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► **To cite this version:**

Manuel de La Fuente, Jean Sulem, Reza Taherzadeh, Didier Subrin. Tunneling in Squeezing Ground: Effect of the Excavation Method. *Rock Mechanics and Rock Engineering*, 2020, 53 (2), pp.601-623. 10.1007/s00603-019-01931-4 . hal-03119942

**HAL Id: hal-03119942**

**<https://hal.science/hal-03119942>**

Submitted on 25 Jan 2021

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# Tunneling in squeezing ground: effect of the excavation method

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## Abstract:

Tunnel excavation in squeezing ground exhibits large time-dependent and often anisotropic deformation. Within the context of the Fréjus road tunnel and its safety gallery excavated under the Alps between France and Italy, an interesting configuration of two parallel tunnels under squeezing ground conditions is observed. The special feature of this case study lies in the fact that both tunnels have been excavated in similar geotechnical conditions but with different excavation techniques. The road tunnel was excavated with conventional drill and blast methods in the seventies whereas the safety gallery was excavated between 2009 and 2016 with a single shield Tunnel Boring Machine (TBM).

The present paper presents monitoring data processing and numerical simulations of both tunnels with the aim of studying the influence of the excavation method on the time-dependent tunnel response. A calibration of a visco-elasto-plastic anisotropic constitutive model based on the back-analysis of convergence measurements retrieved during the excavation of the Fréjus road tunnel is carried out. The identified ground behavior can be extrapolated to the parallel zones of the safety gallery. In particular, we are interested in the prediction of the stress state in the segmental lining of the gallery during its excavation and the comparison with in situ measurements. It is shown that the time-dependent behavior of the ground is affected by the excavation technique. Finally, an attempt to predict the long-term response of both tunnels is proposed.

**Keywords:** Squeezing ground; Conventional drill and blast tunnel excavation; Tunnel Boring Machine; The Fréjus road tunnel; The Fréjus safety gallery

## 1 List of symbols

2

$C_{\infty x}$	Instantaneous convergence obtained in the case of an infinite rate of face advance (no time-dependent effect)
$X$	Parameter related to the distance of influence of the tunnel face
$T$	Parameter related to time-dependent behavior of the system (rock mass formation-support)
$m$	Parameter which represents the relationship between the long-term total convergence and the instantaneous convergence
$n$	Form-factor of the fitting law which is often taken equal to 0.3
$\beta$	Anisotropy ratio of the convergence data
$\xi$	Variability index of the convergence data
$E$	Young's modulus of the solid matrix
$\nu$	Poisson's ratio of the solid matrix
$K$	Elastic bulk modulus of the solid matrix
$G_K$	Kelvin shear modulus of the solid matrix
$\eta_K$	Kelvin dynamic viscosity of the solid matrix
$G_M$	Elastic shear modulus of the solid matrix
$\eta_M$	Maxwell dynamic viscosity of the solid matrix
$c$	Cohesion of the solid matrix
$\phi$	Friction angle of the solid matrix
$\psi$	Dilation angle of the solid matrix
$\sigma_t$	Tension limit of the solid matrix
$c_j$	Cohesion of the weak planes
$\phi_j$	Friction angle of the weak planes
$\psi_j$	Dilation angle of the weak planes
$\sigma_{tj}$	Tension limit of the weak planes
$\alpha$	Variability index of the constitutive parameters (describing the damage degree of the rock mass)

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1 **Acknowledgements**

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This work is part of the PhD thesis of the first author, carried out at Ecole des Ponts ParisTech in partnership with TRACTEBEL ENGIE and CETU (French centre for tunnels studies). The authors wish to thank the SFTRF (Société Française du Tunnel Routier du Fréjus) for providing monitoring data on both tunnels and ITASCA for supporting the first author through the Itasca Education Partnership Program (IEPP).

## 1. Introduction

When dealing with squeezing ground conditions, the technique of excavation has a huge influence on the tunnel response. The excavation can be adjusted to the encountered ground conditions when it is executed with conventional techniques: an active or a passive approach can be adopted. As described in Barla (2001), the active approach refers to the so-called ‘heavy method’ which consists in preventing rock deformation by the installation of a sufficiently strong support/stabilization/lining system, whereas the passive approach refers to the so-called ‘yielding support method’ which aims at accommodating the large deformations. On the other hand, when the tunnel is excavated with a Tunnel Boring Machine (TBM), the adaptation and the optimization of the design to the encountered ground conditions are difficult to achieve as the tunnel geometry and support system are imposed by the TBM characteristics. Large convergence of the ground can lead to sticking of the cutter head, jamming of the TBM and overloading of the segmental lining. The immediate installation of the lining prevents a direct study of the ground response through convergence measurements. Information can be retrieved through the monitoring of the thrust force which has to overcome the friction exerted by the ground over the TBM shield to avoid entrapment (e.g. Ramoni & Anagnostou, 2006, 2008, 2010). Monitoring of strains and stresses in the segmental lining can provide an accurate information on the time-dependent interaction between the ground and the support.

