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Influence of the *in situ* pore water pressure on the stability of deep galleries in saturated porous media

Influence de la pression d'eau *in situ* sur la stabilité de galeries profondes dans des milieux poreux saturés

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ABSTRACT: Among the several parameters involved in the analysis of deep galleries driven in saturated porous media, the paper focuses on the pore water pressure that pre-exists in the medium. Numerical simulations clearly emphasise the influence of this factor on the magnitude of the hydro-mechanical disturbances arising in the surroundings of the gallery as well as on the short and long term soil-structure equilibrium states. Comparing those results with the existing NIM and SSP design methods developed for monophasic media, it comes out that these tools are inappropriate to calculate the stability of galleries in saturated porous media, except for the short term equilibrium if the undrained properties of the monophasic media used in these methods were evaluated from the poro-elasto-plastic data (including the initial pore water pressure!) by means of an equivalence principle.

RÉSUMÉ: Parmi les divers paramètres intervenant dans l'analyse de galeries profondes creusées dans des milieux poreux saturés, l'article s'intéresse à la pression d'eau préexistante dans le milieu. Des calculs par éléments finis soulignent clairement l'influence de ce facteur sur l'amplitude des perturbations hydro-mécaniques se développant aux alentours de la galerie ainsi que sur les situations d'équilibre à court et long terme. En comparant les résultats de ces calculs avec les méthodes de dimensionnement NIM et SSP développées pour des milieux monophasiques, il ressort clairement que ces dernières ne conviennent pas pour vérifier la stabilité de galeries creusées dans des milieux poreux saturés, excepté pour le court terme pour autant que les caractéristiques non drainées du milieu monophasique utilisées par ces méthodes aient été déterminées à partir des données poro-élasto-plastiques (incluant la pression d'eau *in situ*) grâce à un principe d'équivalence.

1 DESIGN OF DEEP TUNNELS

In spite of the development of three-dimensional finite element software, the indeterminate problem which makes up soil mass-supporting structure interaction is generally studied in a state of plain strain. However, even though this two-dimensional strain state may be accepted at a certain distance of the cutting face, the stress state is three-dimensional near the face. Various techniques have, therefore, been developed to take into account the partial decompression of the soil mass before the placement of the supporting structure.

In the particular situation where the problem may be idealised by an axial-symmetric configuration (homogeneous isotropic mass, isotropic pre-existing stresses, circular structure), many contributions exist, resulting primarily in the development of the convergence-confinement method (AFTES 1983, Brown & al 1983, Panet 1995) also known as the characteristic lines method.

In this analytical method, as for numerical simulations, the correct appraisal of the equilibrium between the soil mass and the lining depends on the correct estimate of the decompression which the soil mass has already undergone before the placement of the supporting structure, especially in front of the cutting face. In the early nineties, substantial progress was achieved with the development of two new methods:

1. The new implicit method (NIM) is a semi-analytical tool developed by Bernaud (1991) from numerous numerical calculations with finite elements (sequential simulation of the excavation process). It is based on the same general principles as those of the convergence-confinement method, but permits the inclusion of the coupled character of the soil mass-supporting structure interaction problem, in that the stiffness and the placement distance of the lining also are included in the determination of the initial convergence of the excavation walls.

2. Based on similitude principles and retaining the reasoning of the convergence-confinement method, two methods were proposed by Corbetta (1990) and Nguyen-Minh (1992) to delimit

the soil mass-lining equilibrium state: an inferior value supplied by the method of similitude (SSP) itself and a superior value estimated by an extension of this method. The domain of use and degree of precision of these solution techniques have been evaluated by comparison with results of finite element simulations (carried out according to an integration algorithm based on a stationary regime hypothesis).

2 INAPPLICABILITY TO SATURATED POROUS MEDIA

The new implicit method (NIM) and the methods resulting from the principles of similitude (SSP) were developed for monophasic media and cannot be applied as is to saturated porous media. The following remarks may be made:

1. The relative stiffness of the solid skeleton and of its pore water, and the porosity of the medium, are not taken into account in the solutions.

2. These methods do not yield information concerning an instantaneous decrease in pore pressure generated during the excavation of tunnels as a result of hydro-mechanical coupling.

