Code_Aster

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Responsable : GRANET Sylvie

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Clé : U2.04.06   Révision :
b51375ecdb6c

How to dig a tunnel: methodology of excavation

Summary:

This note proposes a methodology to simulate the digging of an underground gallery with *Code_Aster*. The basic method is a method usually used in this kind of studies: method "convergence – containment".

After a recall on the principle of the method, the principal stages of the command file *Code_Aster* are described. Various digital examples make it possible to validate the procedure.

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1 How to simulate the digging of a tunnel?

1.1 Principle of the method, put in work and validation

Context

The studies of géomechanics are generally based on a simulation of underground roadway drivage. Examples of application can be quoted:

1. to evaluate the zone damaged by excavation (EDZ) around a gallery of storage;
2. to study the resaturation of an cell of storage by water of the site.

A certain number of studies were already conducted by department AMA on this subject, with *Code_Aster*. However, few practical elements are available in documentations to reproduce this kind of calculation. Department MMC undertook such a modeling with *Code_Aster*, in order to adapt the procedure of application of the method classically used for this kind of calculation: method "convergence – containment". It comes out from this experiment which this application is not completely commonplace that it is necessary to raise some practical technology matters of implementation. To capitalize this experiment for the future users seemed rather important, in the collective interest of the studies on storage in particular.

Objective

This note aims main aim to provide some preliminary technical advices to the users of *Code_Aster* wishing to model an underground excavation.

Methodology

This note presents an application to a command file of *Code_Aster* method convergence – containment. After a short recall on the principle of the method, a practical and operational description of the orders to be used is given. The method is illustrated by calculations of validation of *Code_Aster*, of which the command files are provided in appendix.

Result

Thanks to the application of the protocol suggested, two calculations of validation of *Code_Aster* were implemented. The relative difference between digital results and analytical solution is lower than 2%.

Outlines

The method can be extended to the calculations nonlinear (plasticity, damage) and coupled in THM, in particular within the framework of studies intended for the storage of nuclear waste.

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2 Introduction

For several years, studies have been carried out with *Code_Aster* in order to model the behavior of works geotechnics (earth dams, tunnels, barriers worked for the storage of waste…).

Code_Aster was already used in particular to simulate the well or roadway drivage, within the framework of the project *Geological storage of nuclear waste HAVL* (T4-01-10) or at the time of former studies on major storage. The reports written until now (for example [6], [7] or [4]) are focused naturally on the results, in order to answer the precise technology matter which justified the study. However to simulate an excavation using a code finite elements is not inevitably an easy thing, and even if the principles generals are recalled in the documents referred to above, one finds finally few elements on the structure of the command files which were used as support with calculations.

In order to help the engineers in charge of the future studies of underground excavation with *Code_Aster*, this note indicates some practical advices to begin in the realization from this kind of calculation. Indeed, within the framework of the Storage project, MMC decided to adapt completely the approach put in work by AMA in 2000 and in 2001. For that purpose, all the approach was reproduced with version 6 of *Code_Aster*, on the basis of grid new and by exploring some alternatives. MMC also profited from the assistance of the agents of AMA. In addition, this work led to a validation of *Code_Aster* according to classical analytical formulas in linear elasticity (Kirsch formulas and method convergence-containment, [5]).

This report thus presents:

1) classical method of simulation of an underground excavation in 2D by means of a code finite elements;
2) different the option available to apply this method with *Code_Aster* ;
3) two CAS-tests of validation of *Code_Aster* for the problems of underground excavations.

Thenecessary one with an advantageous reading of this note is the basic training with the use of *Code_Aster* like a minimum of familiarization with the software package. The detail of the various orders used is given by the user's documentation of *Code_Aster* (http://www.code-aster.org).

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3 A method to simulate the digging of a gallery starting from a model 2D: the method convergence-containment

3.1 Principle general

This part is inspired largely by [5]. Let us announce that the CIH and TEGG also conducted a certain number of studies with this method (for example, [2]). It is advised with the reader to refer to these documents for more information on the principle of the method. The paragraphs which follow summarize only the essence of the approach.

The method convergence-containment is usually used in the engineering of the underground works. Its objective is to obtain an order of magnitude of displacements of the walls of the tunnel as well as the efforts taken again by the rock and supporting. This method makes it possible to simplify the calculation of a three-dimensional work by a two-dimensional calculation, by the introduction of an adimensional parameter λ called "rate of déconfinement". It rests on the following assumptions:

1) plane deformations with assumption of small disturbances;
2) the tunnel is supposed of circular section and horizontal axis;
3) homogeneous ground of infinite extension;
4) solid mass following a linear or elastoplastic elastic behavior;
5) initial state of the constraints presumedly isotropic and homogeneous;
6) deep tunnel: no significant variation of constraints on the height of the gallery. In practice, if H is the average depth of the work and R its ray, this assumption is supposed to be satisfied if $H/R > 10$;
7) quasi-static balance (not of terms of acceleration).

One is interested in a section located in a plan perpendicular to the axis of the tunnel and one wishes to carry out a two-dimensional calculation. The parameter λ is supposed to take into account the mechanical influence of the proximity of the coal face to this section, i.e. of a phenomenon whose origin is out of plan considered by calculation. λ depends on several parameters (rock, supporting, length of nonconstant tunnel behind the coal face…) and its determination is not inevitably immediate (many publications on the subject, for example [1]). This problem of analytical determination of the rate of déconfinement leaves the framework of this document.

In fact, one introduces λ to consider a fictitious tensor of the constraints $\underline{\underline{\sigma}}$ in the ground, which is a fraction of the initial constraint σ_0 :

$$\underline{\underline{\sigma}} = (1-\lambda) . \underline{\underline{\sigma}}^0 \text{ with } 0 \leq \lambda \leq 1$$

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[the Figure 3.1-a] below the evolution illustrates of λ and of the radial constraint σ_R for a nonconstant tunnel.

