Comparison between physical and mechanical processes observed in the experiment and the assumptions underlying the constitutive models; and
2. Comparison between variations in the hydromechanical parameters during the experiment and their numerical predictions by the models.

The E-REP experiment will provide information and data for making these two types of comparison. Thus, for each process to be observed, Table II shows what is needed to verify the assumptions of the models and, for each hydromechanical parameter to be measured, Table III shows what is needed to verify and improve the constitutive and numerical models.

CONCLUSIONS

The first in situ experiment in the argillite layer of the Meuse/Haute-Marne underground laboratory in eastern France will consist of the real time monitoring of the mechanical and hydraulic behavior of the rock during the excavation of the main shaft. This is a vertical mine-by-test. It will make it possible for the first time, and on a full scale, to measure and understand the behavior of the Callovo-Oxfordian clayey rock in response to the excavation of the underground laboratory. Hence, it will supply important qualitative and quantitative information on this behavior in terms of strains, variations in pore pressure and the state of cracking of the rock.

The E-REP experiment will also improve the predictive capacity of the constitutive models and numerical modeling. The former attempt to reproduce the mechanical or hydromechanical behavior of a sample of argillites with respect to various loads, and the latter the load distribution around an underground opening and the mechanical response of the surrounding rock. In fact, the results of the predictive modeling, made with constitutive models of different levels of complexity, will be compared with the in situ measurements. This comparison will serve to pinpoint the excessively simplistic assumptions of certain models or the inadvisability of accounting for certain physical mechanisms and processes, which proved to be unimportant. It should also help to improve the fitting of certain parameters, which are poorly known or determined on small samples. The first geomechanics experiment constitutes the first opportunity to develop, verify and improve the predictive models, which will be used for the assessment of an underground repository in the Callovo-Oxfordian formation.

The same approach will be followed for each geomechanics experiment. It should help to reduce the uncertainties on the behavior of the rock and will thereby progressively improve the available predictive models for the repository, at least in terms of the short and medium term behavior of the rock (a few days to a few months).

In the same way as an engineer acquires experience throughout his professional life, whenever faced with a difficulty or even a failure, the predictive models of the geomechanical behavior of the Callovo-Oxfordian argillites will progressively be enriched with the results of the comparisons with in situ measurements, so as to reduce the range of variation of the predictive values. These models can then be used to estimate, with controlled uncertainty, the effect of disposal structures on the behavior of the rock, and above all, on its confinement properties.

Table I: Processes to be observed and parameters to be measured according to the major objectives of the E-REP experiment

Major objectives	Processes to be observed	Associated scientific questions	Parameters to be measured
Observe the response of the argillites to construction	Cracking type and mode Stiffness and ductility of adjacent rock Anisotropy and heterogeneity, alterability in air, desaturation, delayed behavior over a few months or years	In situ stress state Representativity of measurements of mechanical properties on samples Validity of conceptual models of the initial status of the host formation and the disturbances induced by excavation	Survey of the trend of the fracture and crack planes, analysis of fracture opening mode Deformation at shaft walls and in the rock during blasting (vibrations) and after blasting (residual strain as a function of the position of the front) Measurement of strains in different directions and at different points to describe the stress anisotropy Stresses in the liner
Characterize the extent and amplitude of hydromechanical disturbances	Variation in mechanical and hydraulic rock properties Degradation of mechanical and hydraulic properties	Representativity of measurements of mechanical and hydromechanical properties on samples Quantified effect of damage on the permeability of the argillites	Variations in the following parameters in the formation and as a function of time: - stresses (and strains), - mechanical properties (E, R_c or other), - pore pressure, - permeability.
Verify conceptual models and test the capacity of the constitutive models and numerical modelings	Changes in state variables, mechanical and hydraulic properties as a function of time and at different distances from the shaft walls	Qualitative and quantitative prediction of the mechanical and hydromechanical constitutive models and numerical models with respect to safety (damage and permeability) and constructibility (mechanical stability, stresses in the liner)	Measurements associated with objectives 1 & 2 Initial stresses and pore pressure In situ rock deformability Strains and stresses in the liner

Table II: Contribution of processes observed during the E-REP experiment for the verification of the model assumptions

Process to be observed	Verified assumption of models
Breakage, fracturing and cracking in the neighborhood of the shaft	- verification of the appropriateness of a continuous-medium model, - choice of the type of constitutive model for the short-term mechanical behavior of the rock.
Stiffness and ductility of the rock	- choice of a constitutive model with or without damage, - evaluation of in situ rock deformability with analysis of the scale effect on these parameters, in order to assess the uncertainties associated with the measurements on samples (which normally supply the modeling parameters).
Anisotropy	- verification of the assumption of isotropy of mechanical behavior in the bedding plane, and of low anisotropy of mechanical properties in the plane perpendicular to the bedding plane, - confirmation of the directions of the natural in situ stresses identified in previous studies and used as initial condition in modeling.

Table III: Contribution of parameters measured during the E-REP experiment for the verification and improvement of the constitutive and numerical models

Parameter to be measured	Contribution for constitutive and numerical models
Variation in strains (ε) and stresses (σ) in the adjacent rock	- verification of the appropriateness of the constitutive models, with or without inclusion of hydromechanical coupling, and validity of the associated parameters, both determined from tests on samples, - test of the overall numerical model, because these parameters result not only from the mechanical behavior of the rock, but also from the hydromechanical coupling, the initial status of the rock (in terms of stresses and pore pressure), the phasing of the shaft excavation (changes in loads over time).
Variation in pore pressure and permeability	- verification of the appropriateness of the poroelastic or poroelastoplastic constitutive models, - verification of the advisability or not of taking account of the effect of rock desaturation in the wall, - verification of the validity of the hydromechanical coupling parameters, determined from sample tests or estimated empirically.
Variation in mechanical properties (measured on samples and in situ) as a function of distance from the wall	- validity of fracture and damage criteria of the elastoplastic constitutive models, - validity of laws of alteration of mechanical properties in fractured or damaged zones, adopted in the elastic or elastoplastic constitutive models with damage.
Strains (ε) and or stresses (σ) in the liner	- first verification of the mathematical formulation of the viscoelastic or viscoplastic models, which are used to simulate the time-dependent behavior of the rock.

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