An interesting question concerns the effect of the excavation method on the ground behavior. Drill and blast methods can significantly damage the rock mass whereas TBM excavation reduces the disturbance of the ground. Therefore, the long term ground behavior might be affected by the excavation method. It has also been observed in several well documented cases that, when the water amount in the ground is important, the deformations observed during the construction of a second parallel tube are smaller than in the first tube although the geology and the construction method of the second tube were the same as in the first tube like for example in the Simplon tunnel (Steiner 1996). This was attributed to the drainage and consolidation effects triggered by the excavation of the first tube. Even when the two tubes are far enough to preclude any mutual interaction, different responses can be observed in relation with the strong heterogeneity and local variability of the properties in squeezing grounds (Mezger et al., 2013).

The Fréjus road tunnel and its safety gallery are two examples of tunnels excavated in squeezing ground. The Fréjus road tunnel was excavated by conventional drill and blast methods in the seventies linking France and Italy under the Alps. The design and construction of the tunnel were on behalf of a two-state company named *Société française du tunnel routier du Fréjus* (SFTRF) for the French part and *Società italiana per il Traforo Autostradale del Frejus* (SITAF) for the Italian part. Since the fire which took place in Montblanc tunnel in 1999, a new safety legislation for tunnels was established. In order to be in accordance with it, the SFTRF and the SITAF decided to excavate a safety gallery between 2009 and 2016 which runs parallel to the existing road tunnel at a 50 m average distance between the axes of both tunnels. The safety gallery was excavated with a Tunnel Boring Machine (TBM).

1 For the Fréjus road tunnel, the ground response can be studied by analyzing convergence  
2 data retrieved during the excavation. Convergences were monitored over a period of four  
3 months until the installation of the final lining. By analyzing convergence data retrieved from  
4 the road tunnel a good understanding of the face advance effects and of the time-dependent  
5 behavior of the ground is reached (De la Fuente et al., 2017). The present paper aims at  
6 studying the effect of the excavation method on the time-dependent response of the tunnel. It  
7 is carried out by calibrating a visco-elasto-plastic anisotropic constitutive model on the  
8 convergence data recorded in the road tunnel during its excavation. This constitutive model is  
9 then used to describe the behavior of the neighboring zones of the safety gallery in order to  
10 compute its time-dependent response. Finally, a numerical prediction of the long-term  
11 response of both tunnels is also carried out.

## 12 13 **2. Case study: The Fréjus road tunnel and its safety gallery**

### 14 15 **2.1 General context of the Fréjus road tunnel and of its safety gallery**

16  
17 The Fréjus road tunnel came into service on July, 12th 1980. A new path between North-West  
18 Europe and the Mediterranean was opened. The tunnel links Modane (France) and  
19 Bardonechia (Italy) under the ridge between the pic of Fréjus (3019 m) and the pic of Grand-  
20 Vallon in the Alps, following an average North-South direction. The geological and  
21 geotechnical context is described in the papers of Beau et al. (1980) and Lévy et al. (1981)  
22 (see also Sulem (2013)).

23  
24 The tunnel is 12.87 km long and 11.6 m wide between the sidewalls with a two-lane horse  
25 shoe section. The overburden along most of the layout is over 1000 m (with a maximum of  
26 1800 m). The Italian tunnel portal is at an altitude of 1297 m whereas the French tunnel portal  
27 is at an altitude of 1228 m. The tunnel slopes down 0.54% from Italy towards France. Two  
28 ventilation shafts have been placed at 1/3 and 2/3 of the tunnel length together with six  
29 ventilation plants.

30  
31 The safety gallery is 9.5 m wide and 13 km long. As for the road tunnel, the safety gallery  
32 slopes down 0.54% from France towards Italy and the average overburden is of 1000 m (with  
33 a maximum of 1800 m). The safety gallery is connected with the road tunnel by means of  
34 34 inter-tubes spaced of 400 m. Among them, 5 by-pass, large enough to allow the circulation  
35 of emergency vehicles between the road tunnel and the safety gallery, have been installed.  
36 Ten technical stations as well as two ventilation plants were also built.