3. According to Giraud (1993), the equivalence between a porous elasto-plastic medium and a monophasic elasto-plastic medium depends on the geometry of the problem (cylindrical or spherical) as well as the initial hydraulic conditions. These aspects are not taken into account in these methods.

These limitations are somewhat commented in subheadings 2.1, 2.2 and 2.3.

2.1 *Monophasic versus porous media*

Since the above-mentioned methods were developed for monophasic media, their domain of use includes dry granular media and compact rock masses; but their use has frequently been extended to include saturated media with low permeability by using equivalent undrained mechanical characteristics. The study

of the response of a saturated porous medium using these methods implies the consideration of the solid skeleton and the pore fluid as one phase and does not differentiate between the respective contributions of these two components.

The mechanics of porous media differentiates itself clearly from this monophasic approach. This theory, developed by Biot in the early 1940's, somewhat constitutes an extension of the "classical" soil mechanics developed by Terzaghi (1925) in that it does not assume the incompressibility of the components. Applied to saturated porous media, this theory differentiates between the relative contributions of the solid skeleton and the pore fluid as well as the deformability of these two components.

2.2 Hydro-mechanical disturbances

In saturated porous media, the excavation of galleries leads to both mechanical and hydraulic disturbances in their surroundings, namely a de-stressed damaged zone and a significant drop in pore water pressures. This not very known phenomenon of instantaneous pore pressure decrease has already been observed in centrifuge tests (Mair, 1979) and around openings in Boom clay, London clay and Opalinus clay formations. It is brought about by hydro-mechanical coupling in the saturated media.

Now, total stress analyses for monophasic media just evaluate the mechanical disturbance associated with the excavation of the structures, and generally do not mention the existence of the hydraulic disturbance. When this is the case (Randolph & Wroth 1979, Mair & al 1992), the pore fluid is considered to be incompressible and the decrease in pore pressure brought about during the excavation is calculated based on the variation in mean total stress in the decompressed zone.

On the other hand, effective stress analyses of tunnels excavated in porous media (e.g. Giraud 1993 and Picard 1994) lead to predictions of instantaneous decreases in pore pressure, even bringing about for large decompressions negative pore pressures (suctions) in the zone near the wall. Beyond this stage of excavation assumed to be instantaneous, it is worthwhile to study the redistribution of pore pressures as a function of time, notably because these are responsible for time dependent effects around the tunnels (essentially variations of convergence and/or support pressure).

2.3 Equivalence principle

The equivalence principle developed by Giraud (1993) establishes that the instantaneous behaviour of a porous elasto-plastic medium undergoing an instantaneous mechanical stress is equivalent to that of a monophasic elasto-plastic medium (undergoing the same stress), and it permits the determination of the equivalent undrained characteristics of the monophasic medium based on the intrinsic characteristics of the soil matrix and pore fluid for usual criteria of plasticity. The practical interest of this principle is to enable the determination of the instantaneous response of a porous medium from available analytical solutions for monophasic media.

Giraud stresses that the equivalent mechanical properties of the monophasic elasto-plastic medium depend not only on the intrinsic characteristics of the porous elasto-plastic medium but also on the geometry of the problem (e.g. cylindrical or spherical) as well as on the initial hydraulic and mechanical conditions, i.e. the initial values of the pore pressure field and the stress tensor (except for a Tresca criterion).

On the basis of this dependence on the geometry of the problem, it comes that simulations of tunnels in which the saturated porous media is treated as a monophasic media with undrained parameters will be tainted with error. Indeed, given that the response of a medium during the excavation of a circular structure is of a spherical type in front of the cutting face and of a cylindrical type behind the face, the equivalent mechanical characteristics will be different in these zones (except for a Tresca material, as confirmed by Benamar (1996)).