$\lambda=1$
$\sigma_R=0$

$0>\lambda>1$
$\sigma_R=(1-\lambda).\sigma_0$
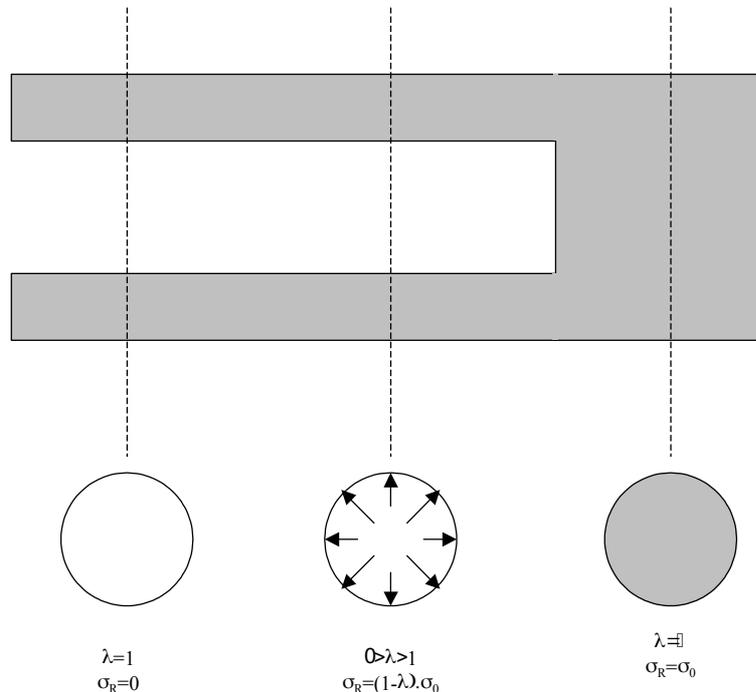
$\lambda=\mathbb{I}$
$\sigma_R=\sigma_0$

Figure 3.1- has: Evolution of the rate of déconfinement λ and of the radial constraint σ_R in the case of a nonconstant tunnel

Let us notice that $\lambda=1$ corresponds to déconfinement total of the rock: the influence of the coal face on the behavior of the slice of tunnel disappeared and the tunnel is comparable to a very thick tube.

Since a part, even the totality of the constraints initially present within the solid mass disappear (it is precisely the phenomenon of déconfinement), the walls of the excavation will tend to approach to reach a new mechanical balance. It is the phenomenon of "convergence". This phenomenon can lead to the ruin of the work if the structure does not manage to find a state of steady balance following the excavation.

If, for safety reasons or on stability, one decides to pose a supporting or a coating with the wall of the tunnel, those go, from their mechanical stiffness, to be opposed to the natural phenomenon convergence. In this case, final balance thus depends on the mechanical interaction between the rock and the coating. Generally, this balance does not make it possible the constraints in the rock solid mass to be cancelled like in the case of the nonconstant tunnel. It is said whereas the ground is confined, from where the name of the method "convergence-containment".

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Graphically, the application of this method amounts searching the point of intersection of the curve of convergence, deduced from the behavior of the ground, and the curve of containment, deduced from the behavior of supporting [Figure 3.1-b].
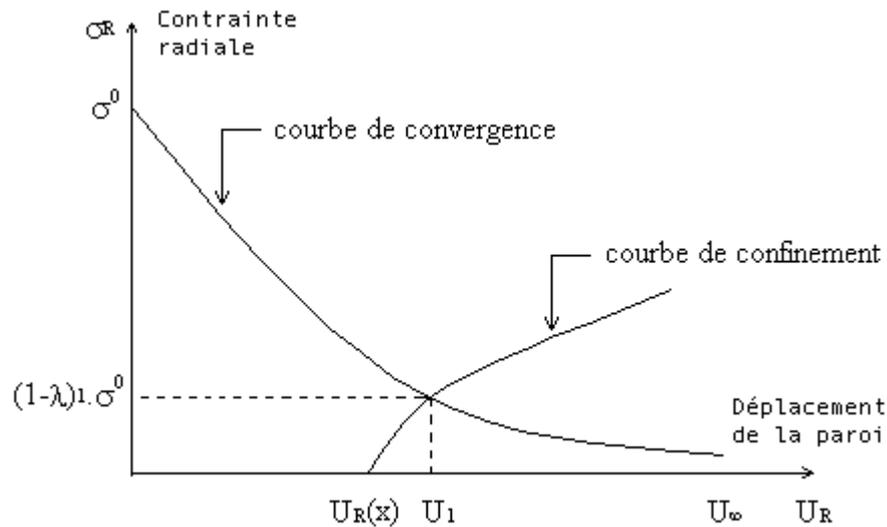

Figure 3.1-b: Example of curves of convergence and containment

The equations of the method "convergence-containment" in the case of a linear elastic solid mass are provided in [§Annexe 1].

That it is for analytical or digital calculations, this method allows, using a simple model 2D, to deal the 3D problem which the simulation of an excavation constitutes.

3.2 Application of the method for a digital calculation by finite elements

A characteristic of calculations of excavation by finite elements is the need for implementing several models (in the broad sense).

Indeed, a classical course of modeling can be summarized by the following stages:

1) stage 1: initialization of the constraints *in situ* ;
2) stage 2: calculation of the nodal reactions on the level of the walls of the excavation;
3) stage 3: déconfinement solid mass to simulate the progressive excavation and the distance of the coal face;
4) stage 4: possible installation of a supporting/coating and end of déconfinement.

If the study requires it, the sequence of stages 2.3 and 4 can be repeated (case of an excavation in divided sections, for example).

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In most case, the sequence of calculations is thus done on the basis of four configuration [Figure 3.2-a].
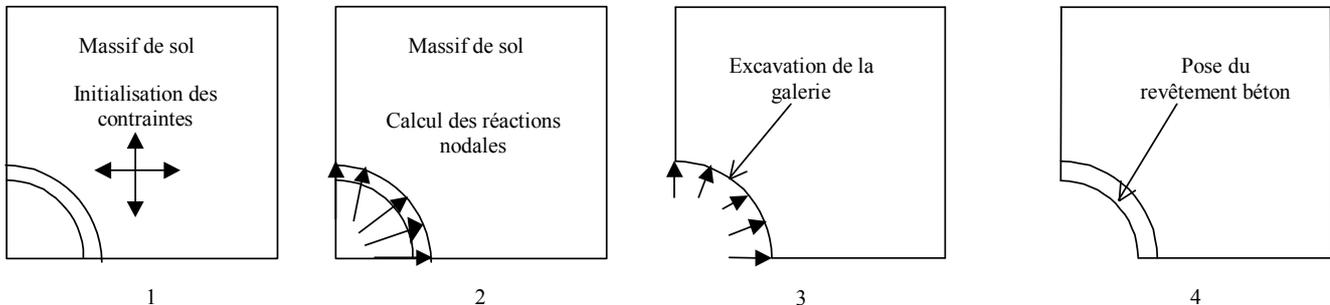

Figure 3.2-a : Typical example of sequence of a calculation of excavation with a computer code

The first configuration is used for:

1. to initialize the constraints of origin geostatics;
2. to initialize the hydrostatic pressure due to the possible presence of water and the temperature (the present note does not discuss this precise item in detail);

The second configuration makes it possible to calculate the reactions to the nodes representing the edge of the excavation.

