http://www.fracsima.com/Disroc/Examples/GroundFreezing/GroundFreezing.html

DISROC 5

Ground Freezing in Tunneling

The artificial ground freezing technique is used in tunneling to provide temporary earth support and groundwater control. Frozen soil has greater strength and lower permeability than unfrozen soil. In the most common freezing approach for tunnel excavation, the refrigeration pipes are installed horizontally around the perimeter of the tunnel. A successful ground freezing design requires that the pipe spacing, refrigeration load, and refrigeration time required to achieve a frozen area of sufficient thickness be properly evaluated.

The groundwater flow introduces additional heat into the freezing zone which opposes freezing. Conversely, freezing decreases the permeability of the soil and opposes the flow of the fluid. These effects make soil freezing a fully coupled hydrothermal process. If the effects of freezing on mechanical properties (especially strength) are also considered, a coupled thermo-hydro-mechanical problem needs to be modeled.

Disroc provides a fully operational numerical tool to model freezing process and design ground freezing technique for engineering applications.

Theoretical basis

The GeliSol material model of Disroc dedicated to model ground freezing effects has a threefold mechanical, hydraulic and thermal constitutive model.

The mechanical behavior corresponds to a Mohr-Coulomb elastoplastic material with 6 parameters which are: Young's modulus, Poisson's ratio, cohesion, frication angle, dilatation angle and tensile strength cutoff. All these parameters can vary between initial and final values corresponding respectively to the unfrozen and frozen states of the ground. However, it suffices to model only the variation of the cohesion which is the most determining and to consider the other parameters constants.

The hydraulic model corresponds to the Darcy's law with and evolving permeability. The permeability depends on the unfrozen water content S_λ which decreases with freezing from a maximum value corresponding to the unfrozen state to a minimum value for the frozen state. The variation of S_λ with the temperature is given by the thermal model of GeliSol.

The thermal model includes the heat transport equation and the freezing behavior. The heat flow has a diffusive part depending on a scalar thermal conductivity Λ and an advective flow depending on the fluid velocity which results from the hydraulic calculation. The function $S_\lambda(T)$ is determined by the freezing behavior of the soil.

Figure 1 summarizes the constitutive equations of the GeliSol model.

Hydraulic: Groundwater flow in a soil with partially frozen pore space:

Darcy's law: $$C_M \frac{\partial p}{\partial t} = div(\frac{\rho_\lambda}{\mu_\lambda} \boldsymbol{k} \nabla p)$$

Permeability depending on the unfrozen water content S_λ:

$$\boldsymbol{k}\,(S_\lambda) = \boldsymbol{k}_0 k^r (S_\lambda)$$

Relative permeability: $$k^r (S_\lambda) = \sqrt{S_\lambda}\left(1-(1-S_\lambda^{1/m})^m\right)^2$$

Thermal : Diffusive and advective heat transport with thermal conductivity Λ and fluid velocity $\underline{v}$:

$$\left(\rho C^p + \rho_\lambda \phi\, L\, G\right)\frac{\partial T}{\partial t} = div(\Lambda\,.\nabla T) - div\left(\rho_\lambda C_\lambda^p T \underline{v}\right)$$

Heat capacity including the latent heat *L* of water to ice phase change. The liquid water content S_λ depends on the temperature (freezing curve of the soil) and:

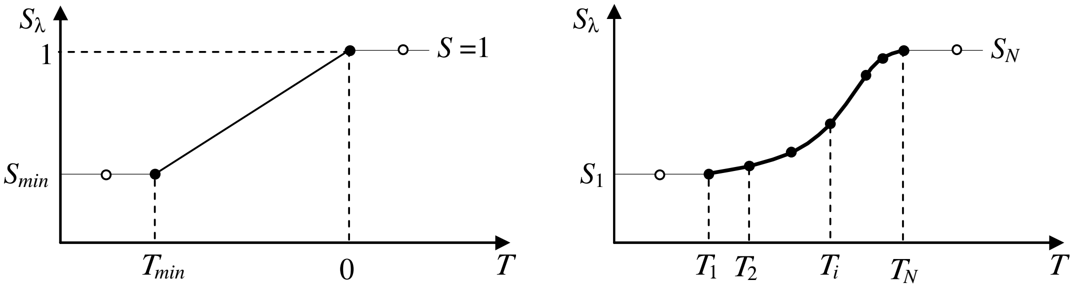
$$G(T) = \frac{\partial S_\lambda(T)}{\partial T}$$

