Influence of different support systems on drifts closure evolution in Callovo-Oxfordian claystone

Frederico Lara
Navier, Ecole des Ponts, Univ Gustave Eiffel, CNRS, Marne-la-Vallée, France

Lina-María Guayacán-Carrillo
Navier, Ecole des Ponts, Univ Gustave Eiffel, CNRS, Marne-la-Vallée, France

Jean Sulem
Navier, Ecole des Ponts, Univ Gustave Eiffel, CNRS, Marne-la-Vallée, France

Jana Jaber
ANDRA, Meuse/Haute-Marne Underground Research Laboratory, Bure, France

Jan Cornet
ANDRA, Meuse/Haute-Marne Underground Research Laboratory, Bure, France

Gilles Armand
ANDRA, Meuse/Haute-Marne Underground Research Laboratory, Bure, France

ABSTRACT: At the Meuse/Haute-Marne Underground Research Laboratory several research programs have been dedicated to: (1) knowledge improvement of the Callovo-Oxfordian claystone response to the excavation; (2) development of the different disposal systems. In order to increase the understanding of the rock mass formation and support interaction, a drift composed of different support systems has been monitored for several years. As this one is oriented along the minor horizontal principal stress, the measurements exhibit an anisotropic closure of the cross section with the vertical convergence being higher than the horizontal one. It is thus of interest to evaluate the effect of flexible support composed of compressible wedges and of the final concrete lining on the closure evolution. Also, extensometers measurements and the stresses on the temporary support are analyzed in different zones of the drift. Finally, the results are compared to those obtained from other drifts excavated in similar conditions.

Keywords: Convergence measurements, Tunnel excavation, Tunnel lining, Deep geological repository, Callovo-Oxfordian claystone.

1 INTRODUCTION

The French National Radioactive Waste Management Agency (Andra) began the construction of the Meuse/Haute-Marne Underground Research Laboratory (MHM URL) in 2000 with the first objective to study the feasibility of radioactive waste deep geological repository in the Callovo-Oxfordian (COx) claystone. Experimental drifts are designed as a mean to test and optimize the construction methods using different excavations and support techniques.

At MHM URL, the principal vertical stress, σ_v, is similar to the principal horizontal minor stress, σ_h, (about 12 MPa) whereas the principal horizontal major one, σ_H, is 1.3 times greater (about 16 MPa). During excavation, an induced fractured zone around the drift was observed (Armand et al., 2014). The fracture patterns depend on the direction of the drift relative to the principal stress directions and lead to an anisotropic closure of the drift. Most of the drifts at the main level of the Laboratory (-490 m) are constructed following the principal horizontal stresses, because it is the direction in which the fractured zones are minimized. Thus, it is the preferred direction for the safe storage of radioactive waste.

The drifts of MHM URL are continually surveyed by different in-situ monitoring systems such as convergence measurements, extensometers and support pressure sensors. In this paper, the measurements of a drift (GER) excavated in the direction of σ_h are evaluated. The convergence data are analyzed using a methodology proposed by Vu et al. (2013) to fit the parameters of the convergence law proposed by Sulem et al. (1987).

This drift was designed to test different types of support systems, including elements such as shotcrete, compressible wedges and final concrete lining. A detailed analysis of data obtained from monitoring performed in sections located in zones with different support systems permits to evaluate the impact of each support system on the evolution of: the drift closure, the stress distribution in the support and the deformation around the drift. Finally, the behavior of the GER drift is compared to other drifts of the MHM URL excavated in similar conditions.

2 GER DRIFT CHARACTERISTICS AND IN-SITU MEASUREMENTS

2.1 Drift description

With a total length of 83 m, the GER drift was excavated between October 2013 and September 2015 using a pneumatic hammer machine for the first 10 m and a road header machine for the following 73 m. It is divided into five segments with different types of supports as presented in Table 1. The main three segments (GER 2, 3 and 4) have a circular section with a diameter of about 5.4 m. The temporary support is installed some hours after the excavation of the section and the final concrete lining is cast in place after about 10 months. A complete description of the GER drift construction and in-situ monitoring can be found in Djizanne et al. (2019).

Table 1. Characteristics of the main three segments of the GER drift.

