SSLP105 - Excavation of a circular tunnel in a linear elastic solid mass

Summary:

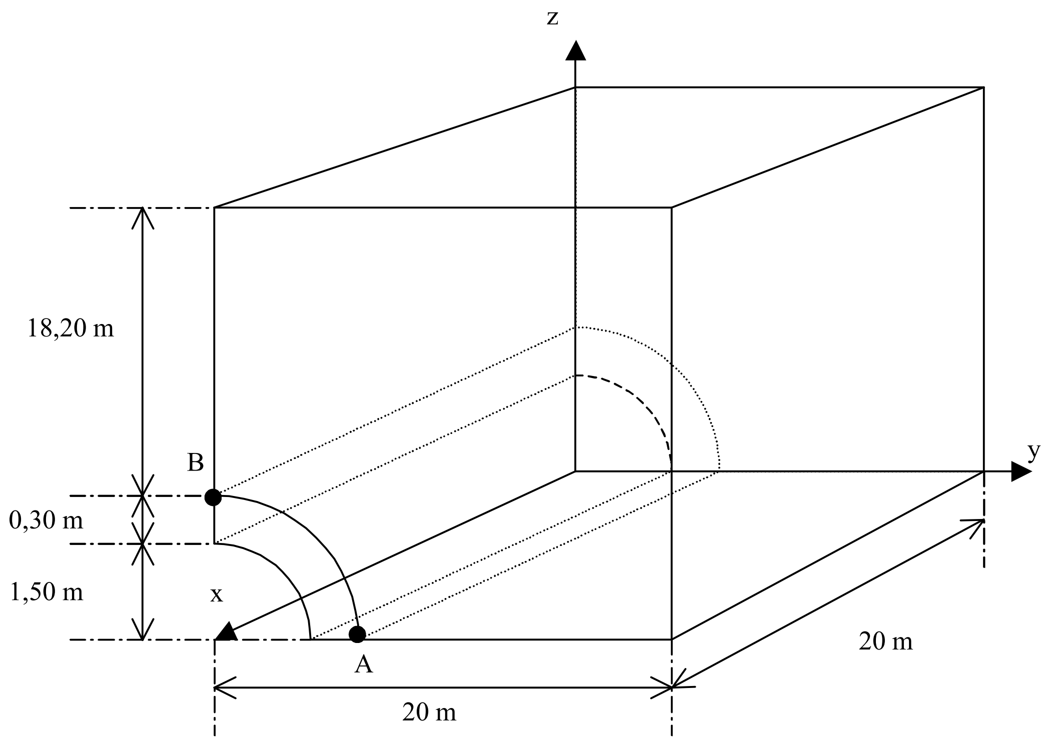
This test constitutes an example of implementation of a total methodology for the two-dimensional simulation of the digging and the supporting of a circular gallery in an underground solid mass with *Code_Aster*.

To validate the approach on the basis of simple analytical solution, one is brought to make restrictive assumptions on the geometry of the problem, the behavior of materials (elastic linear) and the initial stress field (isotropic). The reference solution is given by the method known as “convergence-containment”, classic for this kind of modeling 2D. For more detail on methodologies employed one will refer to documentation [U2.04.06].

1 Problem of reference

1.1 Geometry

It is about a circular tunnel of section, covered by a concrete ring, which one excavates in a solid mass of ground. The two materials are supposed to be elastic linear.



1.2 Properties of material

The materials are elastic linear.

1.2.1 Ground

$E_s = 4\,GPa$

$\nu_s = 0,3$

1.2.2 Concrete

$E_b = 20\,GPa$

$\nu_b = 0,2$

1.3 Initial conditions, boundary conditions and loadings

The constraints in the solid mass are supposed initially isotropic $(\sigma_{xx}=\sigma_{yy}=\sigma_{zz}=\sigma_0)$. The method used to simulate the excavation and the installation of supporting is the method known as "convergence-containment" presented for example in [bib1] and [bib2].