Table 1. Parameters of the problem.

porous media characteristics	
E'	Young's modulus
ν'	Poisson's ratio
c'	cohesion
φ'	friction angle
ψ	dilation angle
n	porosity
K_w	water bulk modulus
k	permeability coefficient
p_0	in situ total stress
p_{p0}	in situ pore water pressure
gallery characteristics	
R	external radius of the gallery
E_l	Young's modulus of the lining
ν_l	Poisson's ratio of the lining
e_l	thickness of the lining
d_0	distance between lining and tunnel face
v	excavation speed

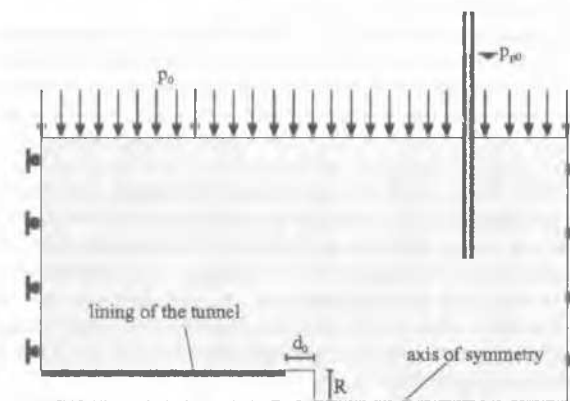


Figure 1. Geometry of the problem.

Since two-dimensional axial-symmetric simulations have been used to develop the "simplified" design methods presented in chapter 1, it may be stated that these methods, available for monophasic media, cannot be applied as is to saturated porous media. Only those simulations based on the mechanics of porous media and the intrinsic characteristics of the components of the medium will be truly adequate and will permit the determination of the domain of use of the new implicit method and the principles of similitude.

3 SIMULATION

3.1 Parameters of the problem

Consider a circular gallery excavated in a saturated porous media characterised by a linear-elastic perfectly plastic stress-strain relationship and a Mohr-Coulomb failure criterion with dilatancy. The analysis of the soil mass-supporting structure interaction is a complex problem involving a large number of factors (Table 1, Figure 1):

3.2 Non dimensional analysis

In order to understand and to quantify the influence of these 16 parameters, it is preferable to work with non-dimensional variables and thus to reduce the number of independent parameters. This has been achieved by means of closed-form solutions that have been developed for the short-term response of a poro-elasto-plastic medium due to the excavation of circular and spherical cavities (Labiouse & Giraud 1998). The 8 non-dimensional parameters resulting from this analysis are summarised in Table 2.

Table 2: Isolated non-dimensional parameters

v'	$\frac{c'}{p'_0}$	φ'	ψ	$\frac{K_w}{n K'}$	$\frac{k_1}{K'}$	$\frac{d_0}{R}$	$\frac{p_{p0}}{p'_0}$	$\frac{v}{k}$
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where : $p'_0 = p_0 - p_{p0}$ is the in situ effective stress

and
$$k_1 = \frac{E' [R^2 - (R - e_1)^2]}{(1 + \nu_1) [(1 - 2\nu_1)R^2 + (R - e_1)^2]}$$

3.3 Finite elements calculations

To analyse the influence of these parameters, numerical simulations are carried out in a two-dimensional axial-symmetric configuration using the finite element code Z_soil 5.0 (2000). A sophisticated non-dimensional FE-model has been developed, taking into account the sequential tunnelling process, the stiffness and placement distance of the lining and the excavation speed.

Two extreme conditions are considered in the calculations: a short term one corresponding to the completion of the gallery construction, and a long term one corresponding to the situation when the excess pore water pressures have dissipated. The hydraulic boundary condition at the gallery wall is either permeable or impermeable depending on the lining material.

4 PRELIMINARY RESULTS

Preliminary results of the calculations in progress are hereafter presented. A reference case corresponding to a real situation is first analysed. Then a parametrical study is performed to assess the influence of the pre-existing pore water pressure.

4.1 Data of the reference case

The reference case is based on the underground research laboratory HADES (Mol / Belgium) built at 223 m depth in an over-consolidated clayey formation. The geotechnical data presented in Table 3 were chosen to be representative of the Boom Clay formation, while the lining characteristics were changed compared to the real ones (for illustration purposes).

Table 3: data of the reference case

porous media characteristics		lining characteristics	
E'	300 [MPa]	R	1.91 [m]
ν'	0.125 []	E_l	5000 [MPa]
c'	0.3 [MPa]	ν_1	0.2 []
φ'	18 [°]	e_1	0.1 [m]
ψ	0 [°]	d_0	0.5 [m]
n	0.39 []	v	2 [m/day]
K_w	2000 [MPa]		
k	$2 \cdot 10^{-12}$ [m/s]		
p_0	4.50 [MPa]		
p_{p0}	2.25 [MPa]		

From the equivalence principle [Giraud, 1993], we can calculate the undrained characteristics of the monophasic medium that are equivalent to the above-mentioned poro-elasto-plastic data. They are reported in table 4. As explained in subheading 2.3, the equivalent strength parameters depend on the geometry of the problem, either cylindrical or spherical.