Mechanical effects: The mechanical parameters and specially the cohesion *C* of the soil vary with S_λ from the state of unfrozen soil to that of frozen soil:

$$C(S_\lambda) = S_\lambda C_{unfrozen} + (1-S_\lambda) C_{frozen}$$

Figure 1: Main constitutive equations of the Thermo-Hydro-Mechanical GeliSol material

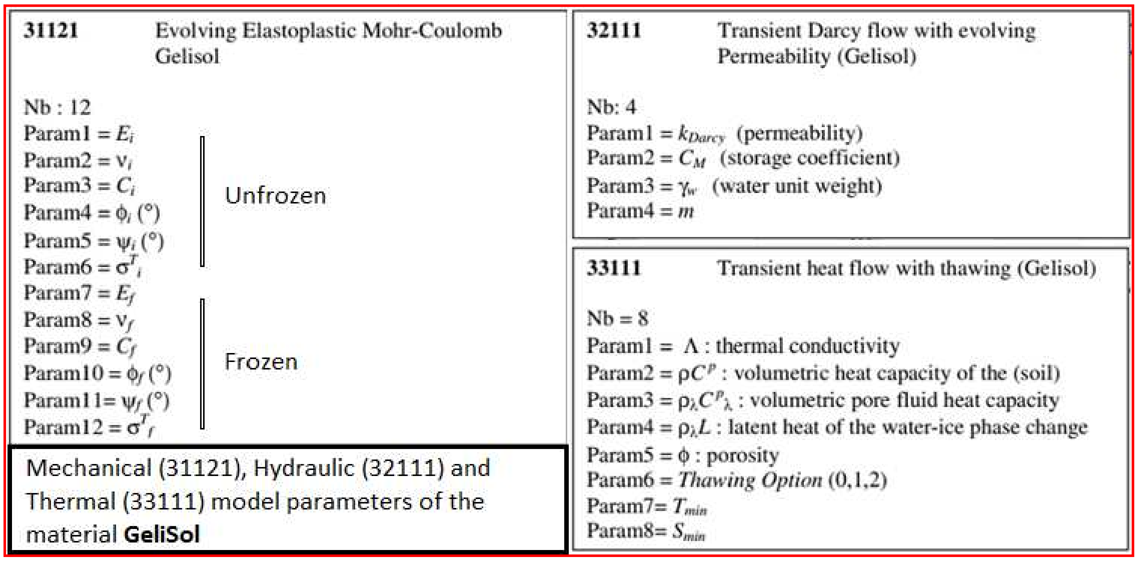
The *freezing curve* of the soil can be defined by simple linear model supposing that the entire freezing process takes place between 0 °C and $T_{min}<0$, or by a set of (T, S_λ) values given by the user (Figure 2).



Option 1: Curve defined by (T_{min}, S_{min}) *Option* 2: Curve defined by (T_i, S_i) in a file

Figure 2: Two methods of definition of the freezing curve of the GeliSol material

The following figure shows the parameters that must be specified for the GeliSol model.



31121 Evolving Elastoplastic Mohr-Coulomb Gelisol

Nb : 12
Param1 = E_i
Param2 = ν_i
Param3 = C_i
Param4 = ϕ_i (°)
Param5 = ψ_i (°)
Param6 = σ^T_i
Unfrozen
Param7 = E_f
Param8 = ν_f
Param9 = C_f
Param10 = ϕ_f (°)
Param11= ψ_f (°)
Param12 = σ^T_f
Frozen

Mechanical (31121), Hydraulic (32111) and Thermal (33111) model parameters of the material **GeliSol**

32111 Transient Darcy flow with evolving Permeability (Gelisol)

Nb: 4
Param1 = k_{Darcy} (permeability)
Param2 = C_M (storage coefficient)
Param3 = γ_w (water unit weight)
Param4 = m