The basic principle rests on a reduction in the nodal reactions generated at the edge of the future gallery by the initial state of stresses. This operation is indicated by name "déconfinement". When déconfinement the value reached which corresponds to the conditions of building site that one wishes to model, one carries out the simulation of the installation of concrete supporting at the edge of the gallery.

The boundary conditions and the loading are summarized in the following table. The phases correspond to those of the diagram above, the edges are composed with the nodes identified on the diagram of the paragraph [§3.1] and between brackets the name of the groups of mesh or node of the file .comm).

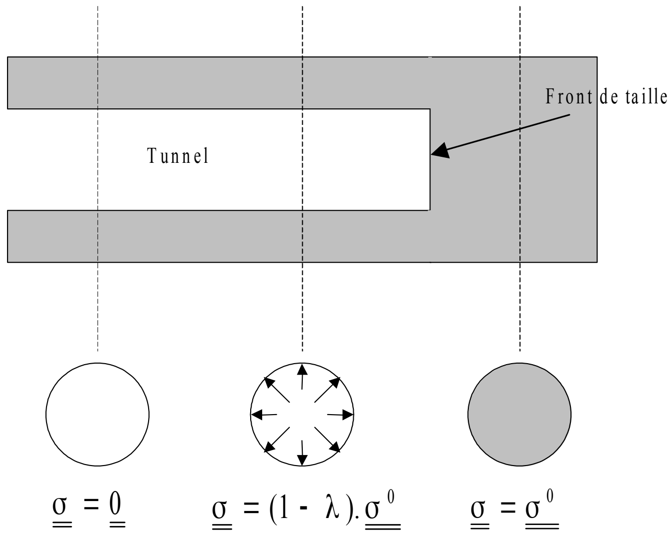
Edges	Phase 1	Phase 2	Phase 3	Phase 4
$N0N1$ (no_bas1)	$DY=0$	$DY=0$	-	-
$N1N2$ (bas_bet)	$DY=0$	$DY=0$	-	$DY=0$
$N2N3$ (no_bas2)	$DY=0$	$DY=0$	$DY=0$	$DY=0$
$N3N4$ (no_droit)	$DX=0$	$DX=0$	$DX=0$	$DX=0$
$N4N5$ (ma_haut)	$\sigma_{yy}=-5\,MPa$	$\sigma_{yy}=-5\,MPa$	$\sigma_{yy}=-5\,MPa$	$\sigma_{yy}=-5\,MPa$
$N5N6$ (no_left2)	$DX=0$	$DX=0$	$DX=0$	$DX=0$
$N6N7$ (no_left_bet)	$DX=0$	$DX=0$	-	$DX=0$
$N7N0$ (no_left1)	$DX=0$	$DX=0$	-	-
$N6N2$ (edge)	-	-	Nodal reactions corresponding to déconfinement	-
$N7N1$	-	-	-	Free

2 Reference solution

2.1 Method of calculating

2.1.1 Behavior of the ground

That is to say λ the rate of déconfinement, which represents the relative position of the section of tunnel considered compared to the coal face. In the method “convergence - containment”, one replaces the future ground excavated by a tensor of the constraint are equivalent, which one cause a drop in the intensity via λ to simulate the digging and the distance of the coal face.



The solution of the problem is thus similar to that of the infinitely thick tube charged by an internal pressure with intensity $(1-\lambda)\sigma_0$ and by an external pressure of intensity σ_0 (see [bib3] for the detail of calculations).

Constraints radial, orthoradiale as well as radial displacement with the wall of the tunnel in springy medium subjected toa rate of déconfinement λ are the following ones

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

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

2.1.2 Behavior of supporting

Supporting will be opposed to the natural movement of convergence of the tunnel and will thus apply an artificial containment to the rock.

