EFFECT OF WATER ON THE MECHANICAL BEHAVIOUR OF SHALES

WAKIM Jad[1], HADJ-HASSEN Faouzi[1], TIJANI Michel[1], NOIREL Jean-Francois[2]

[1] Ecole des Mines de Paris – CGES, 35, rue Saint-Honoré, 77305 Fontainebleau - jad.wakim@ensmp.fr

[2] Charbonnage de France – DTN, 2, avenue Emile Huchet, 57802 Freyming Merlebach

ABSTRACT: This paper aims to presenting the results of a research conducted in order to study the effect of water on the mechanical behaviour of the Lorraine Basin Colliery shale. The work performed can be divided into four main parts. The first part is dedicated to classical tests and it includes geological and mineralogical analysis as well as mechanical laboratory tests. The second part is devoted to the phenomenon of shale swelling under water effect. New procedures and equipment of testing were set up in order to characterise this swelling behaviour and to determine its model parameters. The tests performed in this second part are allowed to develop a phenomenological model which describes the elasto-visco-plastic behaviour of shales before and after saturation. The last phase of the work is dedicated to implement the new model in the finite element code VIPLEF in order to apply in tunnel excavated in swelling anisotropic rocks.

KEYWORDS: shale, swelling, anisotropy, strength weakening, creep, tunnel.

RESUME : L'objectif de l'article est de présenter l'influence de l'eau sur le comportement mécanique des schistes argileux de la houillère du basin de Lorraine. Le travail effectué est composé en quatre parties. La première partie concerne les caractéristiques géologiques et minéralogiques ainsi que les caractéristiques mécaniques des schistes argileux. La deuxième partie a pour but d'appréhender le gonflement des schistes sous l'effet de l'eau. Dans ce contexte, des nouveaux dispositifs expérimentaux ont été développés pour étudier et modéliser le gonflement. Les essais effectués nous ont permis à développer un modèle phénoménologique qui caractérise le comportement élasto-visco-plastique des schistes avant et après saturation. La dernière partie concerne à implanter le modèle développé dans un code de calcul par éléments finis VIPLEF pour l'appliquer sur un tunnel excavé dans une roche anisotrope gonflante..

MOTS-CLES : schiste argileux, gonflement, anisotropie, ramollissement, fluage, tunnel.

1. Introduction

Shale is the major constituent of sedimentary rocks covering approximately three-fifths of the terrestrial surface of earth. Shale may induce many geotechnical problems when they are put in contact with water or humidity. Unfortunately, these problems are found in many underground works such as radioactive waste disposal, mines, tunnels, oil wells and others.

Shale contains fine-grained less than $2\,\mu m$ in diameter of clays. Clays have a very high specific surface area and a residual imbalanced of electrical surface charge. The combination of these factors is the reason why clay particles adsorb polar molecules - like water - and therefore have a high affinity for polar liquids. The results of these factors are the creation of double diffuse layer that has a tendency to separate clay particles. The creation of double diffuse layer has a consequence to induce the macroscopic swelling. Other phenomena can coexist in shale such osmosis and capillarity. These phenomena are often known under the name of total suction.

The swelling of shale can lead to deterioration of the linkage between the layers in the clay particles resulting to reduction of mechanical properties such a Young's modulus and compressive strength. Basically, the increase of water content is the major factor for swelling. Swelling is strongly influenced by microscopic and macroscopic factors. On the microscopic scale, these factors are very complex and mainly depend on the mineralogical properties of the clayey materials and the chemical properties of the pore fluid. Another problem is the geometrical distribution of clayey layers that make the anisotropic swelling.

Although the swelling phenomenon takes place at the microscopic scale, it is a macroscopic approach that is used for prediction of the swelling.

2. Geotechnical properties of shale

The shale, present in the Lorraine Basin Colliery at 900 meters depth, is a sedimentary anisotropic rock. The density of this shale is 2.65. The mineralogical analysis by X-ray diffraction reveals that the rock is composed of 70 % of clayey minerals of which (40/55 %) of illite, (20/45 %) of chlorite and (5/35 %) of kaolinite, the remaining percentage being composed of quartz and feldspars. Both kaolinite and illite are known for being low to moderately expansive materials. The initial water content is 1.2 %. This value corresponds to well preserved samples after coring.

Mechanically, the uniaxial compressive strength is the order of 25 MPa and the indirect tensile strength is 3.7 MPa. The Young modulus, for a direction normal to bedding plan, is equal to 4000 MPa.

3. Effect of water on the Lorraine shale

In this paper, the effect of water on the rock is studied under the following two cases:

- Deterioration of the mechanical property,
- Swelling.