33111 Transient heat flow with thawing (Gelisol)

Nb = 8
Param1 = Λ : thermal conductivity
Param2 = ρC^p : volumetric heat capacity of the (soil)
Param3 = $\rho_\lambda C^p{}_\lambda$: volumetric pore fluid heat capacity
Param4 = $\rho_\lambda L$: latent heat of the water-ice phase change
Param5 = ϕ : porosity
Param6 = *Thawing Option* (0,1,2)
Param7= T_{min}
Param8= S_{min}

Figure 3: Parameters required for the mechanical, hydraulic and thermal properties of GeliSol

When the frozen zone around the tunnel reaches a sufficient thickness, the convergence due to the digging of the tunnel is limited to the admissible values.

Example

A 2.90 *m* radius tunnel about 40 *m* deep in a layer of weathered chalk (Chalk-W) is studied. Weathered chalk rests on a layer of sound chalk (Chalk-S) and is covered with a layer of alluvium (Figure 4).

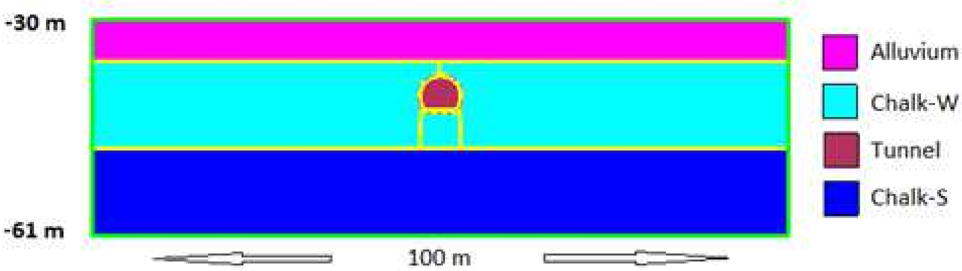
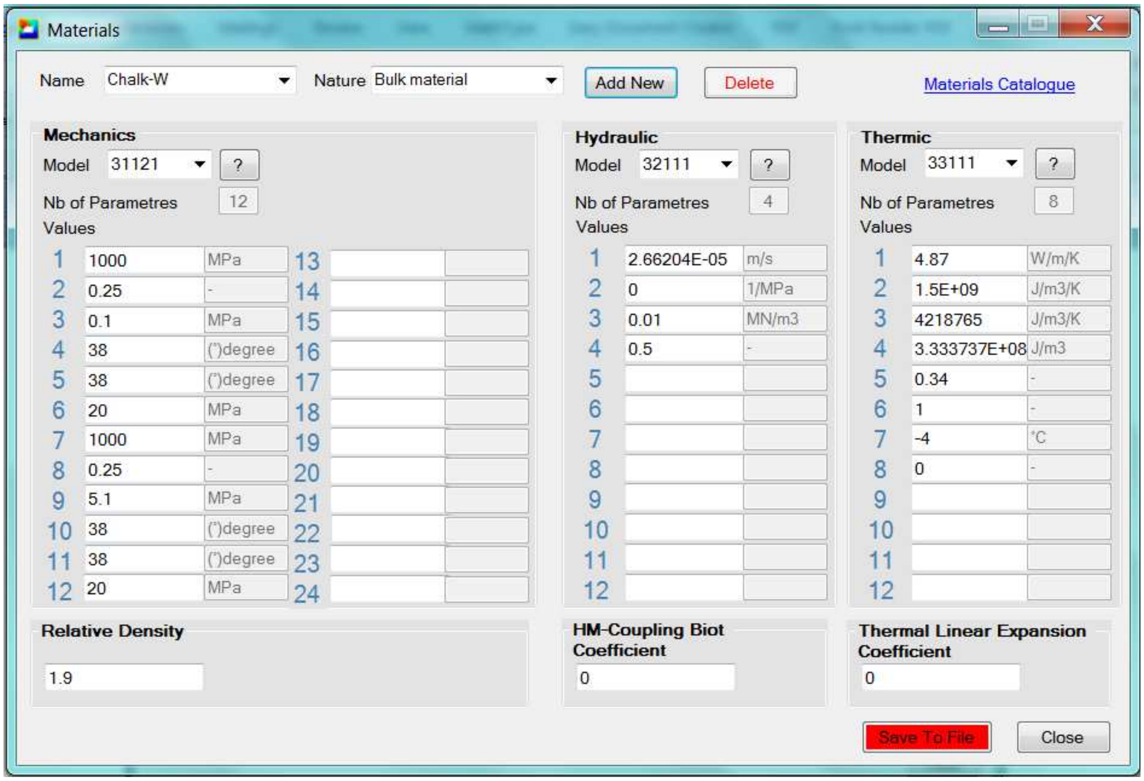


