Time-dependent evolution of the excavation damaged zone in the argillaceous Tournemire site

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Abstract:
The experimental Tournemire site enables the assessment of the Excavation Damaged Zones (EDZ) around three structures excavated in argillites: the century-old tunnel, the ten year-old east and west galleries, and the three year-old main gallery. This paper discusses the main experimental results concerning the EDZ characterisation and their interpretation.

EDZ fracture analyses from the galleries (cartography) and the radial boreholes (core analyses) allow for accurate structural characterisation of the EDZs. The tunnel has an EDZ with dense, homogeneous fracturing parallel to the wall, resembling onion skins. However, the new galleries do not have an EDZ similar to that of the tunnel. Unsaturated micro-cracks, mainly parallel to the bedding planes are observed on the non covered walls of each gallery. The extent of the EDZ does not seem to be affected by the age of the structure. It is approximately 20 % of the mean radius of the structure. Based on the modelling and experimental characterisation work completed, it is considered that the EDZ in this argillaceous Tournemire site is due to a deferred failure. At first time, when the wall of the structures are not covered the desaturation/resaturation phenomena induced a tensile failure around the new galleries. During the time, these desaturation/resaturation phenomena cause a gradual weakening of the material. The EDZ tunnel fractures are explained by this possible hydric damage and a decreasing mechanical strength with the time. These assumptions remain to be confirmed through coupled numerical modelling in unsaturated medium.

1 INTRODUCTION

Deep geological disposal of high-level radioactive waste poses earth science experts the specific problem of how to manage the very long radionuclide containment period. Burying this waste represents a large-scale, protracted activity. The timescales considered are of the order of magnitude of $10^5$ years, which considerably exceeds the lifetime of the earliest engineered structures. There are several ways of partly overcoming the difficulty of extrapolating to large timescales, such as studying observable phenomena in the laboratory at moderate or even low speeds, studying natural equivalents, and studying early structures such as the Tournemire tunnel, which was excavated one century ago. For repository safety assessment purposes, the behaviour analysis of the engineered structures specifically concerns the possible creation of an EDZ. A complete control of the evolution of this EDZ over space and time is an essential factor for long-term repository safety.

The existence of an old tunnel and two more recent galleries (excavated three and ten years ago) in the Tournemire experimental site allows the possibility to study the development of the EDZ in the argillaceous medium over three different time scales. The studies conducted by the IRSN in this site concern the characterisation of the damaged zones around the engineered structures and the subsequent identification of the phenomena associated with their creation and evolution over time. The main objective of these studies is to develop physical models and computer codes that can be used to reproduce in situ observations and reliably predict the behaviour of the engineered structures over time scales not accessible through experimentation.

In this paper, we present the main experimental results concerning the characterisation of this EDZ, as well as their interpretations. Here, the term EDZ (Excavation Damaged Zone) refers to the zone where fractures develop due to failure of the rock mass.
2 TOURNEMIRE SITE

2.1 Geology

The Tournemire site is located in a Mesozoic marine basin at the southern limit of the French Massif Central. The sedimentary formations are characterised by three main Jurassic layers. The argillaceous medium of the Tournemire region consists of a subhorizontal layer 250-m thick located between two layers of limestone and dolomite (300 and 500-m thick) which constitute two aquifer layers (figure 1). This argillaceous medium is composed of argillites and marls of Toarcian and Domerian formations. The Tournemire massif is bounded by two valleys that correspond to a subhorizontal monocline structure with an E-W regional fault cutting through the northern part (Cernon fault). Faults and fractures affect this massif. They are related to different tectonic events (Cabrera, 2002). The present water circulation takes place along the lower and upper limestone aquifer layers and along the Cernon fault.