3.1. Deterioration of the mechanical property

The Lorraine shale is strongly sensitive to the variation of his water content. This reactivity has been initially verified by compressive wave velocity test, which effects in a normal direction to bedding plane, for different samples at different water contents. A linear decrease with increasing water content observed in the figure 1 for normalized p-wave velocity is due to apparition of micro cracks. Fooks and Dusseaulet (1996) found some similar linear variation in case of the Pierre shale.

Triaxial compression tests have been done on the Lorraine shale samples for two conditions of saturation. The first corresponds to the initial state before the saturation of the sample and the second corresponds to the saturation state where the water content is 5 %. The figure 2 presents the Coulomb failure envelopes for two water contents. We can conclude that there is a 70 % loss in the uniaxial compression strength, a 78 % loss in the friction angle and 45 % loss of the cohesion when the water content varies from 1.2 % to 5 %. In the elastic domain, an 80 % loss in the Young modulus has been observed. However, the Poisson ratio has the same value.

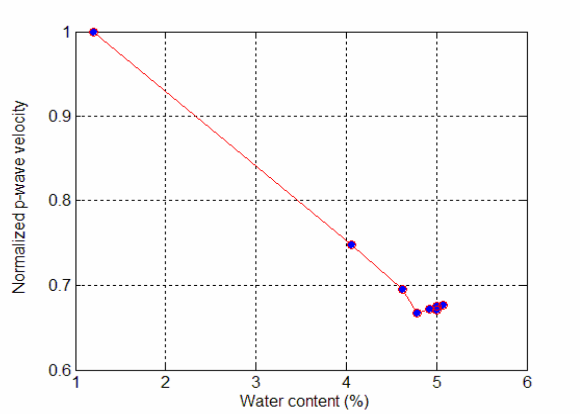


Figure 1. Normalized p-wave versus water content

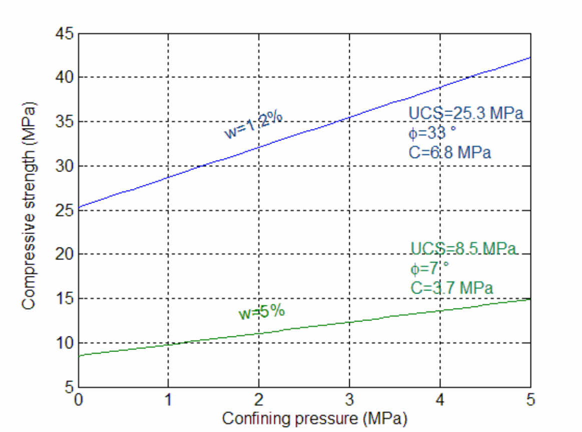


Figure 2. Mohr-Coulomb failure criteria for two water contents

The Fooks and Dusseaulet model considers that the Mohr-Coulomb failure criteria depends on the water content and it can be written as the following equation:

$$\frac{\sigma_1 - \sigma_3}{2} = (-\alpha_1.w + \alpha_2).\frac{\sigma_1 + \sigma_3}{2} - \alpha_3.w + \alpha_4 \quad (1)$$

Using this model, we can estimate, as a function of the water content, the reduction of: uniaxial compressive strength (UCS), friction angle and cohesion (figure 3).

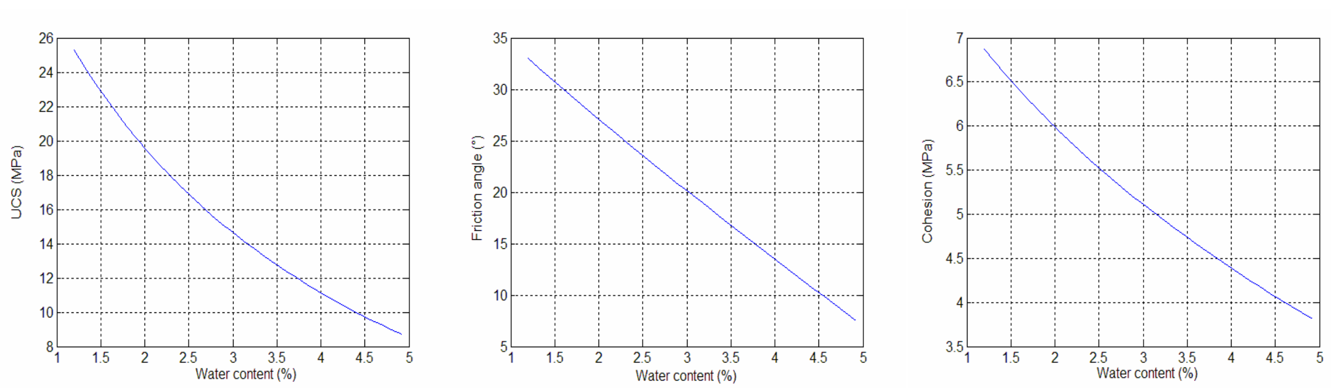


Figure 3. UCS, friction angle and cohesion versus water content

The parameters of model are: α_1=11.12; α_2=0.67; α_3=53.3 and α_4=6.40.