At these stages of modeling, all the elements of the grid thus correspond to a material of type ground or rock. One thus obtains a solid mass of ground in which reign a state of stresses corresponds to the state of stresses *in situ* in the plan perpendicular to the axis of the gallery. One also knows the nodal reactions at the edge of the excavation, which will allow déconfinement partial or total of the solid mass in the stages which follow.

The third configuration is dedicated to déconfinement: one decreases the nodal reactions at the edge of the excavation in order to simulate the digging of the tunnel. At the time of the realization of this stage, the finite elements in the area corresponding inside the gallery should not take part any more in the rigidity of the model. As it further will be seen, this can be taken into account in several ways in practice.

One possibly passes to a fourth stage if one wants to simulate the installation of a supporting concrete in the course of déconfinement for example. In this case, one adds elements with characteristics of concrete and one continues reduction in the nodal reactions calculated in the stage n°1 to complete calculation.

One thus notices that certain parts of the initial model will be seen affecting properties of ground successively, of "concrete vacuum" then. In this sequence the source of some intrinsic difficulties is at this kind of calculation.

The application of this approach by means of *Code_Aster* fact the object of the following chapters. It is based on a simple case.

4 Before attacking card-indexing of order *Code_Aster…*

This chapter relates to some particular points of modeling which it seems important to comment before being interested in the command files themselves. It is made up of a succession of paragraphs treating

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each one a question which an engineer can put when he carries out a classical calculation of excavation using a standard code finite elements like *Code_Aster*.

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4.1   How to define the models starting from a simple grid?

The grid chosen in this study represents a quarter of model representing a cylindrical gallery in infinite medium. The ray of the gallery is of $1,50\,m$, the thickness of concrete is $0,30\,m$ and the grid is a square of $20\,m$ on side. According to the usual rules of modeling, the relationship between the excavated ray R and dimension characteristic of the grid L is sufficient to consider that the boundary conditions do not disturb the behavior of the excavation ($L \geqslant 10 \times R$).
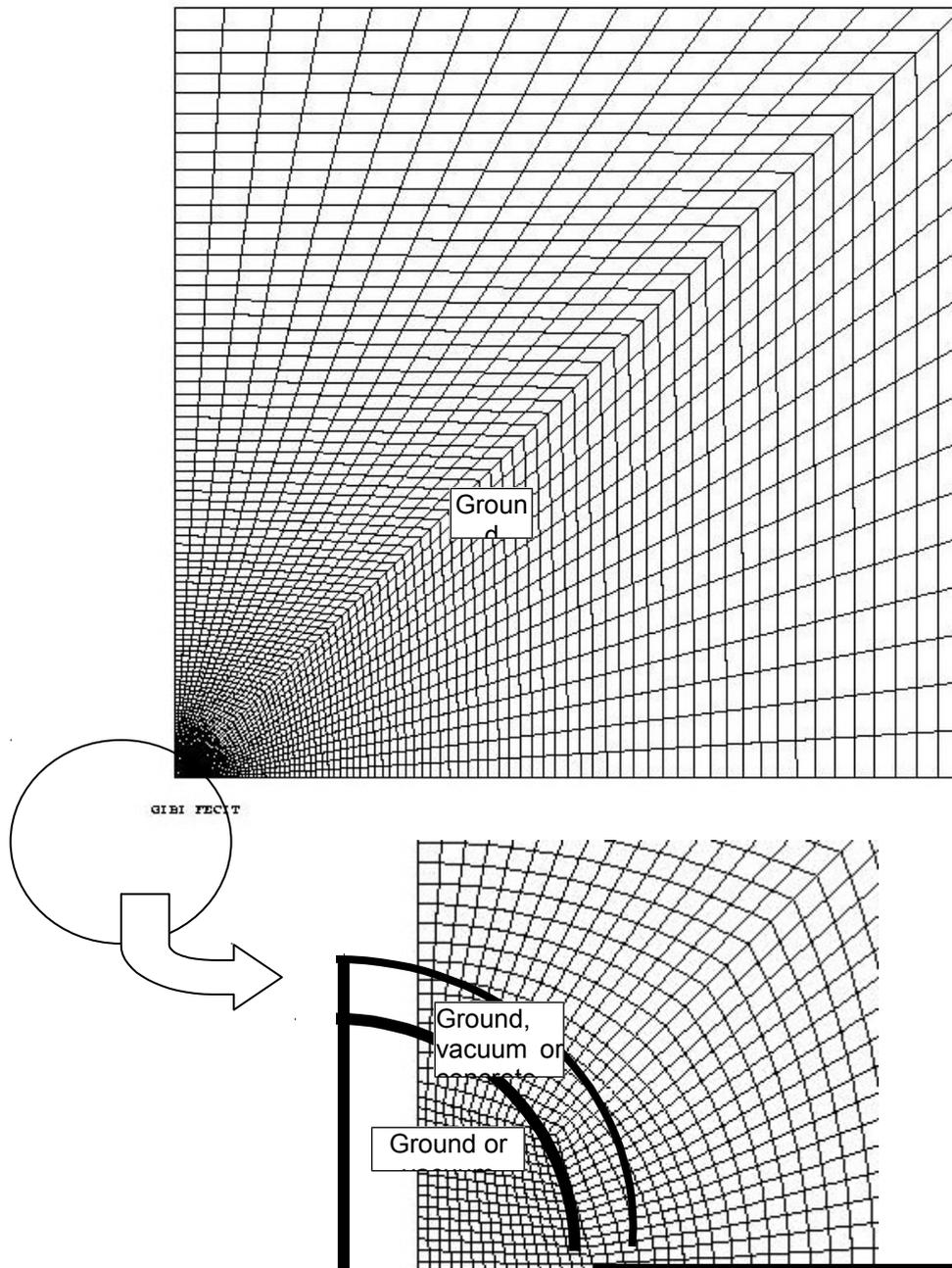
Ground