37  
38 Both tunnels mainly go through a calcareous schist formation, however tunnels entrances  
39 are constituted of a sequence of various grounds (anhydrite, black and green schist, cargneule)  
40 (Fig1.).

#### 41 42 **Fig1. Geological profile of the alignment**

43  
44 The dip direction of the schistosity planes (N270°-N315°) is approximately parallel to the  
45 longitudinal axis of both tunnels and its dip angle varies between 25° and 50°. The calcschist  
46 result from a light metamorphism of marls and limy marls with the formation of phyllitous  
47 minerals (muscovite, chlorite). As noted by Panet, (1996), some variations are observed with

1 zones which are more calcareous and zones which are more micaceous with some graphitic  
2 beds. As mentioned later in the analysis of the convergence data, the mineralogy has been  
3 recognized to have a significant influence on the magnitude of the convergence of the tunnel  
4 walls. These minerals favor the formation of schistosity planes during the metamorphism of  
5 the rock. When the schistosity planes are well formed and are favorably oriented, buckling  
6 phenomenon can be triggered during the excavation of the tunnel. The anisotropy of the  
7 calcschists formation is clearly highlighted by the seismic data. The wave velocity in the  
8 direction of the plane of schistosity varies between 4000m/s and 6000m/s whereas it varies  
9 between 1300m/s and 3000m/s in the direction perpendicular to it. The influence of the  
10 anisotropy of the structure has also been studied by mechanical tests (Beau et al. 1980). In  
11 spite of the strong heterogeneity of the ground, measurements of the Young's modulus carried  
12 out in the parallel direction to the schistosity planes (between 25 GPa and 60 GPa) are slightly  
13 higher than measurements carried out in the perpendicular direction to the schistosity planes  
14 (between 10 GPa and 55 GPa). The uniaxial compression strength (UCS) measured in the  
15 perpendicular direction to the schistosity planes (87% of the UCS measurements vary  
16 between 30 MPa and 100 MPa) is higher than the UCS measured in the parallel direction to  
17 the schistosity planes (80% of the UCS measurements vary between 10 MPa and 70 MPa).  
18 Some laboratory tests carried out along the schistosity planes show values of the cohesion  
19 which vary between 0 MPa (residual cohesion) and 0.28 MPa (peak cohesion) (Lunardi,  
20 1980).

21

22 During the excavation of the safety gallery, the RQD values of the ground have been  
23 recorded and exhibit a very large variation.

24

25 Feedback from the road tunnel excavation suggests that the water amount is very low and  
26 well localized.

27

## 28 **2.2 Excavation and support techniques in the Fréjus road tunnel**

29

30 The works have been executed over a total length of 12500 m (Levy et al., 1981). The  
31 excavation of the section was carried out in one step by drilling and blasting. The average  
32 length of the excavation step was between 3.50 and 4.50 m. After the excavation, the  
33 execution of the invert was carried out at a distance of 300 to 400 m from the tunnel face. A  
34 soft support consisting in 20 punctually anchored rockbolts per linear meter was installed. The  
35 length of the bolts is of 4.65 m, the diameter of 20 mm and the strength of 450 MPa. A wire  
36 grid (10 cm x 10 cm  $\Phi$  5 mm) was also installed to avoid rock debris to fall down. Buckling  
37 of the schistosity planes was observed at the West part of the vault where schistosity planes  
38 are tangent to the tunnel wall. The concreting operations of the final cast-in-place lining were  
39 executed at 600 m from the tunnel face (which corresponds to about 107 days after the  
40 excavation).

41

## 42 **2.3 Mechanized excavation technique of the Fréjus safety gallery**

43

44 The first 650 meters from the French portal of the safety gallery were excavated by  
45 conventional drill and blast methods. The rest of the safety gallery was excavated with a  
46 single shield TBM. The TBM was firstly used to excavate the 6.5 km of the French part of the

1 tunnel. Then it was used to excavate the tunnel through the Italian part. The geological  
2 context of the safety gallery is similar to that of the road tunnel.