Table 4. Undrained equivalent properties

		Cylindrical geometry	Spherical geometry
Young's modulus	E_u [MPa]	397	397
Poisson's coefficient	ν_u []	0.49	0.49
Cohesion	c_u [MPa]	0.934	0.859
Friction angle	Φ_u [°]	0.59	0.41

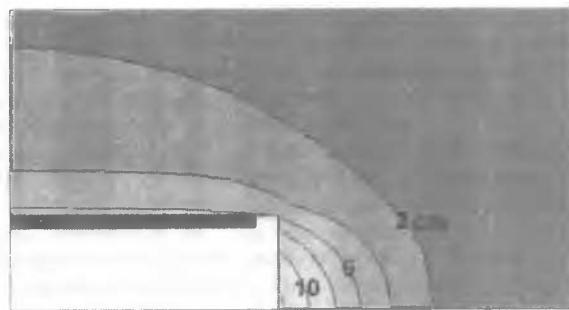


Figure 2: Displacement magnitudes during gallery construction

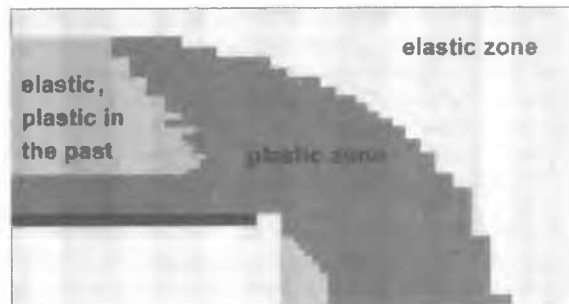


Figure 3: Damaged zone extent during gallery construction

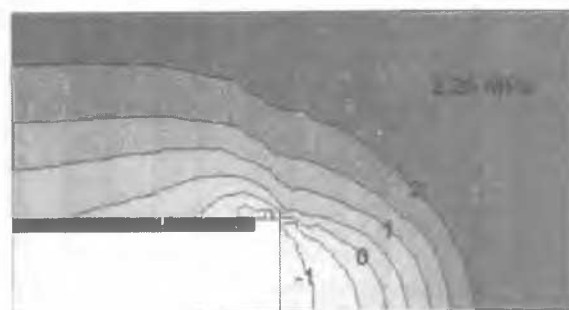


Figure 4: Pore water pressure distribution during gallery construction

4.2 Results of the reference case

Figure 2 is a filled contour plot of the displacement magnitudes in the vicinity of the tunnel face during construction. It shows that a significant part of the convergence occurs before the lining installation and even ahead of the excavation face. Behind the laying distance, further radial deformation of the tunnel side-walls takes place, inducing load in the support system. Equilibrium is finally reached when the soil pressure is exactly balanced by the lining pressure.

The mechanical disturbances that develop in the surroundings of the gallery are illustrated in Figure 3: the plastic zone extends 4.5 m ahead of the front and has a thickness of 3.5 m beyond the excavation wall (→ 11 m diameter damaged zone). Let us however point out a slight elastic recompression of the medium following the lining set-up: some points that were characterised by a plastic behaviour before the support installation (i.e. the yielded region represented by the darker zone) find an incremental elastic behaviour again (grey zone), owing to the build-up in lining pressure.

The filled contour plot of Figure 4 represents the drop of pore water pressure brought about by the mechanical deformations undergone by the clay mass during tunnelling. One notices that, for this axial-symmetric problem, the hydraulic disturbance only occurs in the damaged zone around the gallery (Figure 3).

Analysing in Figures 2 to 4 the shape of the mechanical and hydraulic disturbances that develop in the medium ahead of the gallery front, one clearly notices that the state of stress, pore water pressure and displacement can be reasonably approxi-

mated by a spherical symmetry response. This fact had already been established by Egger (1978) from the orientation of displacement vectors around the heading of a tunnel mock-up

The principal result in the design of underground excavations is the equilibrium state between the lining and the surrounding mass, determined by the total support pressure and its corresponding radial displacement. This equilibrium point is reached at a certain distance behind the tunnel face when this no longer provides any restraint for the soil mass. Our numerical results confirm, as it is commonly admitted, that the lining pressure builds up rapidly after support installation and becomes steady at distances from the front of about 3 to 5 times the tunnel radius.