Figure 4: Geometry of the tunnel model

The weathered chalk is modeled by the GeliSol material model while two other layers are modeled by simple thermo-poroelastic materials. For the weathered chalk, the values of parameters defined in the Figure 3 are given in the Figure 5.



Name Chalk-W

Nature Bulk material

Mechanics

Model 31121

Nb of Parametres 12

Values

1	1000	MPa	13		
2	0.25	-	14		
3	0.1	MPa	15		
4	38	(°)degree	16		
5	38	(°)degree	17		
6	20	MPa	18		
7	1000	MPa	19		
8	0.25	-	20		
9	5.1	MPa	21		
10	38	(°)degree	22		
11	38	(°)degree	23		
12	20	MPa	24		

Hydraulic

Model 32111

Nb of Parametres 4

Values

1	2.66204E-05	m/s
2	0	1/MPa
3	0.01	MN/m3
4	0.5	-
5		
6		
7		
8		
9		
10		
11		
12		

Thermic

Model 33111

Nb of Parametres 8

Values

1	4.87	W/m/K
2	1.5E+09	J/m3/K
3	4218765	J/m3/K
4	3.333737E+08	J/m3
5	0.34	-
6	1	-
7	-4	°C
8	0	-
9		
10		
11		
12		

Relative Density 1.9

HM-Coupling Biot Coefficient 0

Thermal Linear Expansion Coefficient 0

Figure 5: GeliSol parameters specified for weathered chalk layer (Chalk-W)

First mechanical loads are applied to the model to create the ground stresses corresponding to gravity forces. The excavation is modeled at this point just to see what the convergence would be without freezing. The results are shown in the Figure 6 and 7. With a cohesion of 500 *kPa*, there is a plastic zone around the tunnel and a maximum radial displacement of 12 *cm*. This leads to a ratio of the convergence on the radius U_r/R greater than 4 %.

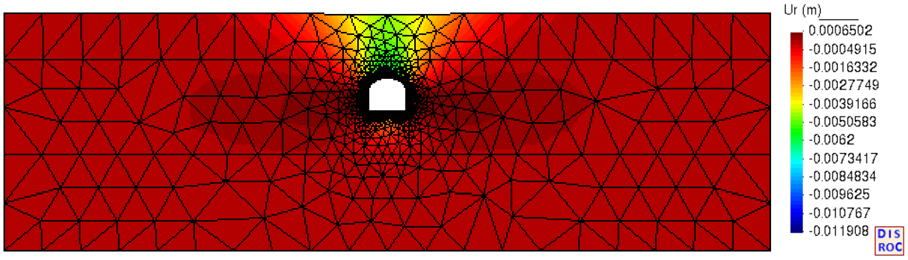


Figure 6: Displacement U_r due to excavation without freezing: maximum value about 12 cm

25 °C

S_{min}

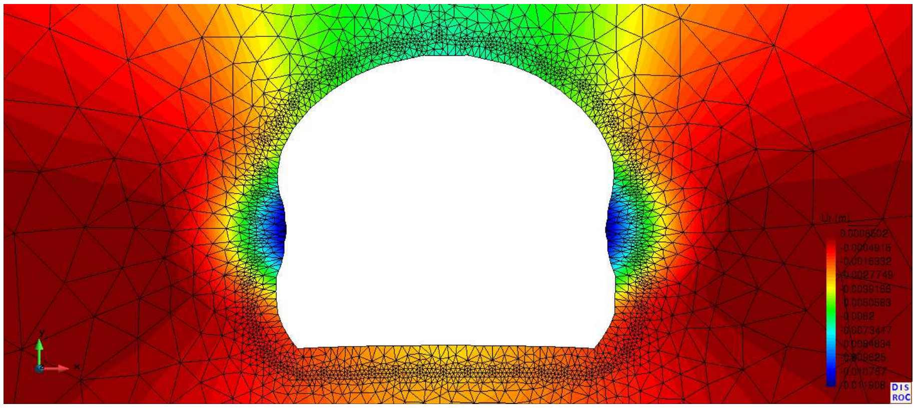


Figure 7: Detail of displacement due to digging without freezing on deformed mesh