	GER2	GER3	GER4
Length [m]	21.2	21.6	25.2
Temporary support	18 cm of shotcrete + compressible wedges	18 cm of shotcrete + compressible wedges	18 cm of shotcrete
Final lining	-	30 cm of concrete	30 cm of concrete

2.2 Convergence measurements

In order to follow the evolution of the drift's closure, several sections of convergence measurements (SMC) using wire-Invar method were installed in three different positions for each of these main segments. Some are anchored in the rock mass one-meter-deep, others on the inner surface of the temporary support and/or on the final lining.

Convergence measurements recorded along vertical and horizontal strings, from 2015 to 2021, are presented in Figure 1. Note that the SMC installed on the temporary support (601B, 601D, etc.) and on the lining (602D, 602E, etc.) do not include the vertical string. Therefore, based on the measurements of the rock SMC (600B, 600D, etc.), it is possible to observe that the vertical closure is greater than the horizontal one. This behavior was also recorded on others drifts constructed in the direction of σ_h. In the GER case, the mean vertical/horizontal convergence ratio for the first days of measurement is about 1.6 for GER2, 1.9 for GER3 and 2.1 for GER4.

At about 50 to 100 days after the opening of the section, an increase in the vertical convergence rate is observed in all sections. This increase in vertical rate is thought to be associated with a delayed development of fractures in the rock mass below the drift's floor (Djizanne et al., 2019). Consequently, the mean vertical/horizontal convergence ratio reaches about 2.4 for GER2, 3.0 for GER3 and 3.4 for GER4. These ratios are close to the ratio found on drifts following the same direction (e.g. GED drift with a ratio of about 4.0 to 5.0) (Guayacán-Carrillo et al., 2016).

After the cast of the final concrete lining, the convergence rates drop significantly. Due to the progressive transfer of loads from the rock to the lining, a gradual decrease of the rates is observed during the first 2 months. Then, the converge rates present low values for the following years.

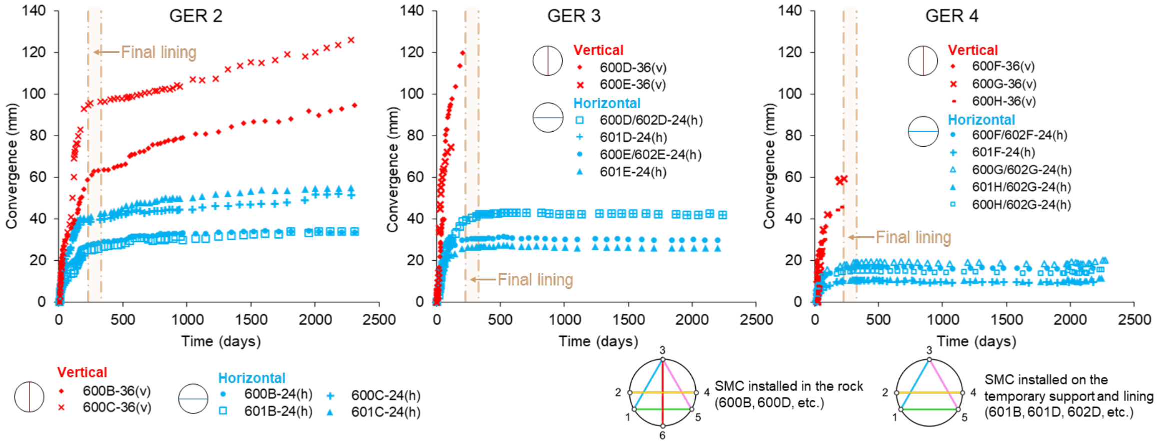

Figure 1. Convergence measurements in the MHM URL, for each segment of the GER drift.

Even though no final rigid lining is installed in the GER2 segment, a decrease of the convergence rate can be observed at the same moment as the concrete lining is being cast over the other segments. Then, for the next years of measurement, the deformation rate remains constant at about 1.5×10^{-6} days^{-1} for the vertical direction and 1.0×10^{-6} days^{-1} for the horizontal one.