The four diagrams of Figure 5 represent the distribution of respectively total stresses (radial σ_r , tangential σ_t and longitudinal σ_l), pore water pressures p_p , effective stresses (σ'_r , σ'_t , σ'_l) and displacements u_r in the clay mass in a cross section located 10 m behind the front. The solid lines are related to the short-term equilibrium reached during the gallery construction. They clearly illustrate the plastic zone that surrounds the gallery ($R_{pe} = 5.5$ m) and the drop of water pressure in this zone ($p_p = 0.68$ MPa at the wall). It is as well interesting to note that the effective stresses are almost constant in this plastic zone.

Consequently, to avoid any influence of the excavation face, the results of the equilibrium state should be determined in cross sections located more than 5 tunnel radius behind the face.

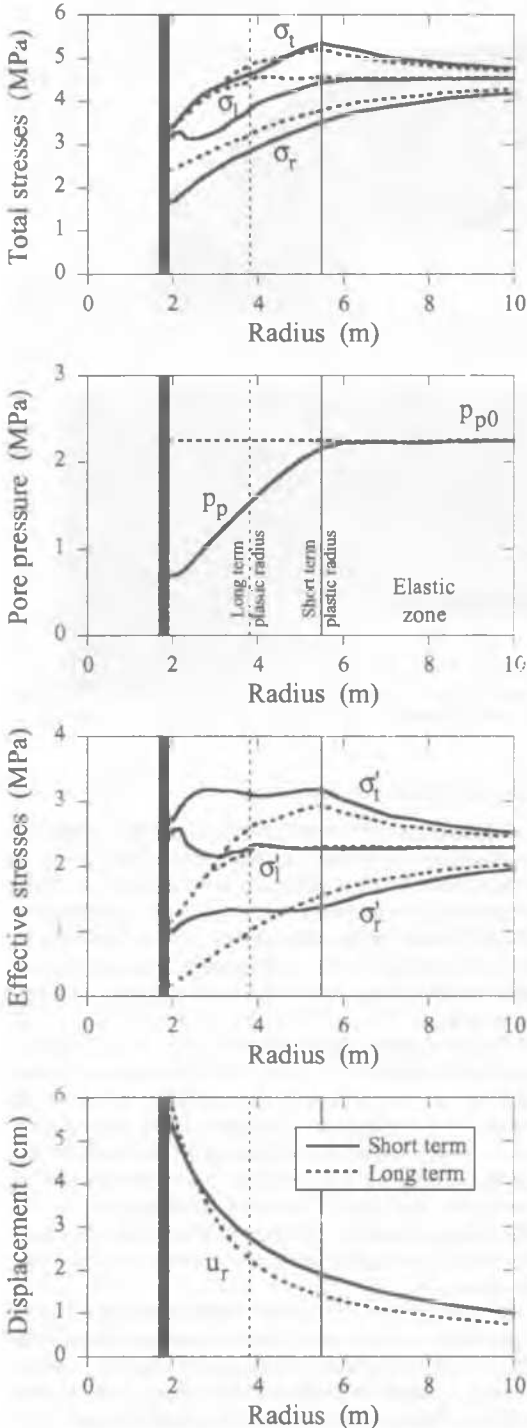


Figure 5: Stresses, pore pressure and displacement in the medium. Solid lines for the short-term equilibrium (completion of gallery construction) and dashed lines for the long-term equilibrium with an impermeable lining.