2.1 Rock mass characteristics

The excavation of an underground structure within a massif causes a progressive modification of the initial stress conditions (mechanical disturbance) and interstitial pressures (hydraulic disturbance), leading to the development of a disturbed zone around the excavated structure. This disturbed zone may evolve over time, depending on the hydric loadings generated by the structure's ventilation system. These hydric loadings are generally important in argillites that desaturate and resaturate rather easily in contact with air. These various disturbances (mechanical, hydraulic and hydric) are often closely associated and mutually influence one another. The chemical disturbances induced by oxidation phenomena, gypsum deposition, etc. are negligible in comparison with the hydromechanical disturbances generated during the excavation and post-excavation phases. The development of the damaged zone considerably depends on the initial hydromechanical properties prior to the excavation of the structure.

The Tournemire argillaceous medium consists of argillites and marls in the form of thin interstratified layers of argillaceous minerals giving the rock mass a naturally anisotropic texture. These argillites have very low water content (1 to 5%), a porosity of between 6 and 9%, and a grain density of approximately $2.7 \times 10^3 \text{ kg/m}^3$. 

Fig. 1: Geological cross-section of the site
2.1.1 Mechanical properties

The mechanical behaviour of the rock mass is governed by its anisotropic character. This behaviour is analysed on the basis of a transverse isotropic material having five independent parameters with the following values, determined on samples:

\[ E_1 = 27,680 \text{ MPa and } \nu_1 = 0.17 \]
\[ E_2 = 9,270 \text{ MPa and } \nu_2 = 0.20 \]
\[ G_{12} = 3,940 \text{ MPa} \]

Directions 1 and 2 are respectively parallel and perpendicular to the bedding planes, which are subhorizontal.

The uniaxial compressive strength and maximum strength before failure vary from 13 to 32 MPa and 20 to 57 MPa, respectively, depending on the orientation of the samples. The tensile strength in the direction parallel to the stratification is approximately 3.6 MPa (Rejeb, 1999). The creep tests show a low primary creep rate of 0.02 to 0.1% under a load of 20 MPa (after 90 days). This low creep rate also depends on the anisotropy of the material (Rejeb, 2003). The initial in situ stress field is around 4 MPa.

2.1.2 Hydraulic properties

Water permeability is very low and approaches the lower sensitivity limit of the devices, regardless of the method used. It is estimated at \(10^{-15}, 10^{-14}\) m/s in the laboratory. In situ permeability is also very difficult to measure. It is estimated at \(10^{-13}\) m/s (Cabrera et al., 2001). These permeability values must be considered with great caution. The mechanical anisotropy of the material is not reflected in the permeability measurements; probably due to their inaccuracy.

The interstitial pore pressure, measured in various vertical and horizontal boreholes, is also low. It varies between 0.2 and 0.6 MPa.

2.1.3 Hydric properties

The Tournemire argillite contains 40% argillaceous minerals, including approximately 10% illite/smectite, making it subject to swelling and contraction in response to desaturation and resaturation processes, like all argillaceous materials. Adsorption isotherms have been obtained for samples in equilibrium with various hygrometries, and measurements of variations in water content and volume have been performed. The lower the hygrometry, the lower the water content and argillite volume. The maximum decrease in volume is 1.5%, for a relative humidity of 15% (Daupley, 1977). The free swelling pressure measured on the samples is 0.5 MPa.

The mechanical properties are very sensitive to the rock saturation condition. When the samples are desaturated, the deformation moduli, strength and cohesion of the material increase, and the Poisson coefficient decreases (Vales et al., 2004).

At the site scale, these phenomena produce capillary pressures of up to 50 MPa, leading to flaking and fissuring of gallery walls and working faces after excavation.