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 thin tube (ν_b is the Poisson's ratio of the concrete):

$$K_s=\frac{E_b\cdot e}{(1-\nu_b^2)\cdot R}$$

If $k_s=\frac{K_s}{2\cdot G}$ represent the relative rigidity of the concrete compared to the solid mass and λ_d the rate of déconfinement with the installation of supporting, then the radial constraints and orthoradiales as well as radial displacement in wall is given by [bib1]:

$$\begin{cases}\sigma_R=\frac{k_s}{1+k_s}\left(1-\lambda_d\right)\sigma_0\\ \sigma_\theta=\frac{k_s}{1+k_s}\left(1+\lambda_d\right)\sigma_0\\ U_R=\frac{1+\lambda_d\cdot k_s}{1+k_s}\cdot\frac{\sigma_0}{2\mathrm{G}}\cdot R\end{cases}$$

2.2 Sizes and results of reference

One tests the following sizes on the level of the wall at the points A and B figure of the paragraph 1.1, at the moment when déconfinement is total:

1) radial constraint: σ_{yy} in A or σ_{zz} in B ;
2) constraint orthoradiale: σ_{zz} in A or σ_{yy} in B ;
3) radial displacement: u_y in A or u_z in B .

2.3 Uncertainties on the solution

None. Exact analytical result.

2.4 Bibliographical references

[1] The calculation of the tunnels by the method convergence-containment, Mr. Panet, Presses of the ENPC 1995

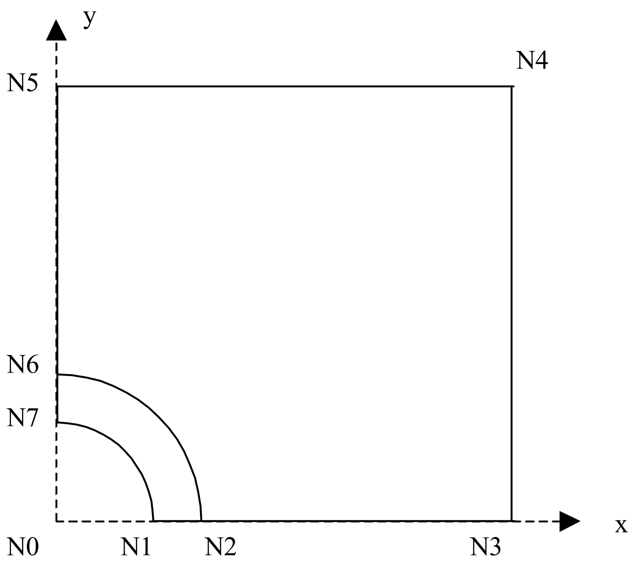
[2] How to simulate the digging of a tunnel with *Code_Aster* ? Principle of the method, put in work and validation, A. Courtois, R. Saidani, P. Sémété, notes EDF HT 2/25/045 /A - 2002

[3] Mechanics of the continuous mediums, volume 2, J. Salençon, ED. Ellipses - 1988

3 Modeling A

3.1 Characteristics of modeling

Modeling 2D in plane deformations. This modeling corresponds to methodology 3 of documentation [U2.04.06]: excavation with supporting with initialization of the constraints by call to CREA_CHAMP and déconfinement according to a method of sequence of models.



3.2 Characteristics of the grid

Many nodes: 8477
Many meshs: 3304 of type QUAD8

3.3 Course of calculation

The objective of this case test is to test a method. The following table presents the principal stages which structure the command file.

Orders	Comments
CREA_CHAMP	Initialization of the constraints geostatics (here isotropic $5\,MPa$ in compression)
STAT_NON_LINE	Blocking of the nodes of the gallery for calculation of the nodal reactions to inject to simulate déconfinement
CREA_CHAMP	Recovery of the nodal reactions
STAT_NON_LINE	Re-injection of the nodal reactions
STAT_NON_LINE	Intermediate calculation to pass from a model without mesh representing the voussoirs concrete to a model with meshs the representative (see [bib2])
STAT_NON_LINE	Progressive Déconfinement of the solid mass

3.4 Sizes tested and results

After the installation of the coating (urgent final), one tests the components σ_{xx} and σ_{yy} with the nodes $N2$ and $N6$ as well as radial displacement in these points (DX for $N2$, DY for $N6$).