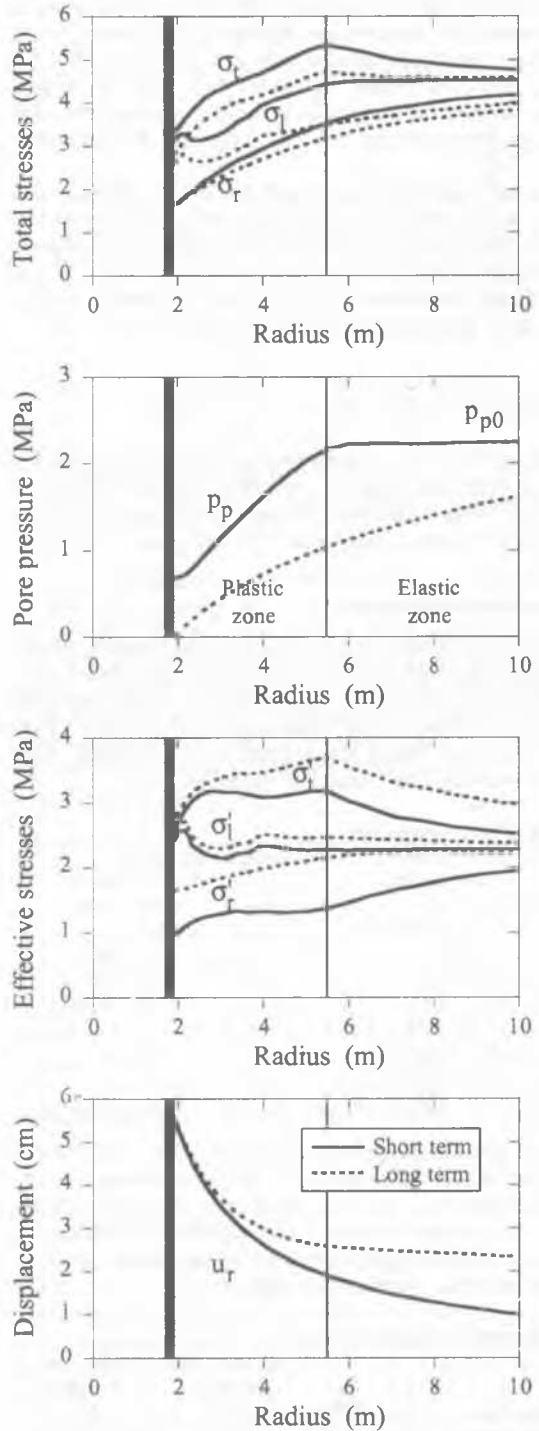


Figure 6: Stresses, pore pressure and displacement in the medium. Solid lines for the short-term equilibrium (completion of gallery construction) and dashed lines for the long-term equilibrium with a permeable lining.

Two situations must be considered for the design of underground excavations in saturated porous media : a short term one corresponding to the completion of the gallery construction and a long term one corresponding to the situation when all the excess pore water pressures are dissipated. The delayed effects associated to this consolidation strongly depend on the nature of the mechanical and hydraulic boundary conditions at the gallery wall (rigid or flexible lining, permeable or impermeable wall). The influence of the latter condition can be assessed from the comparison of Figures 5 and 6 where the dashed lines are related to the long-term equilibrium for respectively an impermeable and a permeable lining.

The distributions of stresses, pore pressure and radial displacement represented in Figure 5 are drawn for an impermeable lining, the solid lines being related to the short term equilibrium and the dashed lines to the long term one. Comparing the results of both situations, one notices an evolution of several variables during consolidation:

1. a significant build up of water pressure on the lining up to the pre-existing in situ value $p_{p0} = 2.25$ MPa.
2. an increase in the total pressure acting on the lining (from 1.65 to 2.4 MPa), although it is less important than the pore pressure one due to a decrease of effective stresses in the damaged zone.
3. further radial deformation of the tunnel wall.

The bends in the distribution of effective stresses at long term clearly illustrate the presence of three different zones around the gallery:

1. a long term plastic zone from 1.9 m to 3.8 m.
2. a zone between 3.8 m and 5.5 m which was plastic during the gallery construction and has found an incremental elastic behaviour again.
3. further in the clay mass (> 5.5 m), a zone keeping an elastic behaviour throughout the excavation and the subsequent consolidation.

Whereas the case of an impermeable lining is more interesting from a design point of view (because of the increase in total pressure on the support), the case of a permeable lining is more representative of the conditions present in the Hades underground research laboratory. The results related to this second hydraulic boundary condition are presented in Figure 6. Comparing the short term and long term distributions (respectively the solid and dashed lines), one can assess the changes induced by the pore water flow towards the gallery:

1. a negligible increase in lining pressure (about 10 kPa!) and consequently almost no further radial displacement of the gallery wall. Let's however mention that calculations with other data predict a more important increase in lining pressure and convergence (even if this remains much lower than the one computed for the impermeable case).