3  
4 A single shield TBM for hard rock with longitudinal support was chosen for performing  
5 the excavation. The length of the shield is of 11.2 m and the maximal thrust force is about 75  
6 300 kN in service conditions. The shield has a diameter of 9.37 m and a conicity of 60 mm  
7 which permits to accommodate the convergences. The cutting head has a diameter of 9.46 m  
8 with a nominal overcutting of 90 mm at the crown. However, the overcutting can be increased  
9 to 190 mm (medium size) and to 290 mm (large size). The excavation began with the nominal  
10 overcutting. The medium size overcutting was activated around chainage 1635. At chainage  
11 2929 the nominal overcutting was activated again. Before facing up the second zone of strong  
12 convergences (see section 3.1), the medium size overcutting was activated once again at  
13 chainage 4346.

14  
15 The lining is composed of concrete rings made of precast segmental lining of 40 cm  
16 thickness. The average length of a ring is 1.80 m and the inner diameter is 8.20 m. The  
17 concrete of the segmental lining is class C45/55 (EuroCode 2). A universal ring constituted of  
18 6+1 elements has been used (4 standard segments, two counter keys and one key segment).

19  
20 After the excavation and the installation of the concrete ring, the annular gap between the  
21 lining and the ground was filled with mortar and gravel. A first lay of mortar C3/5 (Eurocode  
22 2) was injected through the shield in the lower part of the section on a 100° wide zone. This  
23 task was followed by the gradual injection of the gravel through the segmental lining in the  
24 remaining portion of the annular gap. The onsite observations concluded that the gap was  
25 completely filled around the installation of ring n-7 (n being the closest ring to the face)  
26 (Fig2). To improve the backfilling technique and to remedy to some injection problems  
27 encountered in the vault, a new method consisting in a mortar-gravel-mortar filling  
28 ('sandwich technique') was adopted from chainage 1763. The injection of the 60° wide upper  
29 zone with mortar improved the backfilling process.

30  
31 **Fig2. Backfilling technique of the annular gap after Vinnac (2012)**

### 32 33 **3. Study of the monitoring data retrieved during the excavation of the tunnels**

#### 34 35 **3.1 Monitoring data and data processing in the road tunnel**

36  
37 Convergence measurements were monitored in 127 sections along the tunnel. Monitored  
38 sections are in average 30 m spaced. Measurements are carried out by using invar type alloy  
39 wire until the installation of the final lining. At that moment the average rate of convergence  
40 is 0.2 mm/day.

41  
42 Fig3. shows a typical convergence curve. The largest convergence generally occurs along  
43 the direction defined by targets 2 and 4 which is quasi perpendicular to the schistosity planes.  
44 This large convergence is attributed to the buckling of the schistosity planes. Convergence  
45 along direction defined by targets 1 and 4 is parallel to the tunnel invert. In some of the  
46 sections, convergence along direction 1-3 was also monitored. However, convergence data



1 along direction 1-3 have been recorded over a shorter period of time and are missing in many  
 2 sections.

3

4 **Fig3. Convergence curves and schematic position of the targets in section 13 (chainage 1998)**

5

6 The semi-empirical law proposed by Sulem et al. (1987), (equation 1) has been used in the  
 7 analysis of convergence data of the road tunnel (De la Fuente et al., 2017).

8

$$C(x, t) = C_{\infty x} \left[ 1 - \left( \frac{X}{x + X} \right)^2 \right] \left\{ 1 + m \left[ 1 - \left( \frac{T}{t + T} \right)^n \right] \right\} \quad (1)$$

9

10 where  $C_{\infty x}$  represents the instantaneous convergence obtained in the case of an infinite rate  
 11 of face advance (no time-dependent effect),  $X$  is a parameter related to the distance of  
 12 influence of the face,  $T$  is a parameter related to the time-dependent behavior of the system  
 13 (rock mass – support),  $m$  is a parameter which represents the relationship between the long-  
 14 term total convergence and the instantaneous convergence and  $n$  is a form-factor which is  
 15 often taken equal to 0.3. By fitting the convergence data, it is possible to distinguish the total  
 16 long-term convergence  $C_{\infty x}(1 + m)$  from the instantaneous convergence  $C_{\infty x}$  which takes  
 17 place in each section. In convergence data fitting it is important to account for the “lost  
 18 convergence”  $\Delta C$  which is the convergence which takes place between the face excavation  
 19 and the beginning of convergence monitoring (at a distance from the face  $x_0$  and at a time  
 20 elapsed from the face excavation  $t_0$ ):