Some differences in the behavior of sections that include compressible wedges in their temporary support and those which do not can be observed. Globally, GER2 and GER3 segments exhibit higher levels of convergence than GER4 as a result of the presence of compressible wedges. Before the cast of the concrete lining, the convergence in GER4 is approximately 40% lower than the other two for the vertical direction and about 50% lower for the horizontal one. Likewise, as mentioned above, the GER4 segment shows higher vertical/horizontal convergence ratio (of about 3.4) than the other two segments (from 2.4 to 3.0). This could be an indication that, while accommodating the deformation of the rock mass, the compressible wedges reduce the anisotropy of the drift's closure.

2.3 Extensometer measurements

A set of single-point and multi-point radial extensometers were installed in each of the three segments to measure the displacement within the rock mass. The section of measurement is composed of four extensometers installed in the vertical and horizontal directions of the cross section. Figure 2 shows the displacement measurements for GER 3 and GER4 multi-point extensometers at different depths inside the rock. Besides, extensometers were installed 16 days after the excavation of the section for GER3 and 24 days for GER4.

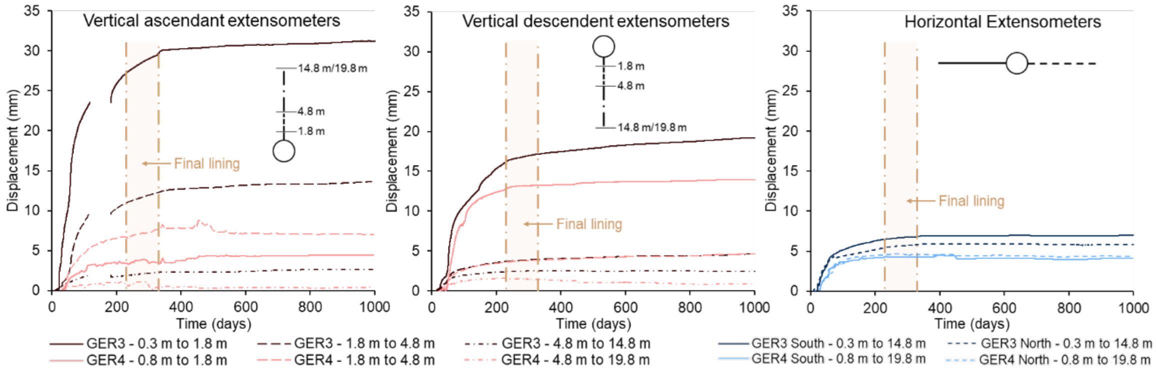

Figure 2. Measurements of multipoint extensometers installed around the drift – MHM URL.

The extensometers of both segments exhibit more displacement in the vertical direction than in the horizontal one. Also, the vertical ascending extensometer exhibits more displacement than the descending one, especially for the GER3 segment. On the other hand, horizontal displacement in both directions (North and South) is quite similar, characterizing a vertical symmetry of the closure for this drift. After the construction of the final lining, the displacements rates decrease to low values.

Based on these measurements, the behavior of the section with compressible wedges (GER3) can be compared to the one without (GER4). Like for the measured convergence, displacement in GER3 section is larger than in GER4 for both vertical and horizontal directions. Also, it is possible to observe a fairly higher displacement rate for GER3 in the vertical ascending direction. On the other hand, similar displacement rates can be observed for the vertical descending and the horizontal directions before the cast of the lining. different

Moreover, the mean vertical/horizontal displacement ratio for GER3 of about 5.5 is greater than the one for GER4, which is about 3.6. So, unlike the convergence measurements, these measurements do not seem to indicate a reduction of the anisotropic character of the closure. It should be noted that the extensometers measure the displacement starting at different depths at the two segments (0.3 m from the drift wall in GER3 and 0.8 m in GER4).

2.4 Temporary support stress measurements

Some monitoring sections were installed along the GER drift to measure the hoop stress inside the shotcrete of the temporary support. The measurements of two sections, placed in the GER2 and in the GER4 segment, are presented in Figure 3. The measurements are performed over one year after the excavation of the section. In both cases, the sensors of the total pressure cell system were installed around the drift at different angles a couple days after the excavation.