The freezing process is modeled in the presence of a groundwater flow. A fluid velocity condition equal to 2.3 *m/day* is applied to the left and right boundaries (flow from left to right) whiles the top and bottom sides are supposed to be closed boundaries. These hydraulic conditions with the existing mechanical loads are kept constant in all the subsequent stages.

The thermal conditions are applied on the model in three steps (Figure 8) .

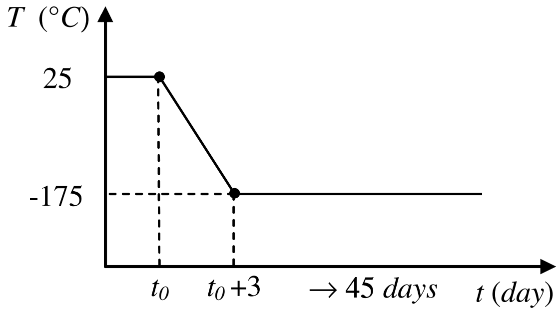


Figure 8 : Temperature conditions applied in three steps to model the refrigeration process

At first the initial uniform temperature of 25°C is applied in a time independent process to the domain. The temperature condition is applied on the boundary as well as on the freeze pipes placed in the model (Figure 9). Mesh details for the elements representing the freeze pipes are shown in Figures 10.

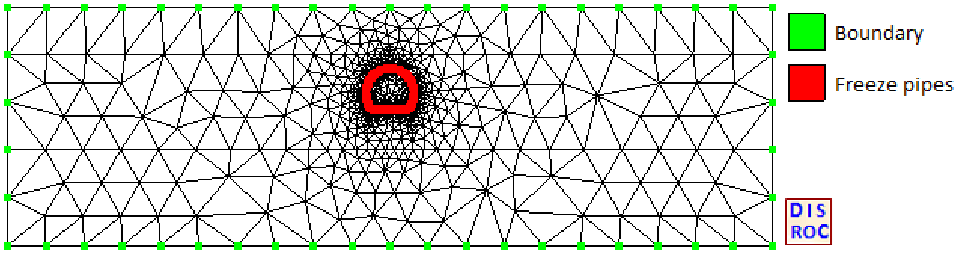


Figure 9: Thermal conditions applied on the boundary and freeze pipes

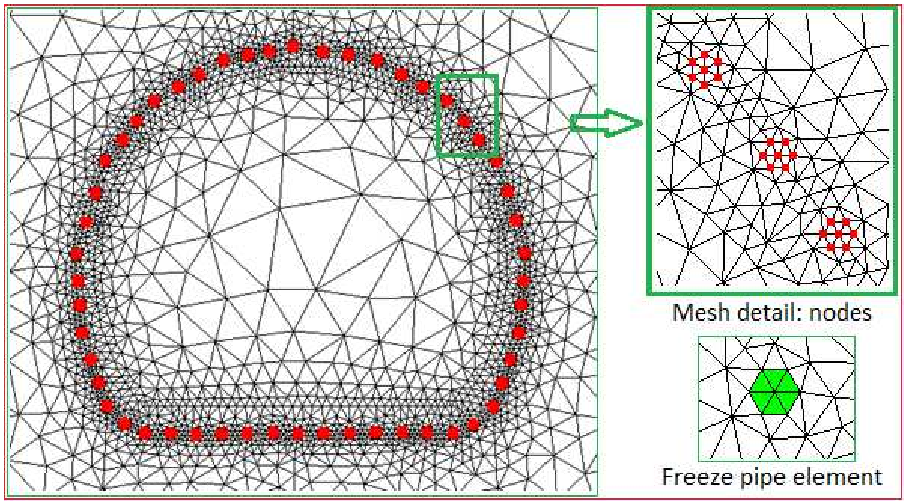


Figure 10: Detail of freeze pipes installed around the tunnel perimeter

In the second step, the temperature is lowered from 25 ° C to -175 ° C in 4 days in a transient process. This corresponds to applying a temperature change rate of -50 ° C/day to the freezing elements.