GIBI FECIT

Ground, vacuum or concrete

Ground or

Figure 4.1-a: Grid used and materials

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From the point of view of the models (to the direction *Code_Aster*), it is necessary to distinguish some particular zones from the grid (besides the other more classical zones, like the edges of the grid) and to create the following objects (the names refer to the command files presented in Appendix):

    1)   the excavated edge where will be applied the nodal reactions to simulate déconfinement (called BORD) ;

    2)   the two points which are located at the ends of this curve, which are concerned at the same time by the loading of déconfinement and the boundary conditions at the edge of the solid mass.
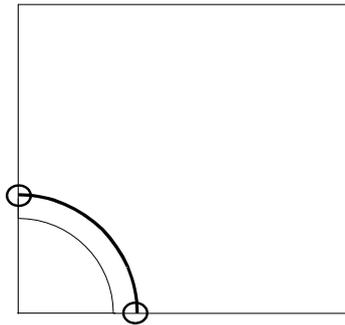

Figure 4.1-b: Points and of points particular to identify together in the models *Code_Aster*

One can thus define (for example, because several configurations are possible):

    1)   a model SOL , in which all the grid is affected finite elements;

    2)   a model $\mathrm{SOL\_REST}$ who does not understand the meshs which correspond to the excavated part (they are not affected finite elements);

    3)   a model $\mathrm{SOL\_REST0}$ who understands $\mathrm{SOL\_REST}$ and affected meshs corresponding to the concrete pavement of finite elements.

Note:

The use of such a geometry to do a real calculation of excavation is partially criticizable, because symmetry suggested risk to generate a nonphysical loading. In the event of application of the actual weight for example, this one would be directed upwards in the lower part of the tunnel!

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Pesanteur

Partie maillée

Tunnel

Pesanteur induite par les
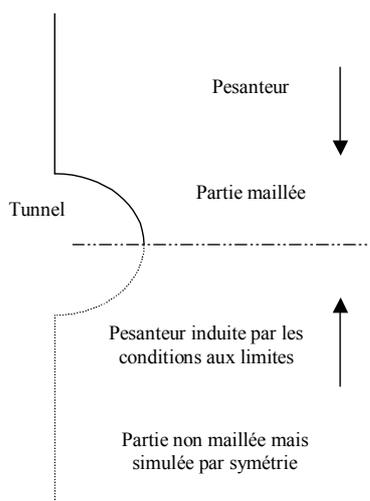conditions aux limites

Partie non maillée mais
simulée par symétrie

**Figure 4.1-c: Example of aberration which the use of a quarter of model can generate
in the simulation of a tunnel**

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For a realistic study where one would wish to initialize the constraints using a loading in actual weight, it would be thus necessary "to net the ground" until the rigid substratum (rock considered indeformable), or all at least until a sufficient depth to free itself from the problem mentioned above. One thus nets a half-model in this case there.

However, within the framework of our study, this constraint of grid did not obstruct us, since we took into account neither the actual weight, nor couplings THM. The simulated loading is completely compatible with the analytical solutions tested.

4.2   How to initialize the constraints?

Constraints *in situ* are generally represented by a tensor of order 2 whose principal directions correspond to the vertical and the horizontal one. The vertical constraint is generally equal to the weight of the various formations located above point considered and the horizontal constraint is proportional to the vertical constraint:

$$\sigma_v = \gamma . z$$
$$\sigma_h = K_0 . \sigma_v$$

with γ the voluminal weight of the overlying ground (in kN/m^3 for example) and K_0 a coefficient without dimension. K_0 can be given by measurements *in situ* or estimated by more or less empirical relations. In the case of a semi-infinite solid mass subjected to an external constraint on its higher edge or to its actual weight, the theory of linear elasticity provides a value of K_0 according to the Poisson's ratio ν :

$$K_0 = \frac{\nu}{1-\nu}$$

Two methods were tested with *Code_Aster* to initialize the constraints in the country rock:

1. realization of a calculation (order `STAT_NON_LINE`) with a fictitious material equipped with a Poisson's ratio allowing to obtain the report K_0 wished. This calculation is carried out on the model which takes again all the grid of the study (for example, the model called SOL in the preceding chapter). In this case, $K_0 \leq 1$ (case of linear elasticity). There exist many cases where $K_0 \geq 1$ (if the ground is subjected to tectonic constraints, for example). In this case, the following method becomes obligatory;
2. to directly assign the constraints to all the elements of the grid by the order `CREA_CHAMP (OPERATION = 'AFFE')` ;

The first solution requires to define a fictitious material and to implement a calculation moreover. However, if the loading is the actual weight (what is not the case of the CAS-test that we propose), this method appeared at the same time intuitive to us and simple. In the case of a uniform stress field, the use of `CREA_CHAMP` is unquestionably the most interesting method: it saves time computing and its call is even simpler. For more complex distributions of constraints, `CREA_CHAMP` also function but we did not use it (to refer to documentation [U4.72.04] who gives an example adaptable to our problem).

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4.3 How to calculate the nodal reactions at the edge of "the future" gallery?

To calculate the nodal reactions at the edge of the gallery, it is necessary to block this part of the grid. This operation should not generate nonphysical constraints by incompatibility with the loading applied at the time of the phase of initialization. constraints. An opportunity given consists in imposing the same loading as at the time of the initialization of the constraints by blocking the nodes of the edge of the gallery *only during this stage of calculation*. This operation is without effect on the total result, which remains identical to that of the preceding stage, but the "temporary" blocking of the nodes of the edge of the gallery makes it possible to evaluate the nodal reactions there.
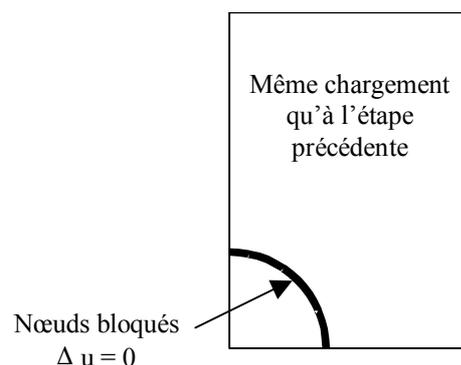

Figure 4.3-a: Blocking of the nodes of the edge of the gallery to calculate there nodal reactions

Concretely, this relative blocking of the edge of the gallery is possible thanks to the option DIDI (for Differential DIrichlet) of the keyword EXCIT of the operator STAT_NON_LINE (Document [U4.51.03]). The blocking of these nodes applies only to the increment of displacement considered and not to total displacement (one imposes $\Delta u=0$ and not $u=0$).