3 EXCAVATION OF TUNNEL AND GALLERIES

The infrastructure of the Tournemire site is shown in figure 2. The oldest component is a 2-km tunnel giving direct access to the Toarcian argillite formation of interest. It was excavated manually in 1881 and is covered with limestone masonry. In 1996, two 30-m long galleries (‘east' and ‘west' galleries) perpendicular to the tunnel were excavated using a road header machine. The west gallery intersected a tectonic fault zone whose presence had been previously identified by radial boreholes drilled in the old tunnel in 1994. The east gallery was excavated in an unfractured zone. These two galleries are devoted to the study of argillite fracturing, desaturation and resaturation phenomena.
In 2003, a new gallery (‘main’ gallery) 40-m long was excavated to conduct ‘mine-by-test’ experiment and study the hydromechanical response of argillites to excavation (Rejeb, 2005). This gallery was excavated using a road header machine with a dust removal system. The galleries excavated in 1996 and 2003 are mechanically stable. Nevertheless, given the existence of tectonic faults and post-excitation flaking, it was decided to support the galleries with steel sets spaced 1-2 m apart and to cover the roof with a steel mesh. The first 10-m section of the gallery excavated in 2003 is completely concreted so as to study the influence of two types of supports on the development of the damaged zone. Figure 3 shows the cross-sections and dimensions of the three engineered structures.

![Fig. 2: Site infrastructure and EDZ along the tunnel](image)

**Fig. 2: Site infrastructure and EDZ along the tunnel**

![Fig. 3: Cross-section and dimensions (meter) of engineered structures](image)

**Fig. 3: Cross-section and dimensions (meter) of engineered structures**

## 4 CHARACTERISATION OF THE EDZ

In order to analyse the possible evolution of the EDZ over time, three sections have been investigated, one in each of the engineered structures. These sections are removed from any faults or zones influencing the intersections or ends of the structures, thus obtaining easily interpretable geometries.
In order to correctly cover the spatial distribution of the EDZ for a given section, eight radial boreholes 6 to 15-m deep were drilled in each of the three engineered structures. The following measurements were performed in these boreholes: ultrasonic wave propagation velocity profiles, permeability profiles, and saturation profiles, to assess the extent of the desaturated zones around the engineered structures.

4.1 EDZ fracturing

The radial boreholes were all drilled dry and systematically core sampled. The observations of the orientation and density of the excavation-induced fractures make it possible to determine the mapping of the EDZ and thereby obtain an estimate of the extent of the failure zones around the engineered structures. The results of these geological investigations are summed up in figures 4 and 5, respectively corresponding to the old tunnel and the new galleries excavated in 1996 and 2003.

The fracturing of the EDZ around the tunnel, resembling onion skins, is fairly dense and parallel to the wall. It has a homogeneous extent making it possible to delimit an envelope with an average thickness of 70 cm around the tunnel. Moreover, the EDZ fracturing around the galleries excavated in 1996 and 2003 is not at all of the same type as the open fracturing observed around the tunnel. A subhorizontal desaturation cracks have developed around the recent galleries on non covered walls. These cracks can be delimited by an envelope approximately 40-cm thick. They are identified by the radial boreholes and are of the same type as those observed on the side walls of the galleries shortly after their excavation. These subhorizontal cracks have developed along the bedding planes (Ramambasoa, 2001).

Fig. 4: EDZ (from core observation) around the tunnel excavated in 1881
4.2 EDZ properties

Indirect techniques have been used so as to supplement the direct observations of EDZ fracturing and determine the EDZ properties.

*Mechanical properties determined on samples:* Uniaxial compressive tests were performed on samples taken at various distances from the side walls of the tunnel and east gallery. The dispersion of results did not enable the detection of significant changes in the mechanical properties of the rock mass (Rejeb et al., 2000).

*Surface reflectometry radar:* A reflectometry radar profile measurement campaign has been conducted (Boisson, 1998). The results clearly show an EDZ of 1 to 1.5 m in the old tunnel. However, the profile obtained for the 1996 gallery provides no information concerning the EDZ in that structure.

*Ultrasonic diagraphy:* The velocity profiles presented by Alheid et al. (2004) generally show low velocities (2700 to 3000 m/s) along the boreholes up to approximately 1 m from the tunnel side wall, and a velocity of 4000 m/s at greater depths. Regarding the new galleries, velocities ranging from 3500 to 3700 m/s were recorded up to 50 cm from the side wall, as shown by the results obtained in the 1996 gallery. These results are consistent with the fracturing directly observed in the core samples from the radial boreholes described in the previous section.