$$\Delta C(x, t) = C(x, t) - C(x_0, t_0) \quad (2)$$

21

22 The study shows that parameters  $X$ ,  $m$  and  $n$  can be considered the same for the fitting of  
 23 almost all of the sections in the tunnel ( $X = 10.5$  m,  $m = 4.5$  and  $n = 0.3$ ). The choice of these  
 24 parameters is in accordance with previous studies found in the literature (Sulem et al, 1987,  
 25 Panet 1996, Guayacan et al, 2018). As suggested by Guayacan et al. 2018, the parameter  $X$  is  
 26 taken equal to  $0.9D$  where  $D$  is the diameter of the tunnel. Parameters  $T$  and  $C_{\infty x}$  are fitted for  
 27 every single section and direction considering the strong heterogeneity of the magnitude of  
 28 convergences and of the mid-term convergence rate observed from in the road tunnel. A very  
 29 good approximation of convergence data is obtained as shown in the examples in Fig4. We  
 30 can observe that  $T$  which controls the convergence rate exhibits a significant variability along  
 31 the tunnel length and varies between 0.5 and 5 days for direction 2-4 (Fig5.). However, some  
 32 “homogeneous” zones corresponding to similar values of the instantaneous convergence  
 33 along direction 2-4 have been identified (Fig6.).

34

35 **Fig4. Convergence evolution along direction 2-4 and fitting with the law of de Sulem et al.**  
 36 **(1987) for section 17 at chainage 2113 (a) and section 118 at chainage 5080 (b). On the left in**  
 37 **function of time and on the right in function of the distance to the advancing face**

38

39 **Fig5. Evolution of  $T$  along direction 2-4 along the road tunnel after De la Fuente et al., (2017)**

1  
2 **Fig6.** Evolution of  $C_{\infty x}$  along direction 2-4 along the road tunnel (the red dotted lines  
3 represent the average convergence value for each zone) (a). Evolution of the anisotropy ratio  
4  $\beta$  along the road tunnel (the blue dotted lines represent the average convergence value for  
5 each zone) (b). After De la Fuente et al., (2017)

6 As it has been highlighted by Lunardi (1980) the largest convergences are not necessarily  
7 related to the largest overburden. For instance, overburden in zone C is smaller than in zone B  
8 but convergences are larger. The magnitude of the convergences is not only influenced by the  
9 overburden but also by the existing sets of fractures and by the content of phyllosilicates  
10 (muscovite and chlorite) and graphite in the rock mass.

11  
12 Fig6. shows the anisotropy ratio between the instantaneous convergence along direction 2-  
13 4 and the instantaneous convergence along direction 1-4 :  $\beta = C_{\infty x 2-4}/C_{\infty x 1-4}$  for each  
14 section along the road tunnel. The “homogeneous zones” cannot be characterized by the  
15 anisotropy ratio as this parameter varies significantly along the tunnel.

### 16 17 **3.2 Monitoring data and data processing in the safety gallery**

18  
19 During the excavation of the safety gallery, an important survey campaign was carried out:  
20 convergence data was retrieved at the inner face of the concrete ring; convergence data of the  
21 ground was measured with hydraulic jacks through the TBM shield, these hydraulic jacks  
22 measure the existing gap between the shield of the TBM and the tunnel wall; cracks  
23 observation was carried out; monitoring data was obtained from strain gauges embedded in  
24 the segmental lining of 49 sections which can provide information on the state of stress in the  
25 lining and other information was also obtained during the excavation of the safety gallery  
26 such as the thrust force and the torque exerted over the cutting head of the TBM. These  
27 measurements have three objectives: the collection of information to improve the excavation  
28 technique and/or the lining design during the excavation of the gallery, the prevention of risks  
29 that might be encountered during tunnel execution and the creation of a useful data base in  
30 order to back analyze the tunnel behavior.

31  
32 Monitoring data from strain gauges represent the most reliable source of information. Six  
33 pairs of strain gauges were embedded in the segmental lining (Fig7.). Each pair represents the  
34 response of the extrados and intrados fibers of the segmental lining. It should be noted that,  
35 unfortunately, many interruptions exist in the recorded strain data.