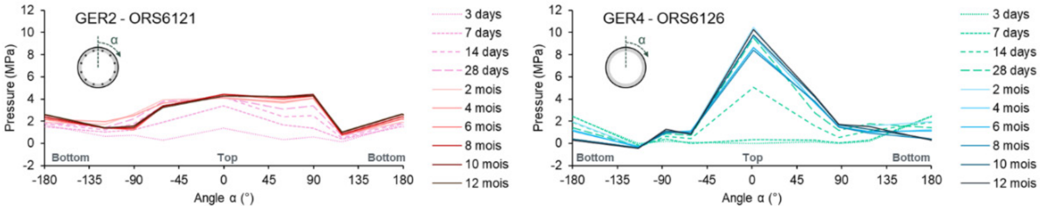

Figure 3. Total pressure measurements on the shotcrete of the temporary support – MHM URL.

For GER2, the pressure in the top part of the temporary support reaches 4 MPa after 14 days. Around the drift, the pressure takes values in between 2 and 4 MPa. This maximum pressure corresponds to the peak resistance of the compressible wedges (Djizanne et al., 2019). The wedges have a post-peak quasi perfectly plastic behavior that allows for a redistribution of the stresses around the drift. Consequently, this leads to a more isotropic closure of the section.

In GER4, a peak value of 11 MPa is measured in the support top after 28 days. The rest of the section, especially in the horizontal direction, remains at a lower level of the pressure, around 1 MPa. In absence of compressible wedges, the ground load on the support is not homogeneously distributed around the section. Therefore, the anisotropic closure of the rock mass tends to be conserved.

3 CONVERGENCE ANALYSIS

3.1 Fitting of the convergence law

The anisotropy of the drifts' closure is taken into account by considering that the initial circular section of the drift deforms to an elliptical shape. Following the methodology proposed by Vu et al. (2013) the main axes of the fitted ellipse are identified and the evolution in time of their length gives the principal direction of deformation and the maximal and minimal closure of the walls. For drifts following the direction of σ_h, as GER, the major convergence coincides with the vertical direction, and the minor convergence with the horizontal one (Guayacán-Carrillo et al., 2016). Then, the vertical and horizontal closures are fitted with the convergence law proposed by Sulem et al. (1987):

$$C(x,t) = C_{\infty x}\left(1-\left(\frac{X}{x+X}\right)^2\right)\left(1 + m\left(1-\left(\frac{T}{t+T}\right)^n\right)\right) \qquad (1)$$

In the above equation, the convergence evolution is a function of the distance, x, to the excavation face, and of time passed since the opening of the section, t. $C_{\infty x}$ is the instantaneous convergence considering an infinitely rapid excavation; X is a parameter related to the distance of influence from the excavation face; T is the parameter related to the time-dependent behavior of the rock mass and support system; m is the parameter describing the relationship between the instantaneous and the time-dependent convergence; and n is an exponent often taken equal to 0.3.

3.2 *Results of the analysis of the closure data*

An analysis of the convergence was performed following the methodology explained above on the measurements of the seven SMC installed in the rock. The results permit to characterize the impact of the final lining on the closure of the drift. It should be noted that the vertical convergence of the GER3 and GER4 sections after the lining installation were obtained using the elliptic fit based on horizontal and transversal strings measurements.

Then, a fit of the first 300 days of vertical and horizontal measurements was done for the parameters T and $C_{\infty x}$ of the convergence law while the other parameters are the same as the ones obtained by the analysis of a parallel drift, the GED drift (Guayacán-Carrillo et al., 2016). Thus, X is taken equal to 4.7 m or 4.9 m (0.9 times the diameter of the section), m is equal to 5.7 and n is equal to 0.3. The results of the analysis are presented in Table 2 and in Figure 4.

Table 2. Mean parameters resulted of the convergence law fitting analysis.