*Permeabilities from boreholes measurements:* Pneumatic and hydraulic tests have been performed in boreholes using a multi-packer system. For each of the three engineered structures, two permeability profiles have been established in both horizontal directions and oriented downwards 45°. These profiles show that the permeability can reach $10^{-12}$ m$^2$ in zones extending up to 1 m in the old tunnel and 0.50 m in the 2003 gallery (Matray et al., 2006). Outside these zones, the measured permeability varies between $10^{-16}$ and $10^{-17}$ m$^2$, which seem to be the limit values obtainable with the used method. The measurements obtained in the two boreholes of the east gallery are fairly dispersed. These gas permeability measurements have generally served to confirm the extent of the damaged zones, not to give the permeability in the EDZ.

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**Fig. 5:** EDZ (from core observation) around the new galleries (1996, 2003)**
In addition, these same boreholes have been used to perform petrophysical measurements on samples so as to determine the extent of the desaturated zones. The hole set data shows the consistency between EDZ fracturing, desaturation and decrease in permeability within the same zone. It is clearly apparent that desaturation is closely associated with material damage.

5 TIME-DEPENDENT EVOLUTION OF THE EDZ

Considering the various results of the characterisation work for the EDZ in the Tournemire site, it is clear that the new galleries do not have an EDZ as developed as around the old tunnel. At this stage, the following question arises: Is the EDZ in the Tournemire site evolving with time? In other words, will failure zone similar to that observed around the century-old tunnel develop around the 1996 and 2003 galleries? To answer this question, a comparative analysis of the three engineered structures is essential.

5.1 Comparison of the three galleries

The development of the EDZ depends on various factors. The most important are the following: dimensions and geometry of the structure, initial stress condition ($\sigma_0$), orientation of the structure with respect to the initial stress field, excavation method, excavation rate, supports, use of the structure (ventilation), and hydromechanical behaviour of the massif. A detailed analysis of each of these factors and their influence on the development of the EDZ does not justify the difference between the EDZ in the old tunnel and those in the new galleries. In the analysis, we have assumed that the failure observed around the tunnel is a mechanical failure that developed instantaneously during excavation. In such a case we should have observed a similar failure around the new galleries immediately during their excavation. The fact that the galleries have smaller cross-sections than the tunnel and that they are not oriented in the same trend as the latter with respect to the initial stress field is not sufficient to justify the absence of instantaneous mechanical failures around them. If we deliberately ignore the unknown excavation condition and usage factors for the old tunnel, only the time factor can explain the difference in fracturing between the tunnel and the new galleries.

In order to analyse this time factor and its influence on the development of the EDZ, table 1 shows the extent of the damaged and desaturated zones and the type of fracturing observed around each of the three engineered structures. $R$ is the mean radius of each structure. Taking into account the error associated with determining the extent of the EDZ through direct observation of fractures, it can be concluded that the three structures generally have an EDZ of the same extent, i.e., approximately 0.2 $R$. However, the typology of the EDZ fracturing seems to be affected by the age of the engineered structure. The extent of the desaturated zone ($Z_{\text{desaturated}}$) has been estimated based on the gas permeability and saturation profiles. However, certain results obtained around the tunnel are rather scattered and the assessment of the desaturated zone needs to be refined. The experimental problems encountered are due to the presence of masonry and the difficulties to obtain samples and measurements in the desaturated zone around the tunnel. Contrary to what was expected, the extent of the desaturated zone is generally of the same order of magnitude for the three engineered structures. The desaturation process seems to be developed quickly in the structures submitted to the natural ventilation. In fact, the extent of the desaturated zone is the same in the two different age’s galleries. In addition, the masonry covering probably acted as a screen interrupting the advance of the desaturation front around the tunnel. The extent of the desaturated zones slightly exceeds that of the fractured zones in the massif surrounding the three engineered structures.
5.2 Failure mechanisms

Based on the fracturing observed around the three engineered structures, it can be assumed that the development of the EDZ around the old tunnel is due to deferred failure. The phenomena causing such deferred failure are generally the following: pore pressure dissipation, creep and relaxation of the material, and desaturation/resaturation. These phenomena are closely coupled.