36  
37 **Fig7.** Distribution of the strain gauges in the ring 1821, Chainage 3917 (raw data)

38  
39 Fig8. shows some typical results of the data processing of the safety gallery as described in  
40 detail in De la Fuente et al 2017. The maximal compression stress recorded in the lining along  
41 the tunnel is plotted and compared with the evolution of the lateral friction exerted by the  
42 ground over the TBM and values of RQD retrieved from the gallery. Fig8. also shows the  
43 “homogeneous” zones as previously identified in the road tunnel which are overlaid here onto  
44 the safety gallery data. Monitoring data from both tunnels are in accordance. The areas of the  
45 road tunnel which exhibit larger convergence correspond to the zones of the gallery with  
46 higher stress level in the lining. We can observe that in the areas where lateral friction exerted  
47 by the ground over the TBM is higher, the values of the RQD are lower than the average of 70

1 % . This can mainly be observed around chainage 1550 which corresponds to a very fractured  
2 rock. However, the RQD index is only representative of the degree of fracture and cannot  
3 describe the overall quality of the rock. Around chainage 1550 the highly fractured zone can  
4 also be identified with the increasing lateral friction over the TBM. The maximum friction  
5 which is observed around chainage 6430 is the result of the resumption of the excavation after  
6 a standstill of 126 days.

7  
8 **Fig8.** Lateral friction exerted by the ground over the TBM skirt, maximal compression stress  
9 measured in the lining (the distance to the excavation face at which the stress has been  
10 retrieved can be found next to each point representing the stress state) and RQD values of the  
11 ground retrieved from the East or the West side of the vault during the excavation, as a  
12 function of chainage in the safety gallery (De la Fuente et al., 2017)

## 14 **4. Numerical simulations of the Fréjus road tunnel**

### 16 **4.1 Anisotropic time-dependent constitutive model**

17  
18 In the numerical simulations of the Fréjus road tunnel, the assumed constitutive behavior  
19 for the ground is visco-elasto-plastic and anisotropic. This constitutive model has been  
20 successfully used by Tran-Manh et al. (2015) to reproduce the response of Saint-Martin-La-  
21 Porte access adit within the framework of Lyon-Turin railway project. This model considers  
22 one family of weakness planes embedded in an isotropic rock matrix. It combines the CVISC  
23 model which describes the behavior of the rock matrix and the ubiquitous joints model which  
24 introduces the anisotropy resulting from the presence of weakness planes (Fig9.).

26 **Fig9.** Ubiquitous joint model in a viscoplastic matrix

27  
28 CVISC model considers an elasto-plastic volumetric behavior and a visco-elasto-plastic  
29 deviatoric behavior driven by a Burgers visco-elastic element and a plasticity element. The  
30 model can describe both instantaneous and delayed deviatoric strains (Boidy et al., 2002).  
31 This model is implemented in FLAC<sup>3D</sup> and has been previously used in many numerical  
32 simulations (e.g. Barla et al. 2007, 2008, 2010, 2011, Pellet 2009, Sharifzadeh et al. 2013,  
33 Hasanpour et al. 2015).

34  
35 The presence of discontinuities such as schistosity planes is taken into account by means of  
36 the “ubiquitous joints model”. It consists in a set of joints of a given orientation which pass  
37 through any point in the rock mass. These joints are activated if the yield criterion is reached  
38 (Coulomb criterion with tension cut-off). The ubiquitous joint approach permits to model a  
39 jointed rock-mass (Kazakidis and Diederichs, 1993). This model has been largely used in the  
40 simulation of underground excavations (Cartney 1977, Li et al. 2003, Plana et al. 2004, Russo  
41 et al. 2009, Wang & Huang 2009, 2013).

42  
43 This constitutive model is characterized by 13 constitutive parameters. The mechanical  
44 behavior of the solid matrix is described by 9 parameters (elastic bulk modulus  $K$ , Kelvin  
45 shear modulus  $G_K$ , Kelvin dynamic viscosity  $\eta_K$ , elastic shear modulus  $G_M$ , Maxwell dynamic  
46 viscosity  $\eta_M$ , cohesion  $c$ , friction angle  $\phi$ , dilation angle  $\psi$ , and tension limit  $\sigma_t$ ). The  
47 behavior of the weak planes is described by 4 parameters (joint cohesion  $c_j$ , joint friction  
48 angle  $\phi_j$ , joint dilation angle  $\psi_j$  and joint tension limit  $\sigma_{tj}$ ). Two additional geometric

1 parameters describe the orientation of the weak-plane (dip angle and dip direction of  
2 weakness plane).

#### 4.2 Identification of the envelope of the convergences in the Fréjus road tunnel

6 As shown in §3.1 some “homogeneous” zones in terms of the amplitude of the convergences  
7 have been identified (De la Fuente et al., 2017). The present chapter aims at reproducing the  
8 behavior observed in the “homogeneous” zone A. Along this area of the tunnel, a moderate  
9 buckling phenomenon was observed during construction. Fixing  $n = 0.3$ , the parameters  
10  $(T, X, C_{\infty x}, m)$  have been obtained for each section from the fitting of the convergence data  
11 with the convergence law of Sulem et al., (1987).