The initial state of this calculation (keyword ETAT_INIT of the operator STAT_NON_LINE) is defined by the stress field obtained at the conclusion of the preceding stage.

Once this intermediate calculation carried out, the calculation of the nodal reactions is carried out simply with the order CALC_CHAMP (FORCE = 'REAC_NODA'). It is then advisable to provide to the order CALC_CHAMP all loadings having produced the result from which the nodal reactions are calculated, without omitting the loading voluminal if they exist (not taken into account in the examples treated here).

One then builds a vector of loading by the recovery of the nodal reactions (CREA_CHAMP with the keywords TYPE_CHAM = 'NOEU_DEPL_R' , NOM_CHAM = 'REAC_NODA' and OPERATION = 'EXTR'). It should be noted that according to the paragraph [§3.1.1] of the user's documentation of *Code_Aster* [U4.72.04], the option TYPE_CHAM = 'NOEU_DEPL_R' order CREA_CHAMP is in fact without effect here (but nevertheless obligatory from the syntactic point of view), since an extraction is carried out. This vector is then defined by the order AFFE_CHAR_MECA with the keyword VECT_ASSE as a loading for the call following to the order STAT_NON_LINE (corresponding to the progressive excavation of the gallery). This loading is associated with a function (operator DEFI_FONCTION) describing the evolution of the rate of déconfinement as the progression of the digging.

Also let us notice that all the nodal reactions are extracted: those which act on the edge of the gallery as those which act on the other edges of the model. Since these last act on blocked points *with all the stages of the calculation of excavation*, their injection as a loading in STAT_NON_LINE according to is without effect on the constraints and the deformations within the structure.

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4.4 How to simulate the creation of a "vacuum" in the solid mass and the installation of the concrete?

Once carried out the calculation of the nodal reactions the question of the "elimination" of the excavated part of the digital model arises so that its rigidity does not block the convergence of the tunnel. For that purpose, we adopted two methods [Figure 4.4-a]:

1) method A : quasi-cancellation of the mechanical properties of the elements located in the excavated zone (example: $E = 0,0001\,Pa$), then introduction of more realistic properties during the installation of supporting or the coating. This method makes it possible to simplify the command file *Code_Aster* and gives correct results for the simple case that we studied (small circular gallery, excavated in only one section in an elastic solid mass). To conduct more elaborate studies where the digital processing could be affected by the presence of element with very low rigidity, it seems nevertheless preferable to us to be based on the following method;

2) method B : initialization of the constraints directly by creation of fields at the points of Gauss resulting from a calculation concerning a preceding stage.
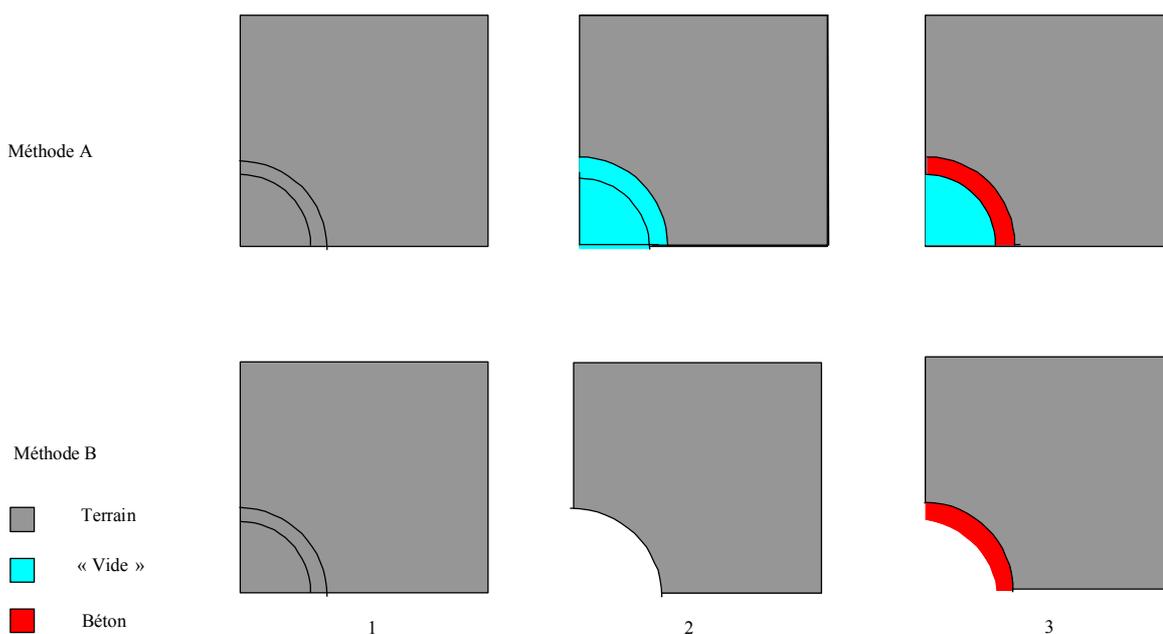

Figure 4.4-a: Various principles of modeling to simulate déconfinement solid mass

Other methods that we did not test can undoubtedly be applied to the studied problem (as the creation of double nodes at the borders between materials who allow to bind or not the two structures).

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4.4.1 Method A

Method A do not call for a particular observation: it is enough to assign very weak mechanical characteristics to the meshs becoming "empty" during calculation of déconfinement.

One proceeds in two times:

1. a first order STAT_NON_LINE, which makes it possible to reinject the loading made up of the vector of the nodal reactions and the boundary conditions. The "empty" meshs thus correspond to a very soft material;
2. a second call to STAT_NON_LINE who introduces supporting or the concrete pavement while assigning to the corresponding meshs of the realistic characteristics for such a material.

With each call, the initialization of calculation takes again the entirety of the fields resulting from preceding calculations (operand EVOL_NOLI for the keyword ETAT_INIT).

4.4.2 Method B

This procedure is based on the sequence of several models (to the direction *Code_Aster*). Calculation is carried out by copying certain fields from one model to another.