In the last step, the temperature is kept constant on the freezing pipes as well as the domain boundary for a transient process. This freezing process lasts 45 days in this example.

The zone of negative temperatures after 45 days of freezing is shown on the Figure 11.

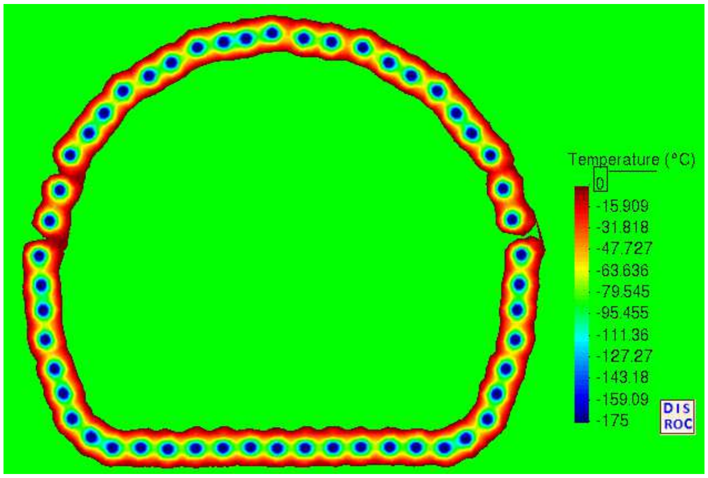


Figure 11: Temperature field after 45 days freezing (click on the image to see video animation).

Note that the permeability also decreases with freezing and the frozen ring created around the section of the tunnel prevents the flow of fluid in this area (Figure 12).

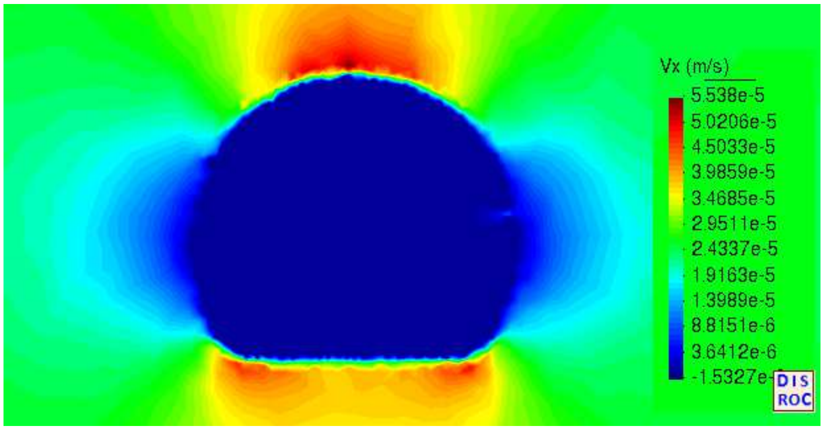


Figure 12: Fluid velocity V_x after 45 days freezing (click on the image to see video animation).

The cohesion of the frozen soil is taken equal to 5 MPa. Freezing creates a ring-shaped area around the perimeter of the tunnel with cohesion of about 5MPa. This area acts as a temporary support during the excavation process (Figure 13).