3.2. Swelling

Swelling depends on different macroscopic parameters such as the initial water content, the chemical properties of solution and the applied stress.

This paper will concentrate on the influence of the stress in three-dimensional anisotropic swelling of shale.

From the bibliographic researches, three contradictory cases are cited to explain and to model the three-dimensional swelling of argillaceous materials:

1- Independence of swelling following a principal direction with the stress following the other directions (Zhou et al., 1992; Kiehl, 1989; Froehlich, 1987), 2- Increase of swelling following a principal direction with the stress following the other directions (Yesil et al., 1993; Windal, 2001),

3- Decrease of swelling following a principal direction with the stress following the other directions (Hawlader, 2003; Wong, 1997; Lo. 1989).

These different observations have directed us to conduct different experimental tests in order to understand the swelling behaviour of the Lorraine shale.

4. Experimental apparatus

The experimental program is completed from different apparatus that are:

- *Triaxial apparatus:* it allows to apply different paths of axial and radial stress and to measure the axial swelling or the axial swelling pressure generated after blocking completely or partially the axial displacement. The sample has a 50 mm in diameter and 25 mm in height. The axial stress is applied by a hydraulic piston with a rate of deformation equal to 120 micron/m/min and the confining pressure is applied by an oil injector. This pressure is then transmitted to the sample by an impervious silicone jacket. The saturation of the sample is assured by the injection of water from bottom to top through the porous stone.

- *Uniaxial apparatus*: This apparatus can measure the axial swelling and the radial swelling for different paths of axial pressure. The diameter of samples is 50 mm and the height is 35 mm. The axial swelling is measured by two LVDT sensors while the radial swelling is measured diametrically by a steel ribbon surrounding the sample and linked to a LVDT sensor.

- *Zero swelling apparatus*: This cell allows to measure the axial swelling pressure of a sample prevented to swell axially and laterally. The device is constituted of a rigid metallic ring with interior diameter of 63.1mm. The height of samples can vary from 10 mm to 20 mm.

- *Free swelling apparatus*: it can measure the axial and radial swelling of a sample with a 50 mm in diameter. The height can vary between 20 to 60 mm.

5. Laboratory swelling behaviour of the shale

The purpose of this experimental study is to show the influence of a lateral condition or an axial stress on the axial swelling or a radial swelling. In this study, the sample show transverse isotropy.

5.1. Influence of the deviator stress and the mean stress

Two tests of axial swelling measurement have been done for the same deviator stress $Q = \sigma_1 - \sigma_3$:

- Free swelling test ($\sigma_1 = \sigma_3 = 0$),
- Triaxial swelling stress ($\sigma_1 = \sigma_3 = 1$).

For the free swelling test, the axial swelling normal to the bedding plane is 3 %. On the other hand, the axial swelling observed in the triaxial test is 0.3 %. These results show that the deviator stress does not affect a swelling.

Globally, for anisotropic shaly rocks, the swelling in a direction is not affected by the mean stress. This stress can have an effect on the clayey soils generally presenting an isotropic behaviour.

5.2. Influence of the radial tolerated swelling on the axial swelling pressure

To study the influence of the radial tolerated swelling on the axial swelling pressure normal to the bedding plane a sample of which diameter is 61 mm. The tolerated radial swelling is then extensively elevated with regard to the free radial swelling.

On the figure 4 we can note that, even though the radial swelling is prevented or not, the axial swelling pressure is for each situation nearly comparable to 0.65 MPa.