2. an increase in the mean effective stress and a decrease of the deviatoric stress, inducing an elastic recompression of the plastic zone appeared during the tunnel excavation.

4.3 Parametrical study

To determine the relative influence of the various parameters involved in the problem, a parametrical study was performed in the following way : the case study presented in subheadings 4.1 and 4.2 and corresponding to a mean set of parameters (Table 3) was first calculated and considered as reference case. Then, one after the other, the influence of each parameter was studied by changing its value within a certain range.

Among the several parameters studied in the framework of this analysis, we will merely focus in this paper on the pore water pressure p_{p0} pre-existing in the clay mass before excavation. This factor is found to have a significant influence on the equilibrium states, influence which can not be pointed out by means of total stress analyses.

Other parameters being equal (inclusive the in situ total stress $p_0 = 4.5$ MPa), the in situ pore pressure p_{p0} has been changed

from 1.69 to 2.81 MPa ($\pm 25\%$ variation from its mean value). Figure 7 reports the influence of this factor (expressed in terms of percentage variation from the mean value) on the lining pressure, the convergence and the plastic zone extent. In each diagram, four curves are drawn:

1. solid lines with squares for the short-term equilibrium computed with the finite element code Z-Soil.
2. solid lines with circles for the long-term equilibrium in the case of an impermeable lining again computed with Z-Soil.
3. long dashed lines for the SSP method based on similitude principles (see chapter 1).
4. short dashed lines for the New Implicit Method NIM (see chapter 1)

These two last methods were developed for the (short-term) equilibrium of galleries driven in monophasic media. Now, by means of Giraud's equivalence principle (see point 2.3), it is possible to evaluate the undrained characteristics of the monophasic media that are equivalent to the poro-elasto-plastic data (including the initial pore water pressure!) and then apply the SSP and NIM methods. Their results, reported in Figure 7, were obtained with equivalent strength parameters calculated for a cylindrical geometry.

The diagrams in Figure 7 clearly illustrate a rise of lining pressure, convergence and plastic zone extent for increasing initial pore water pressures (under constant total stress condition).

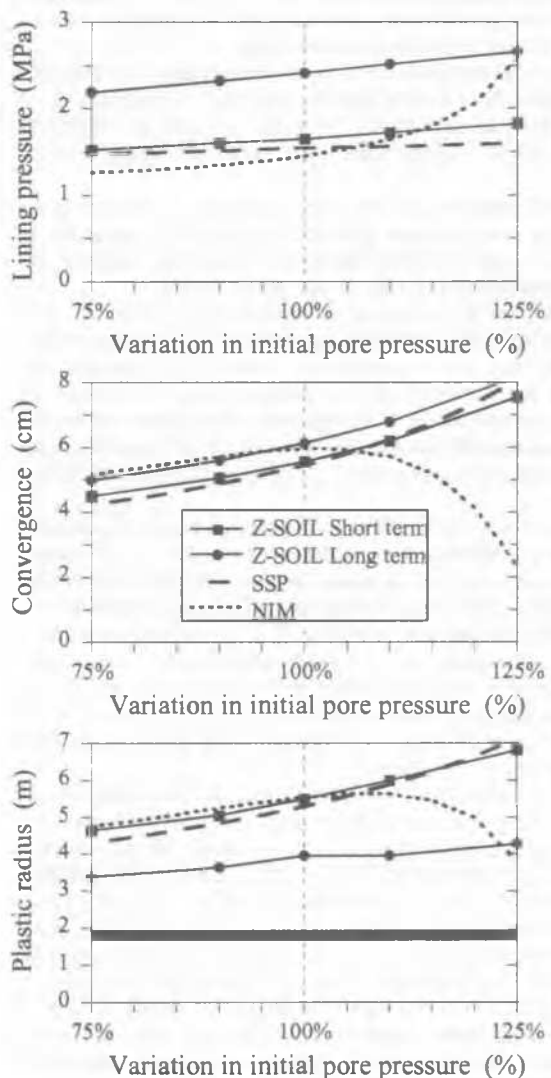


Figure 7: Influence of the in situ pre-existing pore water pressure on the soil-structure equilibrium. Solid lines for the Z-Soil calculations (with squares for the short term equilibrium and circles for the long term one); long dashed lines for the Self Similarity Principle method (SSP) and short dashed lines for the New Implicit Method NIM.