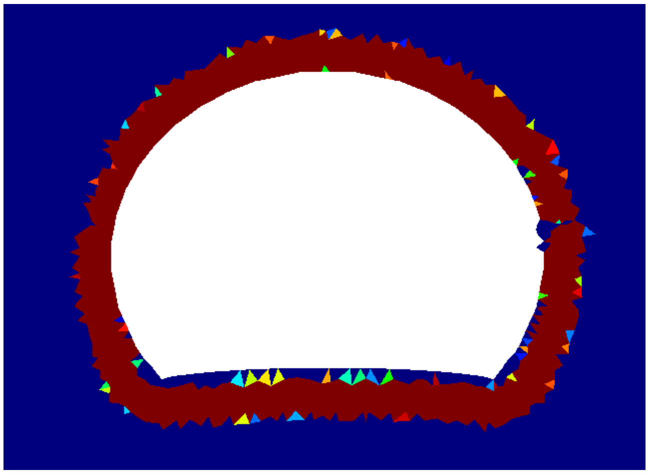


Figure 13: After 45 days of freezing, a ring of approximately 40 *cm* thick of frozen soil with high cohesion, about 5 MPa, is created around the section of the tunnel. Dark red corresponds to the maximum value of 5 MPa and dark blue to the minimum of 500 kPa (click on the image to see the video animation).

A freezing anomaly is observed in a small area halfway up the right wall of the tunnel. The cohesion does not reach its maximum value in this zone and the ring-shaped zone is not completely closed after 45 days of freezing. This anomaly is due to the flow of the fluid which concentrates on this point when the gel in other areas prevents the fluid from passing there. This phenomenon can be observed on the diagram of the velocities at intermediate times (see the video animation of the evolution of the fluid velocity). The stress anomaly induced by this phenomenon is visible also in Figure 14 showing the radial stress. This anomaly can be corrected by increasing the density of the freezing pipes.

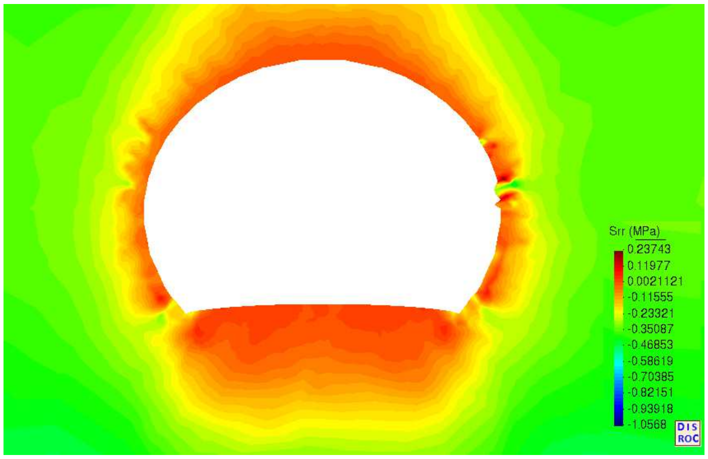


Figure 14: Radial stress σ_{rr} after 45 days freezing. A freezing anomaly creates a small area of stress anomaly at halfway up on the right wall.

The analysis of the displacement field proves that this freezing process is sufficient to limit the convergence induced by the excavation to acceptable values. In fact, the maximum radial displacement observed after total excavation is about 5 *mm* (Figure 15). For 290 *cm* tunnel radius this leads to an U_r/R which is less than 0.2%.

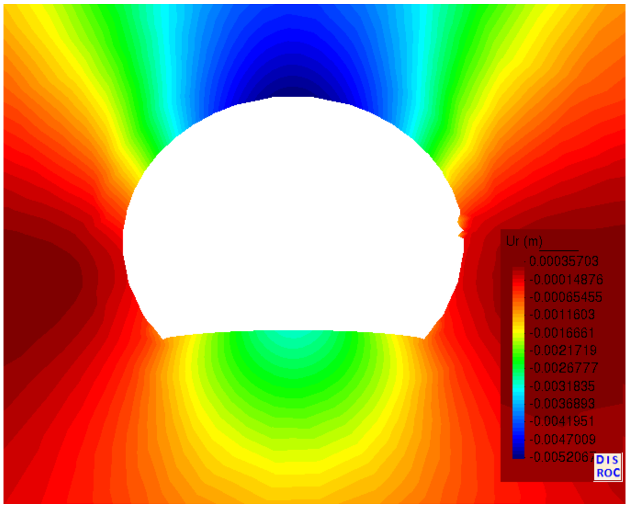


Figure 15: The maximum displacement on the wall after total excavation in the frozen ground is about 5 *mm* for a tunnel diameter of 290 *cm*.

The bibliographic references below provide more information on the freezing process and its use for geotechnical structures.

References

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