Fields to be assigned to the model corresponding at the stage $B-3$ [Figure 4.4-a] are formally the linear combination of two fields:

1. fields resulting from the preceding stage of calculation ($B-2$) and which relates to only the model corresponding to the solid mass of private ground of the excavated zone;
2. fields assigned to the elements of the group of mesh which represent the concrete voussoirs, in the model which understands the solid mass and the gallery lining. In our case, these fields must be initialized to 0 in $B-3$. For that, one can for example assign a null weight to their contribution in the linear combination. Thus these fields can in fact being obtained by an intermediate calculation without real physical significance, for example the simple application of the boundary conditions.

The order is used CREA_CHAMP with the option ADZE to assign to the points of Gauss of the third the linear combination of fields resulting from preceding calculations models.

4.5 Summary of the methods suggested

To initialize the constraints, one can call on two methods:

1. Method I : to do a calculation (call to STAT_NON_LINE) on fictitious material;
2. Method II : to create the stress field wished by CREA_CHAMP.

To simulate the digging and the installation of the voussoirs, one has the choice between:

1. Method A : who consists in mechanically affecting "flexible" characteristics very in the excavated zone;
2. Method B : who makes the use of several models which are connected and which is closer to the physical reality of the modelled structure, the materials appearing and disappearing by activation from one model to another. This method will be privileged.

A synthetic flow chart is proposed in [§Annexe2].

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5   Examples of command files

This part presents examples of structures of command file *Code_Aster* concerning a circular excavation in infinite and elastic medium linear, within the framework of a purely mechanical study (not of coupling THM). The cases presented here are the object of the cases test of validation SSLP105A, SSLP105B and SSLP105C.

Three calculation cases are presented in this part:

1. an excavation without supporting with initialization by a bearing calculation on a fictitious material to obtain the stress field wished (method I) ;
2. an excavation with supporting, initialization of the constraints by a call to CREA_CHAMP and followed by the method A for déconfinement and poses it voussoirs (methods $II + A$) ;
3. an excavation with supporting, initialization of the constraints by a call to CREA_CHAMP and followed by the method B for déconfinement and poses it voussoirs (methods $II + B$).

For cases 2 and 3, the scenario of digging is the following: excavation, déconfinement to 50% ($\lambda = 0.5$), poses voussoirs of $30\,cm$ of thickness and end of déconfinement.

5.1   With the dealt problem

The geometry of the grid is listed in the paragraph [§4.1]. It contains 8477 nodes and 3304 elements. The ray of the gallery is of $1,50\,m$, the thickness of concrete is $0,30\,m$ and the grid is a square of $20\,m$ of with dimensions. The other data are summarized in the following table.

Material	Parameter	Value
	K_0	1
Rock	$\sigma_v = \sigma_h$	$5\,MPa$
	E	$4\,GPa$
	ν	0,3
Concrete	E	$20\,GPa$
	ν	0,2

Table 5.1-1: Data of the cases tests suggested

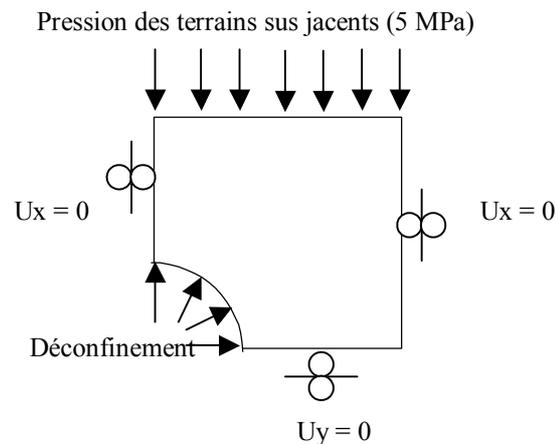The boundary conditions and the loading are illustrated by the following figure:

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Pression des terrains sus jacents (5 MPa)

Figure 5.1-a: Boundary conditions imposed and loading

at the end of the process of déconfinement, $\lambda = \dfrac{2.G}{\sigma_0.R}.U_R = 0,69$.

5.2 Case n° 1: excavation without supporting with initialization of the constraints by a calculation and "softening" of the "excavated" elements

This example is relatively simple: it is a question of simulating an excavation without installation of supporting, with déconfinement total at the edge of the gallery. One thus uses one model for all calculation.

The initial state is generated by a calculation (STAT_NON_LINE) who relates to the whole of the grid. The properties of the elements are affected according to the state of stresses which one wants to reach (here $K_0 = 1$ thus $\nu = 0,4999$, the value of $0,5$ meaning the incompressibility of the rock not being able to be used).

Following calculation relates to the nodal reactions at the edge of the future gallery. It is initialized starting from the constraints resulting from the first call to STAT_NON_LINE.

The last call to STAT_NON_LINE is used to reinject the nodal reactions in a model where mechanical properties of the excavated elements were very strongly weakened (E tends towards $0.$). One déconfine then completely the ground while making tighten these reactions towards 0 .

The command file corresponds to the case test SSLP105C.

5.3 Case n°2: excavation with supporting with initialization of the constraints by call to **CREA_CHAMP** and déconfinement according to method A

One follows the scenario of excavation described above. One uses that only one model for all calculation. An order STAT_NON_LINE additional allows to introduce the voussoirs with a realistic rigidity after déconfinement of 50%.

The command file corresponds to the case test SSLP105B.

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5.4 Case n°3: excavation with supporting with initialization of the constraints by call to CREA_CHAMP and déconfinement according to the method B

One always follows the scenario of excavation describes higher. This time, three models are used and an intermediate calculation (without physical reality, called "can") is necessary to transfer the fields variables from one model to another at the time of the installation of the voussoirs after déconfinement of 50%.

The command file corresponds to the case test SSLP105A.