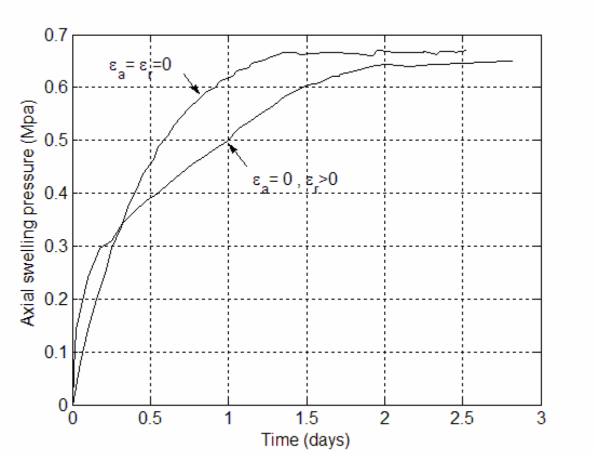


Figure 4. Swelling pressure versus time for two differents lateral confinement

5.3. Influence of the axial pressure on the radial swelling

Two tests have been carried out for different steps of unloading of the axial stress measuring simultaneously the radial swelling and the axial swelling.

Chosen stress paths are the following:

- 0.7, 0.4, 0.2 and 0.1 MPa
- 1.01, 0.7 and 0.5 MPa

These two tests are illustrated on the figure 5.

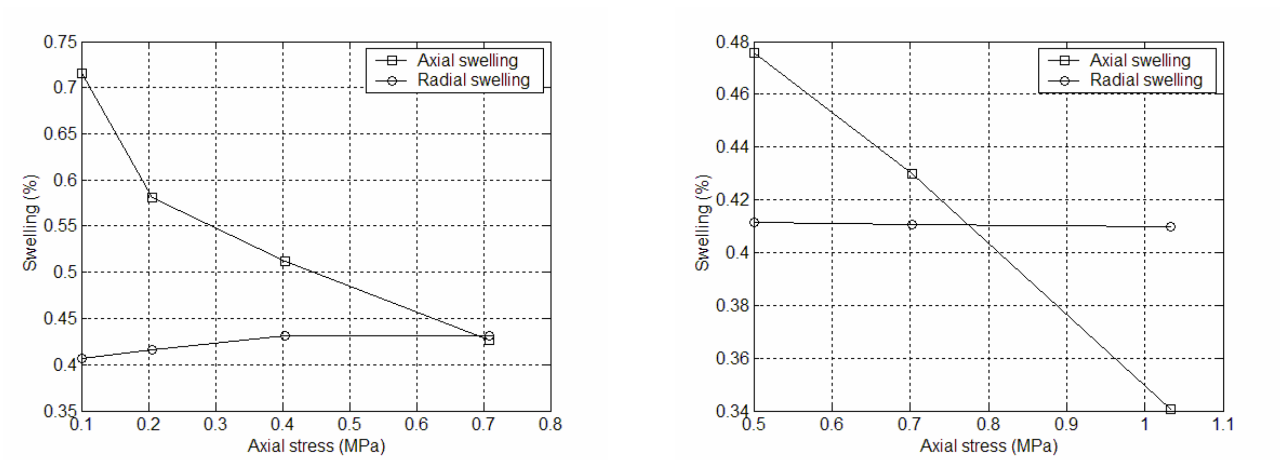


Figure 5. Axial swelling and radial swelling versus axial stress

For these tests, although the axial swelling increases with the reduction of the axial stress, no considerable difference of radial swelling has been observed. We can deduce that the lateral swelling is not influenced by the applied axial stress and by the path of axial stress.

The figure 6 presents two tests one of them done with oedometric apparatus and the other by uniaxial apparatus.

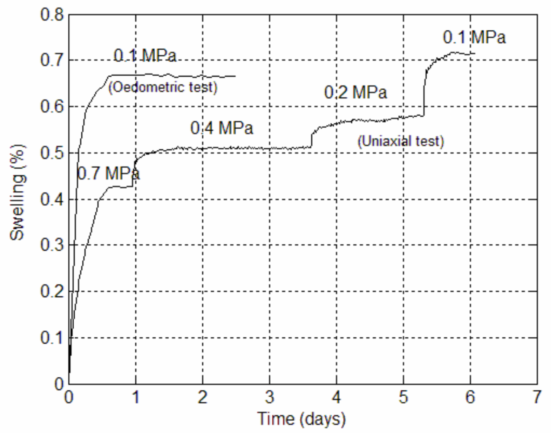


Figure 6. Comparison between unaxial test and oedometric test for 0.1 MPa of axial stress

For the same axial stress of 0.1 MPa, the axial swelling is approximately the same whatever is the lateral confinement.

To confirm the previous results, a swelling test conducted in triaxial apparatus in conditions of isotropic stress of 1 MPa generates an axial swelling of 0.3 %. A uniaxial swelling test with an axial stress equal to 1 MPa generates an axial swelling equal to 0.34 %. This value is approximately similar to the axial swelling measured by triaxial cell.

These results illustrate that the axial swelling is independent from the applied confining pressure.