In the case of the Tournemire site, the deferred deformations associated with pore pressure diffusion cannot explain the deferred failure around the tunnel, since the interstitial pressures in the site are quite low. However, given the low deferred deformations associated with the material viscosity, the excavation-induced stress deviator relaxes slowly and may persist on the wall for a long time, eventually causing the deferred failure.

Moreover, since the behaviour of argillite is highly sensitive to desaturation/resaturation phenomena, the major loading able to cause failure around the tunnel is probably of hydric origin. This loading, necessarily associated with mechanical one, leads to material contraction, which in turn induces tensile stresses (Miehe, 2004). In the short term, these stresses produce flaking and crack in the walls. The cracks propagate progressively through the massif, as observed in the 1996 and 2003 galleries (figure 5). These tensile stresses cause failure, since they largely exceed the tensile strength of the material, i.e., approximately 3.5 MPa (Ramambaso, 2001). The flaking can probably propagate slowly. To stop this process, we can assume that the structure walls must be confined within an adequate atmosphere. We believe that the confinement provided by the masonry covering has enabled the stabilisation of the fractured zone around the tunnel. However, this flaking process induced by desaturation-resaturation does not explain the development of open fractures (onion skins) around the tunnel (figure 4). We believe that the tensile failure mechanism is not responsible for the creation of these fractures.

Based on the modelling work completed (Rejeb et al., 2006) and the experimental characterisation results, we strongly believe that the EDZ in the Tournemire site was created in a deferred manner. During the first years after excavation, the desaturation/resaturation phenomena induced a tensile failure around the new galleries. Many years after, these desaturation/resaturation phenomena possibly cause hydric damage and a decrease in mechanical strength, thus leading to the observed onions skins fracturing. Figure 6 sums up our current knowledge on the development of the EDZ in the century-old tunnel and in the 2003 gallery, respectively.
6 CONCLUSION

The analysis of excavation-induced disturbances in an argillaceous medium is highly complex. This is due, on one hand, to the complex behaviour of the material and, on the other hand, to the coupled phenomenology of the disturbances.

From the experimental investigations, various methods have been used to characterise the damaged zones in the Tournemire site. These various methods have produced consistent and complementary results. The direct observation of the fracturing by means of radial boreholes is the most relevant method to characterise the EDZ. A maximum depth of 5 R for each borehole is largely sufficient. Indirect measurements such as velocity and permeability measurements in boreholes and saturation measurements on samples are required to assess the damaged and desaturated zones. In addition, these methods produce data that can confirm the characterisation of the EDZ through core observation. At least three 4 R-long radial boreholes are required (parallel, perpendicular and oriented 45° with respect to the bedding planes) to obtain these indirect measurements and thereby estimate the extent of the damaged and desaturated zones around the engineered structure. It is recommended to perform a maximum number of measurements in the first two meters from the wall to obtain profiles as accurate as possible. Investigations via radial boreholes have the advantage of allowing for endoscopic or ultrasonic velocity measurements at different dates so as to detect a possible evolution of damage over time and over the relative humidity in the galleries.

Theoretically speaking, EDZ creation and development mechanisms are only partly understood in most argillaceous sites. These mechanisms are obviously specific to each site. The instantaneous failure mechanism induced by the deconfinement of the rock mass is generally understood and well predicted. On the other hand, the deferred failure mechanism induced by various closely coupled processes is far from understood and requires important theoretical developments. As the EDZ problem concerns the creation and the development of fractures, we think that the continuum mechanical approach shows its limitation for predicting the EDZ and the propagation of fractures theory should be considered on the ongoing work.
7 REFERENCES