	Reference	***Aster***	**Difference (%)**
Node $N2$			
σ_{xx}	$-1,52821.10^{6}$	$-1,53154.10^{6}$	0.218
σ_{yy}	$-8,47179.10^{6}$	$-8.52772.10^{6}$	0.660
DX	$-1,6925.10^{-3}$	$-1,6684.10^{-3}$	-1.422
Node $N6$			
σ_{xx}	$-8,47179.10^{6}$	$-8,41147.10^{6}$	-0.712
σ_{yy}	$-1,52821.10^{6}$	$-1,52943.10^{6}$	0.080
DY	$-1,6925.10^{-3}$	$-1.7184.10^{-3}$	1.529

4 Modeling B

4.1 Characteristics of modeling

Modeling 2D in plane deformations. This modeling corresponds to methodology 2 of U2.04.06 documentation: excavation with supporting with initialization of the constraints by call to `CREA_CHAMP` and déconfinement using only one model and materials "flexible" for the excavated zone.

The grid is the same one as for modeling A.

4.2 Course of calculation

The objective of this case test is to test a method. The following table presents the principal stages which structure the command file.

Orders	**Comments**
`CREA_CHAMP`	Initialization of the constraints geostatics (here isotropic $5\,MPa$ in compression)
`STAT_NON_LINE`	Blocking of the nodes of the gallery for calculation of the nodal reactions to inject to simulate déconfinement
`CREA_CHAMP`	Recovery of the nodal reactions
`STAT_NON_LINE`	Re-injection of the nodal reactions
`STAT_NON_LINE`	Progressive Déconfinement of the solid mass

4.3 Sizes tested and results

After the installation of the coating (urgent final), one tests the components σ_{xx} and σ_{yy} with the nodes $N2$ and $N6$ as well as radial displacement in these points (DX for $N2$, DY for $N6$).

	Reference	***Aster***	**Difference (%)**
Node $N2$			
σ_{xx}	$-1{,}52821.10^{6}$	$-1{,}53619.10^{6}$	0,52
σ_{yy}	$-8{,}47179.10^{6}$	$-8.53167.10^{6}$	0,71
DX	$-1{,}6925.10^{-3}$	$-1{,}6687.10^{-3}$	-1,41
Node $N6$			
σ_{xx}	$-8{,}47179.10^{6}$	$-8{,}41158.10^{6}$	-0,71
σ_{yy}	$-1{,}52821.10^{6}$	$-1{,}52967.10^{6}$	0,1
DY	$-1{,}6925.10^{-3}$	$-1.7180.10^{-3}$	1,51

5 Modeling C

5.1 Characteristics of modeling

Modeling 2D in plane deformations. This modeling corresponds to case 1 of documentation [U2.04.06]: excavation without supporting with initialization of the constraints by call to CREA_CHAMP and déconfinement using only one model and a “flexible” material for the excavated zone. This modeling will thus give different results since there are no supportings. The analytical solution is provided here by the equation (1).

The grid is the same one as for modeling A.

5.2 Course of calculation

The objective of this case test is to test a method. The following table presents the principal stages which structure the command file.

Orders	Comments
STAT_NON_LINE	Initialization of the constraints geostatics
CREA_CHAMP	Recovery of the constraints initialized
STAT_NON_LINE	Blocking of the nodes of the gallery for calculation of the nodal reactions to inject to simulate déconfinement
CREA_CHAMP	Recovery of the nodal reactions
STAT_NON_LINE	Re-injection of the nodal reactions

5.3 Sizes tested and results

After the installation of the coating (urgent final), one tests the components σ_{xx} and σ_{yy} with the nodes $N2$ and $N6$ as well as radial displacement in these points (DX for $N2$, DY for $N6$).

	Reference	*Aster*	Difference (%)
Node $N2$			
σ_{yy}	-10.10^{6}	$-1{,}013.10^{6}$	1,13
DX	$-2{,}4000.10^{-3}$	$-2{,}4375.10^{-3}$	1,54
Node $N6$			
σ_{xx}	-10.10^{6}	$-9{,}89.10^{6}$	1,13
DY	$-2{,}478.10^{-3}$	$-2{,}4375.10^{-3}$	1,66

6 Summary of the results

Values obtained with *Code_Aster* are in agreement with the values of the analytical solution of reference.