5.4. Study of the reversibility of swelling

Two triaxial tests, for the same confining pressure of 1 MPa, have been done for different steps of unloading of the axial stress. The applied axial stresses are:

- 4.5-3.5-2.5 MPa
- 3.5-2.5-1.5 MPa

These tests present the two identical stress which are 3.5 and 2.5 MPa. For the same axial stress, the difference of axial swelling between the two tests is small in the order of 0.03 %.

In addition to the previous tests, the two uniaxial tests presented on the figure show that for the same stress of 0.7 MPa the difference of deformation is 0.01 % which is negligible.

6. Rheological model

The presented theoretical model concerns to study the evolution versus the time of the strain of the anisotropic shaly rock before saturation and after saturation by water.

These strains are clearly presented in the figure 7 that represented a uniaxial test with measuring of axial strain normal to the bedding plan. The applied axial pressure is equal to 1.2 MPa.

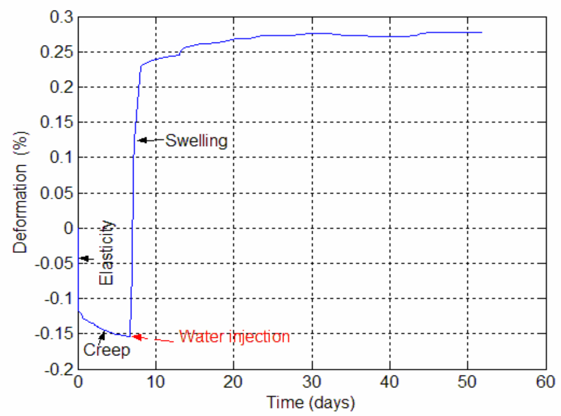


Figure 7. Three phases of deformation

These three phases can be summarised as following:

- Elastic phase
- Creep phase
- Swelling phase

A phenomenological model has been developed to predict the elasto-visco-plastic behaviour of the shale and can be summarized by the following equation:

$$\varepsilon(t) = \left[\varepsilon^{e} + \varepsilon^{vp}(t)\right].He\,(t_s - t) + \varepsilon^{s}(t).He\,(t - t_s) \qquad (2)$$

where ε^e , ε^{vp} and ε^s: are respectively the elastic, the visco-plastic, and the swelling strain at a given time t, t_s : the time of saturation and He: the Heaviside function.

6.1. Creep

The presented creep model is inspired by the Lemaître's visco-plastic law but it is generalized to anisotropic materials (Tijani, 2004). In case of triaxial stress, the creep in the vertical direction is:

$$\varepsilon_3^{vp}(t) = -\sqrt{A}.\left(\frac{\sigma_1 - \sigma_3}{k_\theta}\right)^{\beta}.t^{\alpha} \qquad (3)$$

With,

$$k_\theta = \frac{k}{A^{\left(1+\frac{1}{\beta}\right).\frac{1}{2}}} \quad \text{and} \quad A = 1 + \frac{w}{4}.\sin^2(2\theta)$$

w designs the anisotropic creep and θ is the angle between the vertical axis and the normal vector to bedding plane. β, α and k are the same parameters of Lemaître's law.

6.2. Swelling

Based upon the results of swelling tests, the law of swelling is based on the following assumption:

- Reversibility of swelling,
- The direction of principal swelling $\varepsilon_{i\infty}^{s}$ (i=1, 2, 3) coincides with the direction of principal normal stress σ_i ,

- The main swelling $\varepsilon_{i\infty}{}^{s}$ only depends on the principal stress σ_i,

- The anisotropic of swelling can be deduced by a geometrical transformation.

(The notations s, i and ∞ corresponds respectively to swelling, to the direction of swelling and to the stabilization time).

For time t=∞, the following equation describes the relationship between swelling and the stress following a principal direction "i" (Wong et al., 1997).

$$\varepsilon_{i\infty}{}^{s} = A_i.\left[1-\left(\frac{\sigma_i}{\sigma^s{}_i}\right)^{c_i}\right].He\left(\sigma^s{}_i - \sigma_i\right) \qquad (i=1,2,3) \tag{4}$$

where $\varepsilon_{i\infty}{}^{s}$ and σ_i: the maximal swelling strain and stress parallel or perpendicular to the anisotropy and A_i $\sigma^s{}_i$: the free swelling and the swelling pressure parallel or perpendicular to the anisotropy, c_i: the power factor parallel or perpendicular to the anisotropy and.

It is necessary to note that in this case the swelling pressure doesn't correspond to the one measured by zero swelling test. The method used to estimate this pressure is identical to the parallel stress method.