As already noted for the reference case, the redistribution of pore water pressure during consolidation induces an increase in the total pressure acting on the lining, further radial displacement of the tunnel wall, but no further extent of the plastic zone.

Comparing the results of the three methods (FEM, SSP and NIM), one can establish that:

1. for pore water pressures lower than 2.25 MPa, both simplified design methods are close to the short-term results of the finite element code Z-Soil.
2. for pore water pressures higher than the reference case, the SSP method remains close to the short term FEM-predictions while the NIM method significantly diverges (due to a stability ratio N_s outside the range of applicability of the method).
3. None of the simplified tunnel design methods is able to evaluate the long-term equilibrium for this impermeable hydraulic boundary condition. However, should the lining be permeable, their predictions would remain sufficiently good, owing to the small increase in lining pressure during consolidation.

5 CONCLUSIONS

The New Implicit Method (NIM) and the methods resulting from the Principles of Similitude (SSP) are extremely useful "simplified" design tools for engineers of underground structures. Nonetheless, these methods were developed for monophasic media and the following remarks may be made concerning their application to saturated porous media :

1. They use the characteristics of a monophasic medium and do not differentiate clearly between the relative contributions of the solid skeleton and of its pore water. In particular, the stiffness of these two components is not taken into account in the solutions.
2. These methods do not yield information concerning the decrease in pore pressure generated during the excavation of tunnels as a result of hydro-mechanical coupling, whereas this hydraulic disturbance is a significant phenomenon.
3. Based on the principle of equivalence of Giraud, it is known that the equivalence relationship between a porous elasto-plastic medium and a monophasic elasto-plastic medium depends on the geometry of the problem (e.g., cylindrical or spherical) as well as the initial hydraulic conditions. As certain of these aspects are not taken into account in the "simplified" design methods, their application to porous media must be tainted with error.

The axial-symmetric analysis of galleries driven in saturated porous media (with a Mohr-Coulomb criterion) is a complex problem involving 16 variables. Before carrying parametrical studies, their number was reduced to 8 non-dimensional factors.

To determine the relative influence of the various parameters, numerical simulations are in progress with the FEM code Z-Soil. The preliminary results presented in the paper are based on the Belgian underground research laboratory Hades and focus on the up-to-now misappreciated role taken by the pre-existing pore water pressure in the medium.

The FEM simulation of a gallery driven in a saturated porous media predicts both mechanical and hydraulic disturbances, namely a de-stressed plastic zone and a significant drop in pore water pressure brought about by hydro-mechanical coupling. The magnitude of these disturbances as well as the characteristics of the short-term soil-structure equilibrium (i.e. lining pressure and convergence) are influenced by the initial pore pressure value. Now, this influence can not be pointed out by means of common total stress analyses of monophasic media, except if undrained equivalent properties are evaluated from the poro-elasto-plastic data by means of Giraud's equivalence principle. So it is for the applicability of the SSP and NIM design tools.

After the completion of the gallery, fluid flow occurs, causing time-dependent changes for both the structure and the medium: variation of the total pressure acting on the lining and redistribution of stresses and displacements in the medium. The nature of

the hydraulic boundary condition at the gallery wall (permeable or impermeable lining) has an important influence on those delayed effects. Since total stress analyses of monophasic media can only calculate time-dependent effects using creep constitutive models, one can conclude to the inability of the existing design tools to calculate the long term behaviour of galleries in saturated porous media (at least if their lining is impermeable).

6 PERSPECTIVES

Based on the results and the methodology used for the elaboration of the simplified design methods valid in monophasic media (NIM and SSP), a Ph. D. research is in progress, that will endeavour to establish analogous relationships applicable to tunnels excavated in saturated porous media. Its main object is to clarify the three-dimensional aspect of the stability of circular tunnels excavated at great depth in porous media having elasto-plastic behaviour and characterised by a Mohr-Coulomb failure criterion. Not only should the short and long-term equilibrium between the soil and the lining be determined, but also the amplitude of the hydraulic and mechanical disturbances.

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