13 With these values of parameters  $(T, X, C_{\infty x}, m)$ , convergence curves are plotted in Fig10.  
14 assuming a constant face advance rate of 5.6 m/day for all sections. Therefore, the various  
15 convergence curves can be better compared as the effects of the arrests of the face advance  
16 are removed. In doing so, it is assumed that the parameters of the convergence law do not  
17 depend on the advancing rate of excavation. Furthermore, all the curves are plotted  
18 considering that the first measurement is retrieved at a distance of 4.5 m from the tunnel face  
19 which corresponds more or less to the average length of one step of excavation. This means  
20 that the installation of the monitoring targets is assumed to be done 0.8 days after the opening  
21 of the section. Within “zone A”, section 12 (chainage 1976) exhibits the largest convergence,  
22 whereas section 29 (chainage 2322) exhibits the smallest one.

24 **Fig10.** Convergence curves in the “homogeneous zone A” along direction 2-4 (a) and along  
25 direction 1-4 (b)

#### 4.3 Back-analysis of the short-term response of the Fréjus road tunnel

29 A 3D numerical simulation is carried out with FLAC<sup>3D</sup> in order to simulate the behavior of  
30 the Fréjus road tunnel. Fig11. shows the geometry of the model. The model is large enough in  
31 order to simulate the excavation and minimize boundary effects. Far field boundaries are  
32 placed at a distance of 28 radii (considering the vault radius) and the length of the model in  
33 the axial direction is 90 m. Mesh is discretized into small elements of 0.45 m ( $< 1/10 R$ ). The  
34 in-situ stress state is initially imposed everywhere in the domain (average depth of 1067 m  
35 and average specific weight of the ground of 27 kN/m<sup>3</sup>). Gravity effects are neglected. The  
36 step of excavation is 4.5 m and an advancing rate of 5.6 m/day is imposed in the computations  
37 in accordance with the average values observed during the excavation of the tunnel. The  
38 coordinates of the targets in the simulations are the average coordinates of all the targets  
39 along the tunnel (Fig12.).

41 **Fig11.** Geometry of the model (a). Detail of the displacements around the tunnel during its  
42 excavation for section 12 (chainage 1976) (b). R is the radius of the vault of the excavated  
43 tunnel (5.8 m)

45 **Fig12.** Geometry of the tunnel and average position of the targets considered in the numerical  
46 model

48 The possible interaction between the two tunnels has been disregarded. This assumption is  
49 based on the fact that the axes of the tunnels are at a distance of 50 m. From extensometers

1 data, the maximal thickness of the plastic zone around the road tunnel was estimated of  
2 around 10 m. The two tunnels are thus sufficiently far from each other so that the assumption  
3 of no interaction is acceptable.  
4

5 In order to guarantee a quasi-static mechanical equilibrium, it is necessary to choose a  
6 sufficiently small time step (Billiaux and Cundall, 1993). The maximum creep time step  
7  $\Delta t_{max}^{cr}$  is here estimated as the ratio of the material viscosity to the shear modulus  $\Delta t_{max}^{cr} \leq$   
8  $\min\left(\frac{\eta_K}{G_K}, \frac{\eta_M}{G_M}\right)$  (ITASCA, 2011).  
9

10 The dip direction of the schistosity planes is assumed parallel to the tunnel axis and its dip  
11 angle is fixed at an average value of  $45^\circ$  for the numerical simulations. The support composed  
12 of 20 rockbolts/m is simulated by introducing cable structural elements which are punctually  
13 anchored to the tunnel wall and to the ground. Each cable can yield in tension but cannot  
14 resist a bending moment. The length of the rockbolts is 4.65 m with a diameter of 20 mm and  
15 a strength limit of 450 MPa.  
16