		GER2			GER3			GER4		
		Horiz.	Vertical		Horiz.	Vertical		Horiz.	Vertical	
T	[days]	6	16	36	6	16	36	6	16	36
$C_{\infty x}$	[mm]	8.1	18.4	22.0	7.7	25.7	30.7	4.4	15.6	18.4
Total convergence	[mm]	54.3	123.5	147.4	51.3	172.1	205.5	29.3	104.5	123.3

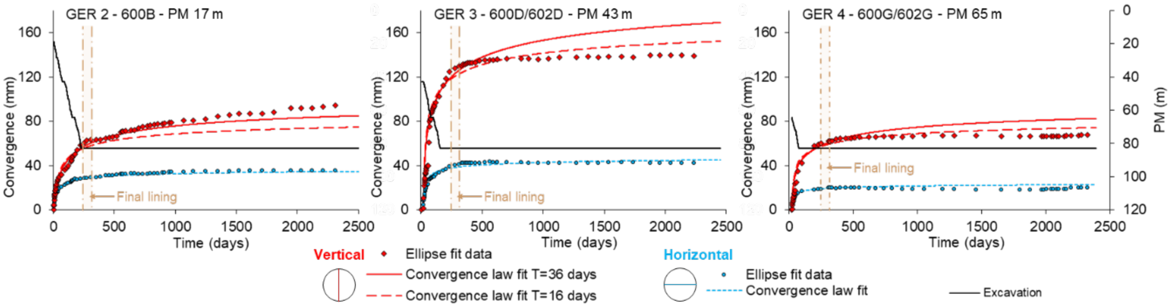

Figure 4. Results of the convergence law fitting analysis.

In a recent analysis of the GED drift, it was obtained that two values of the parameter T (16 and 36 days) should be considered for fitting the vertical convergence (Lara et al. 2023). The highest value of T permits to better represent the medium-term convergence rates whereas the lowest value should be used for the short-term data. For GED, the fitted vertical parameter $C_{\infty x}$ lies in between 24 and 32 mm for $T = 16$ days and in between 30 and 35 mm for $T = 36$ days. In the horizontal direction, $C_{\infty x}$ is about 5 to 8 mm for $T = 6$ days. The same values of parameter T are used for fitting the convergence data of GER. We obtain very similar values of $C_{\infty x}$ compared to those obtained for GED. Moreover, it can be observed that the medium-term rates of the vertical convergence in section 600B of GER2 are better represented by the fitted curve with the higher value of T (36 days). This is consistent with the observations obtained from GED analysis providing that both sections are supported by a soft system: shotcrete/compressible wedges for GER2 and sliding arches for GED.

Comparing GER4 results with the other segments, lesser values of $C_{\infty x}$ were obtained for both directions. Moreover, the vertical/horizontal ratio of this parameter is slightly lower for GER2 and GER3 indicating the influence of the compressible wedges.

The extrapolation of the fitted curves, can provide an insight on the potential convergence that has to be accommodated by the final concrete lining in GER3 and GER4. At 2000 days, the mean difference between the horizontal extrapolated curves and the measurements of the lined sections is about 12% for GER3 and 18% GER4. In the vertical direction, for $T = 16$ days, the difference is about 15% for GER3 and 13% for GER4. For $T = 36$ days, it is respectively 24% and 22%.

So, while the fit in the vertical direction with higher values of T better reproduces the convergence rates in the medium term, the extrapolation to the long term also leads to stronger convergence. This indicates that stronger lining pressure would be expected.

In the horizontal direction, the difference obtained is higher for GER4. This means that the compressible wedges could reduce the amount of convergence to be accommodated in this direction. In the vertical direction, an opposite behavior is obtained. As a matter of fact, before the cast of the final lining, in the absence of compressible wedges more deformation occurs in this direction which leaves less vertical convergence to be accommodated later by the final lining. Yet, after the cast of the lining, the anisotropic character of the closure is greater for the sections without wedges.

4 CONCLUSIONS

In-situ measurements of the GER drift of the MHM URL were presented and analyzed. For drifts following the direction of σ_h an anisotropic closure is observed (with a vertical displacement greater than a horizontal one) due to the stress state conditions and the development of induced fractured zones around the drift. Additionally, the hoop stress measurements in the temporary support indicate that the presence of compressible wedges in some segments of the drift significantly reduce the anisotropic distribution of the load around the section. Likewise, the convergence measurements seem to exhibit a similar reduction of the anisotropic closure due to the wedges.

A vertical and horizontal fit of the convergence law showed similar results compared to the ones obtained for the GED drift in previous works. This analysis also permits to confirm the observations of the measurements and extrapolate the drift closure in the long term. Further analysis will be performed on the stress measurements of the concrete lining to better evaluate its response to the different support conditions.

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