6.3. Integration of the time

The rate of swelling vector $\left\{\dot{\varepsilon}^{s}(t)\right\}$ is expressed by the following expression:

$$\left\{\dot{\varepsilon}^{s}(t)\right\} = \frac{1}{n_s}.\left[\left\{\varepsilon_{i\infty}{}^{s}\right\} - \left\{\varepsilon^{s}(t)\right\}\right] \tag{5}$$

n_s is the kinetic of swelling and $\left\{\varepsilon^{s}(t)\right\}$ is the swelling vector in the local cartesian system .

For $t \to \infty$, the rate of swelling reaches zero.

For one loading step, the principal swelling in "i" direction is:

$$\varepsilon_{i,1}{}^{s}(t) = F_1.\left[1-\exp\left(\frac{-t}{n_s}\right)\right] \tag{6}$$

For several unloading steps, the swelling is:

$$\varepsilon_{ik}{}^{s}(t) = \varepsilon_{i,1}{}^{s}(t) + \sum_{k=2}^{n} \Delta F.\left[1-\exp\left(\frac{t_{k-1}-t}{n_s}\right)\right].H_e(t-t_{k-1}) \tag{7}$$

With,

$\Delta F = F_k - F_{k-1}$

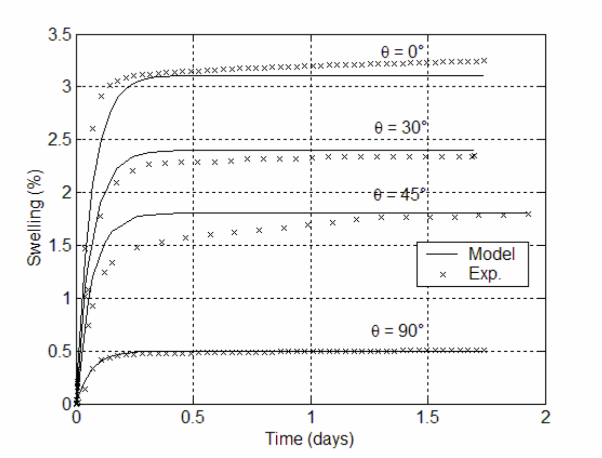
$F_k = A_i.\left[1-\left(\frac{\sigma_{i,k}}{\sigma^s{}_i}\right)^{c_i}\right]$

k corresponds to the number of loading steps and t_k is the beginning time of the loading step $k+1$.

6.4. Validation of the proposed model

The presented model has been adjusted on different tests with axial measuring:

- Free swelling for four orientations (0°, 30°, 45°, 90°)
- Uniaxial tests for two orientations (0°, 90°)
- Maximal swelling for different axial stress and for two orientations (0°, 90°)



. Figure 8. Free swelling.

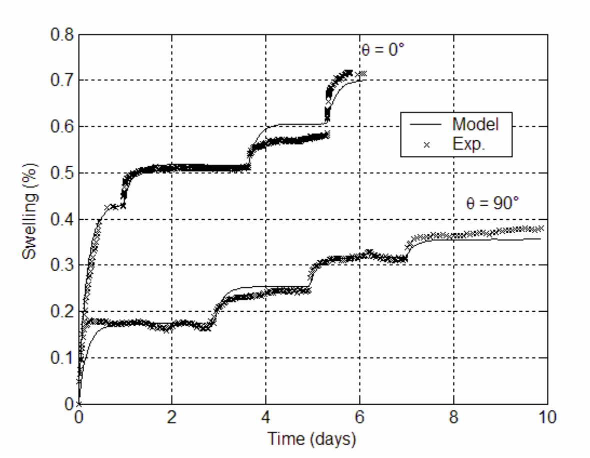


Figure 9. Uniaxial swelling.

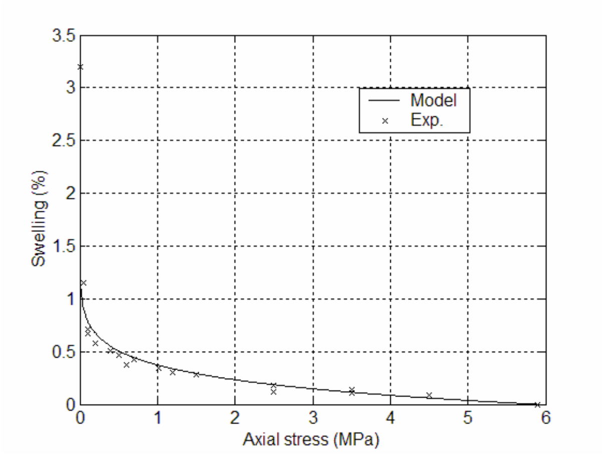


Figure 10. Maximal swelling for $\theta = 0°$.