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6 Validation of *Code_Aster* on an example of excavation in linear springy medium

Validation of *Code_Aster* rest on the comparison of the digital results resulting from the cases n°1, 2 and 3 listed above with the analytical solution of [§Annexe 1]. For each calculation, one presents the results got to the level of the keystone and the oven wall of the gallery, in term of radial constraint σ_R constraint orthoradiale σ_θ and radial displacement U_R ([Table 6-1], [Table 6-2] and Table 6-3]). [§Annexe 7] presents two graphs describing the space evolution of the constraints along the vertical axis of the model, with the right of the excavation. The good agreement between analytical solution and digital results makes that the difference between these curves is hardly visible.
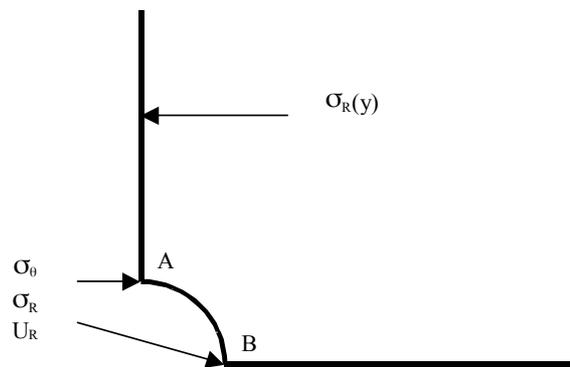

Figure 6-a: Sizes compared for the validation of *Code_Aster*

	Not A			Not B		
Variable	Analytical	Aster	Relative variation	Analytical	Aster	Relative variation
σ_R (Pa)	0.	$-8.411\,E3$	It is checked that $\lvert\sigma_R\rvert \ll \lvert\sigma_\theta\rvert$	0.	$-1.625\,E4$	It is checked that $\lvert\sigma_R\rvert \ll \lvert\sigma_\theta\rvert$
σ_θ (Pa)	$-1.\,E7$	$-9.883\,E6$	1,2%	$-1.\,E7$	$-1.011\,E7$	1,1%
U_r (m)	-0.0024375	-0.0024772	1,70%	-0.0024375	-0.0023982	1,6%

Table 6-1: Case n°1, analytical comparison solution/results *Code_Aster* for constraints radial and orthoradiale and for radial displacement in A and in B

	Not A			Not B		
Variable	Analytical	Aster	Relative variation	Analytical	Aster	Relative variation
σ_R (Pa)	$-1.52821\,E6$	$-1.52974\,E6$	0.1%	$-1.52821\,E6$	$-1.52652\,E6$	0,1%
σ_θ (Pa)	$-8.47179\,E6$	$-8.40987\,E6$	0,7%	$-8.47179\,E6$	$-8.52586\,E6$	0,6%
U_r (m)	-0.0016925	-0.0017218	1,7%	-0.0016925	-0.0016664	1,5%

Table 6-2: Case n°2, analytical comparison solution/results *Code_Aster* for constraints radial and orthoradiale and for radial displacement in A and in B

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Variable	Not A			Not B		
	Analytical	Aster	Relative variation	Analytical	Aster	Relative variation
σ_R (Pa)	$-1.52821\,E6$	$-1.52943\,E6$	0,1%	$-1.52821\,E6$	$-1.53171\,E6$	0,2%
σ_θ (Pa)	$-8.47179\,E6$	$-8.40822\,E6$	0,8%	$-8.47179\,E6$	$-8.52418\,E6$	0,6%
U_r (m)	-0.0016925	-0.0017211	1,7%	-0.0016925	-0.0016658	1,6%

Table 6-3: Case n°3, analytical comparison solution/results *Code_Aster* for constraints radial and orthoradiale and for radial displacement in A and in B

The maximum difference between analytical and digital results is lower than 2%, except for the radial constraint at the edge of the gallery excavated in the case n°1, where the theoretical value is 0. The validity of calculation is checked by considering that the radial constraint is quite negligible in front of the constraint orthoradiale.

Of course, all these variations can be reduced if the grid is still refined.

7   As a conclusion: advices and prospects

This note proposes a methodology which makes it possible to carry out calculations of excavation using *Code_Aster*. Several scenarios of excavation reviewed and several methods are proposed.

The method and the software package are validated in the case of a circular gallery, dug in an infinite solid mass consisted a linear elastic material. *Code_Aster* reproduced in a completely satisfactory way the behavior of such an underground structure, with or without taking into account of supporting and/or the coating.

From the point of view of the user, it seems more practical and faster to initialize the constraints by a call to the order `CREA_CHAMP` rather than by a calculation on fictitious material.

If one seeks to model a purely mechanical behavior and if the phasage of the excavation is relatively simple, to work with only one model appears to be the easiest method. It is enough to assign very weak material properties to the meshs becoming "empty". In the more complicated cases, the implementation of several models used successively can prove more reliable from the point of view of implementation the practical (error of modeling) and from the digital point of view (miscalculation), in spite of the intermediate procedures of transfer of the fields (forced, internal displacements, pressures, temperatures, variables…) from one model to another.

A later stage of validation of *Code_Aster* could be done on the linear coupled problems (THM in medium saturated and elastic) or coupled and/or nonlinear (model CJS 1 being connected with the model of Mohr-Coulomb, short-term excavation in not drained to compare with [3]).

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8 Bibliography

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[3] A. GIRAUD: Couplings Thermo-Hydro-Mechanics in the not very permeable porous environments: application to deep clays, thesis of the ENPC – 1993

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Annexe 1 Analytical formulas to apply the method convergence-containment to the case of a rock and a supporting rubber bands and linear solid mass

The medium is supposed to be elastic linear isotropic and subjected to an also isotropic stress field initial ($K_0 = 1$).

Radial constraint, forced orthoradiale and radial displacement with the wall of the tunnel in springy medium subjected toa rate of déconfinement λ

$$
\begin{cases}
\sigma_R = \left(1 - \dfrac{\lambda \cdot R^2}{r^2}\right) \cdot \sigma^0 \\[2mm]
\sigma_\theta = \left(1 + \dfrac{\lambda \cdot R^2}{r^2}\right) \cdot \sigma^0 \\[2mm]
U_R = \lambda \cdot \dfrac{R^2}{r} \cdot \dfrac{\sigma^0}{2G}
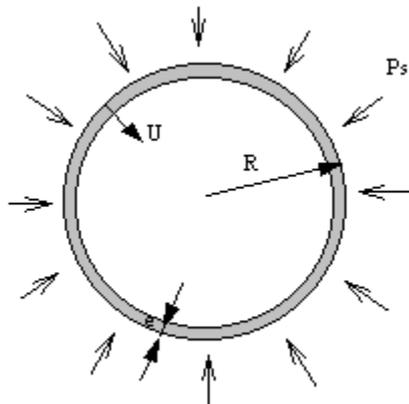\end{cases}
$$

G is given by the following relation: $G = \dfrac{E}{2 \cdot (1 + \nu)}$

Behavior of supporting:

That is to say K_s the stiffness of supporting, it is given by the following relation if it is considered that supporting is comparable to a thick or thin tube (ν_b is the Poisson's ratio of the concrete):

$$
K_s = \begin{cases}
\dfrac{E_b \cdot e}{(1 - \nu_b^2) \cdot R} & \text{si } R > 10 \cdot e \\[4mm]
\dfrac{E_b \cdot (R_e^2 - R_i^2)}{(1 + \nu_b) \cdot \left[(1 - 2 \cdot \nu_b) \cdot R_e^2 + R_i^2\right]} & \text{si } R \le 10 \cdot e
\end{cases}
$$

That is to say P_s confining pressure defined on the following figure

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One thus has:

$$P_s \cdot R = \sigma_b \cdot e$$

If $k_s = \dfrac{K_s}{2 \cdot G}$ represent relative rigidity and λ_d the rate of déconfinement with the installation of supporting,
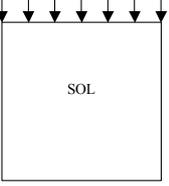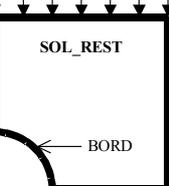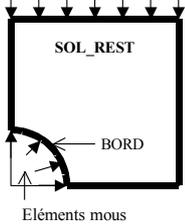
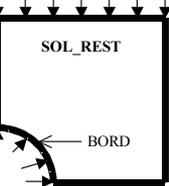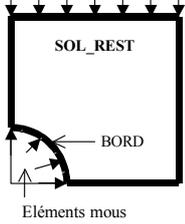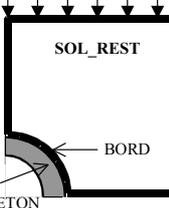then the pressure of supporting and radial displacement in wall are given by:

$$\begin{cases} P_s = \dfrac{k_s}{1+k_s} \cdot \left(1-\lambda_d\right) \cdot \sigma^0 \\ U_R = \dfrac{1+\lambda_d \cdot k_s}{1+k_s} \cdot \dfrac{\sigma^0}{2 \cdot G} \cdot R \end{cases}$$

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# Annexe 2 Flow chart of synthesis on the methods allowing to simulate an excavation

Notations

The names of the objects are those of the command files presented in the appendices following.

SNL mean STAT_NON_LINE ; CC mean CREA_CHAMP ; CL mean boundary conditions

Stage 1: Initialization of the constraints		
I : $SNL1$ with the loading of weight actual or pressure wished and a material equipped with a possibly fictitious Poisson's ratio	II : assignment by order CC desired field	

Stage 2: Recovery of the nodal reactions at the edge of the future gallery			
CC to extract the constraints resulting from $SNL1$ $SNL2$ with CL on the object $BORD$ in DIDI Recovery of the reactions	$SNL1$ with CL on the object $BORD$ in DIDI on model SOL Recovery of the reactions	$SNL1$ with CL on the object $BORD$ in DIDI on model SOL_REST Recovery of the reactions	

Stage 3: Déconfinement			
$SNL3$ with the loading of the vector of the nodal reactions and a "soft" material instead of "vacuum"		$SNL2$ (model SOL) with the loading of the vector of the nodal reactions and a "soft" material instead of "vacuum"	$SNL2$ (only one material and model SOL_REST) with the loading of the vector of the nodal reactions	

Stage 4: Pose supporting			
$SNL4$ with 3 materials: rock, concrete and vacuum (method A) to complete déconfinement		$SNL3$ with 3 materials: rock, concrete and vacuum (method A) to complete déconfinement	CC to extract the results from $SNL2$ $SNL3$ on model SOL_REST + CONCRETE) for intermediate calculation Combination of the fields CC $SNL4$ to complete déconfinement	

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Annexe 3 Comparison of the constraints obtained by digital calculation and the analytical solution

Case of the nonconstant tunnel
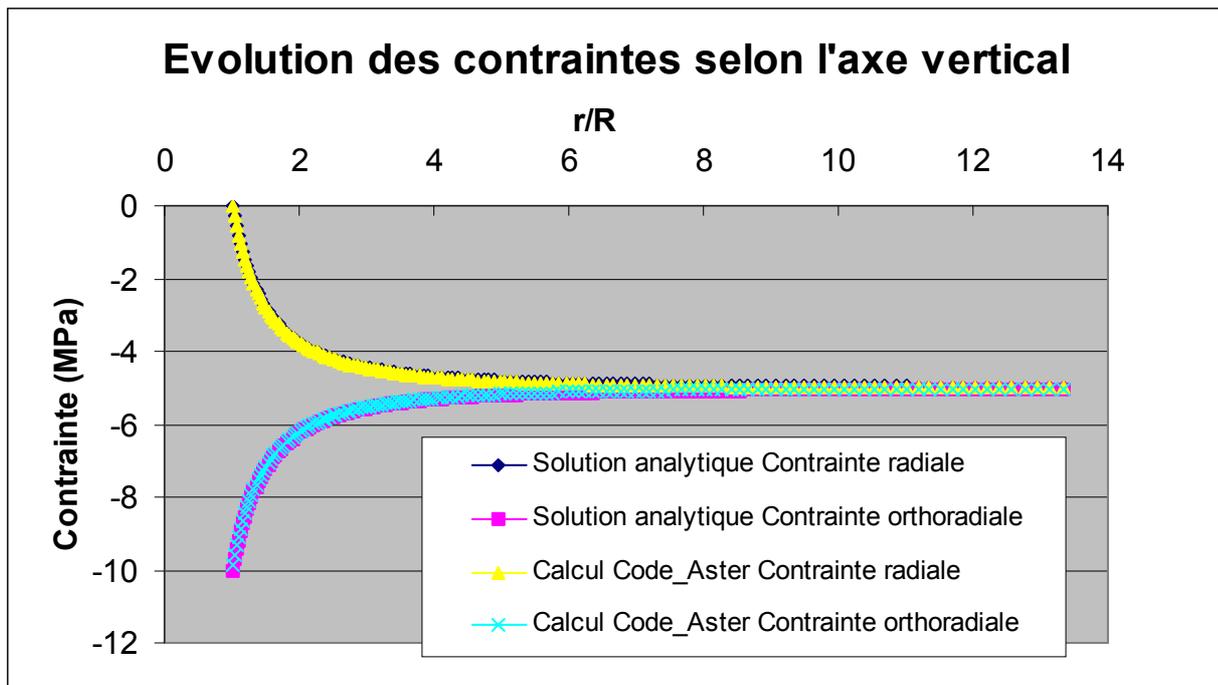
Case of the constant tunnel (from 50% of déconfinement)