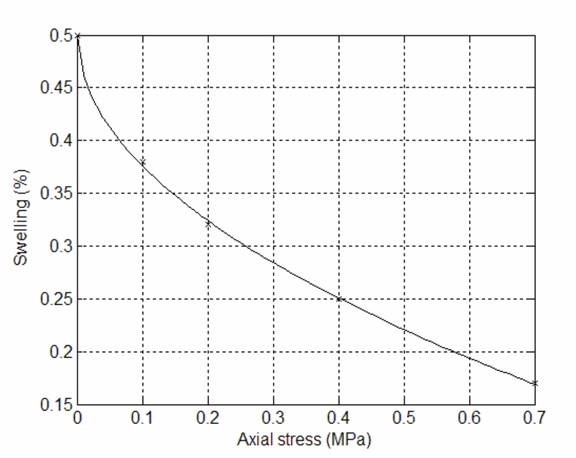


Figure 11. Maximal swelling for $\theta = 90°$.

For combined test creep-swelling, the model has been applied to one uniaxial test:

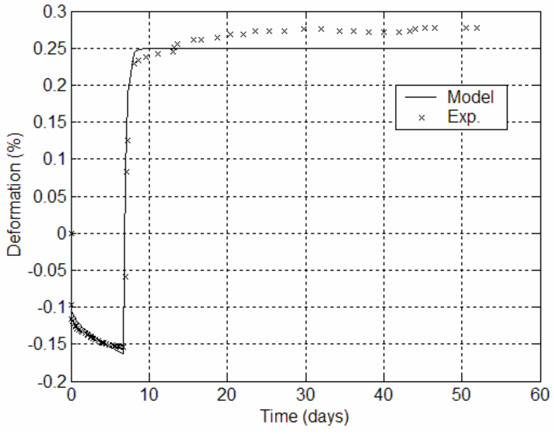


Figure 12. Combined test for $\theta = 0°$

The parameters of proposed model are illustrated in the following table:

Table 1. Parameters for model (stress in MPa and time in days)

Swelling parameters	**Value**
Free swelling $(\theta = 0°)$	0.032
Free swelling $(\theta = 90°)$	0.005
Swelling pressure $(\theta = 0°)$	6 MPa
Swelling pressure $(\theta = 90°)$	2.1 MPa
C $(\theta = 0°)$	0.068
C $(\theta = 90°)$	0.504
Mean n_g	0.1
Creep parameters	**Value**
β	1.236
α	0.496
k	$1.573.10^3$

6.5. Simulation of swelling with VIPLEF

The model developed has been integrated in finite element code VIPLEF. The objective of this part is to show results of simulation the anisotropic swelling behaviour of the ground with a shistosity inclined at 20° regarding the horizontal and especially around a tunnel. The tunnel has a-400 meter height of overburden. The initial overburden pressure is approximately equal to 10 MPa.

The tunnel has an arch shaped cross section (Figure 14). The tunnel is located with the invert in shale and with the crown in a limestone which elastic behaviour. After excavation and installation of 50 cm thick of the reinforced concrete lining, the rock mass underneath the tunnel was watered.

A cross-section view of the plane strain element finite mesh used in the analyses is shown in figure 13.

Appropriate boundary conditions were applied at the boundaries (in the extremity of works u=0 for lateral boundary and v=0 for bottom boundary).

The simulation has been executed in two phases:

- Excavation of tunnel in elastic domain,
- Swelling.

The figure 14 presents the displacement due to swelling of lining, we show that the swelling is not symmetric because the anisotropic swelling primordial in the direction normal to bedding plan.

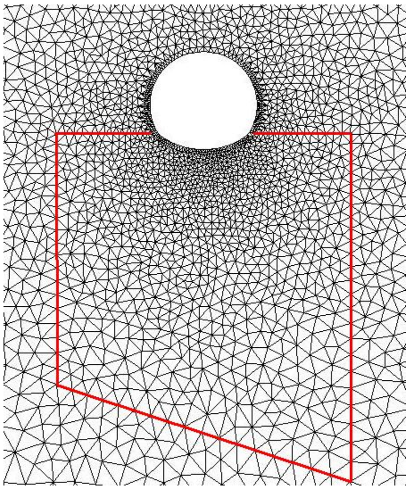


Figure 13. Detailed of the mesh used in modelling

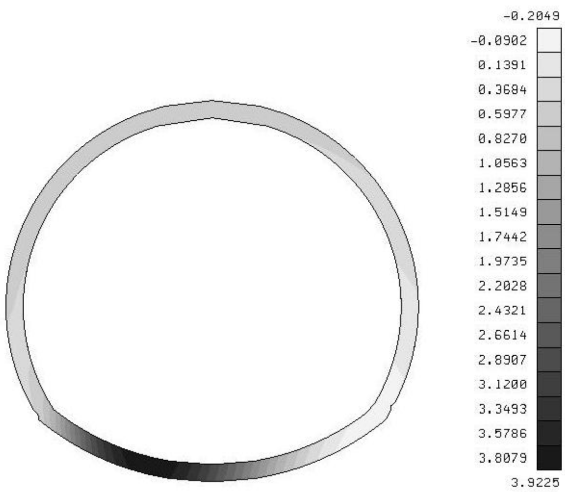


Figure 14. Vertical displacement of lining (mm)

The figure 15 presents the normal swelling along invert section, the maximum swelling is 3.5 mm at 3.2 m from left extremity of inverted arch. In fact, in the centre of inverted arch, the swelling is 2.1 mm.

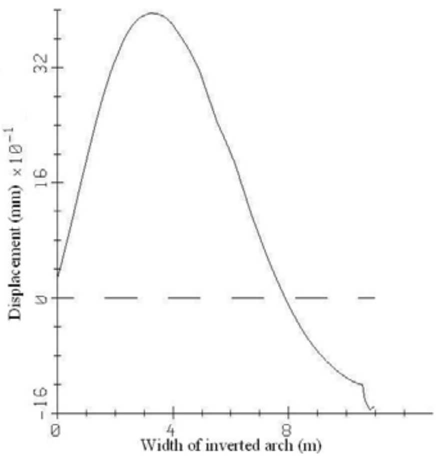


Figure 15. Normal displacement to invert (mm)

7. Conclusion

Lorraine shale is very sensitive to water as a result swelling and reduction of mechanical property are observed.

The accomplished experimentations have permitted to develop a phenomenological swelling model. This model has been applied on different experimental tests and a good agreement has been found with the theory.

The integration of the model in VIPLEF has allowed to visualize the anisotropic swelling along the invert of the tunnel.

For the future research, some new experimental tests need to be conducted to analyse the effect of the chemistry solution on the swelling.

8. References

Fooks J.C., Dusseault M.B. (1996). *Strength of Pierre I shale as function of moisture content.* Eurock 96, Eds. Barla, 77-82.

Froelich O.B (1978). *Anisotropic swelling behaviour of diagenetic consolidated claystone* . Commision of swelling rock. Int. Soc. Rock. .Mech., 1487-1488.

Hadj-Hassen F, Gordine .D, Accarie H. (2002). *Rapport sur le gonflement des schistes argileux. Rapport interne.* CGES-ENSMP.

Hawalader B.C, Lee Y.N, Lo K.Y (2002). *Three-dimensional stress effects on time-dependent swelling behaviour of shaly rocks*. Canadian Geotechnical Journal, Vol. 40, 501-511.

Kiehl J.R (1990). *Ein dreidimensionales quellgesetz und seine anwendung auf den felshohlraumbau*. Proc. 9th Natn. Felsmechanik Symp.,Aachen Germany, 185-207

Lo K.Y, LEE Y.N (1989). *Time dependent deformation behaviour of Queenston shale*. Canadian Geotechnical Journal, Vol. 27, 461-471.

Tijani M. (2004). *L'aisotropie transverse*. Note interne CGES, Ecole des Mines des Paris, 2004.

Windal T. (2001). *Etude en laboratoire du gonflement des sols: mise au point d'un oedomètre flexible et étude du gonflement tridimensionnel*, Phd Thesis, laboratoire de Mécanique de Lille, Université des .Sciences et Technologie, 128 pages.

Wong R.C.K, Wang E.Z (1997). *Three-dimensional anisotropic swelling model for clay shale – A fabric approach.* Int. J. Rock. .Mech. Min. Sci.. Vol. 34, 2, 187-189

Yesil M.M., Pasamehmetoglu A.G. et Bozdag T. (1993). *Technical Note, A Triaxial Swelling Test Apparatus*, Int. J. Rock. .Mech. Min. Sci, Vol. 30, 4, 443-450.

Z.H.Zhou, R.Z.Huang, Y.F.Chen (1992). *Constitutive equations of shale and clay swelling: Theoretical model and laboratory test under confining pressure*, Society of petroleum engineering , 22382, 529-540.