17 Sections showing the largest convergence and the smallest convergence are back-analyzed  
18 by using the above constitutive model, (Fig13.) (see also De la Fuente et al., 2018a). A  
19 horizontal pressure coefficient  $K_0$  of 1.4 has been assumed in accordance with the value  
20 adopted in the design project of the Fréjus safety gallery. The values of the mechanical  
21 parameters of the joints are fitted to best reproduce the anisotropy of the convergence  
22 measurements and are identical in both cases ( $c_j = 0,15$  MPa,  $\phi_j = 20^\circ$ ,  $\psi_j = 5^\circ$  and  $\sigma_{tj}$   
23  $= 0.01$  MPa). The values of some of the parameters of the rock matrix are assumed the same in  
24 both sections:  $E = 40$  GPa (mean value obtained from measurements of the Young's modulus  
25 in the parallel direction to the schistosity planes by Beau et al. (1980)),  $\psi = 15^\circ$  (value  
26 adopted in the design project of the Fréjus safety gallery),  $\phi = 40^\circ$  (fitted value),  $\sigma_t = \sigma_c / 10$   
27 and  $\nu = 0.3$  (value adopted in the design project of the Fréjus safety gallery). The four other  
28 parameters of the matrix are fitted and differ from one section to another, Fig13. The largest  
29 values  $(.)_{max}$  of parameters  $c$ ,  $\eta_K$ ,  $G_K$  and  $\eta_M$  are assigned to the smallest convergence (section  
30 29) and *vice versa*. The *in situ* observed behavior is accurately reproduced with the model.  
31

32 **Fig13.** Back analysis of convergence data of section 29 (chainage 2322) ( smallest  
33 convergence) and schematic average distribution of the targets (right) in the section (a) back  
34 analysis of convergence data of section 12 (chainage 1976) (largest convergence) and  
35 schematic average position of the targets (right) in the section (b)  
36

37 The developed plastic zones around the tunnel and the rockbolts stress state 90 days after  
38 the excavation of the tunnel are shown in Fig14. (a) for section 12 and Fig14. (b) for section  
39 29. It is observed that the extent of the plastic area is much more important in the direction  
40 perpendicular to the weak planes. It brings out the important role of the weak plane yield  
41 criterion in the constitutive model.  
42

43 **Fig14.** Plastic zones around the tunnel excavation and stress state in the rockbolts in section  
44 12 (chainage 1976) (largest convergence) (a) and plastic zones around the tunnel excavation  
45 and stress state in the rockbolts in section 29 (chainage 2322) (smallest convergence) (b) .  
46 Red zones are the areas where the matrix is in plastic state, green zones are the areas where  
47 joints are in plastic state and blue zones are the areas where matrix and joints are in plastic  
48 state at the same time. Rockbolts drawn in red have reached the elastic limit  
49

Sections within zone A can be simulated by fitting the cohesion of the joints  $c_j$  and a variability parameter  $\alpha$  with values between 0 and 1, which can be seen as a variable describing the degree of damage of the ground, taking as reference values 0 for section 19 giving the smallest convergence and 1 for section 12 giving the largest one. This parameter permits to simply evaluate the time-dependent parameters of the matrix and the matrix cohesion for all sections in zone A (Equation 3). The variability index  $\alpha$  is evaluated for each section by fitting the convergence measured along direction 1-4. As this direction is sub-parallel to the weakness planes, it is assumed that the convergence measurements along 1-4 are representative of the rock matrix behavior. Once parameter  $\alpha$  is evaluated,  $c_j$  is fitted from the convergence measurements along direction 2-4. The stronger the convergence along 2-4, the stronger the anisotropy of the section and the lower the value of  $c_j$ . The other parameters remain the same for all the sections.

$$\begin{aligned}
c &= c_{min} \alpha + (1 - \alpha) c_{max} \\
G_k &= G_{k_{min}} \alpha + (1 - \alpha) G_{k_{max}} \\
\eta_k &= \eta_{k_{min}} \alpha + (1 - \alpha) \eta_{k_{max}} \\
\eta_M &= \eta_{M_{min}} \alpha + (1 - \alpha) \eta_{M_{max}}
\end{aligned} \tag{3}$$

The comparison between computed and measured convergences along directions 2-4 and 1-4 for the various sections in zone A is shown in Fig15. The fit for the rest of the sections within zone A can be found in Online resource (De la Fuente et al., 2018b). The agreement of the numerical results with the observed field measurements over a period of 90 days is very good. A quasi-constant convergence rate is reached after four or five months because of the presence of a Maxwell viscous element  $\eta_M$  in the rheological model.  $\alpha$  and  $c_j$  take different values for each section. The values of  $c_j$  retained for the numerical simulations are of the same order of magnitude as the values of the cohesion of the schistosity planes measured from laboratory tests. Some of the sections which exhibit very strong anisotropy of the convergences are simulated by assuming cohesionless joints ( $c_j = 0$ ). The values of  $\alpha$  and  $c_j$  for each section are reported in Tab1. Within the studied range of values assigned to the parameters of the constitutive model, sections showing an anisotropy ratio ( $\beta = C_{\infty x 2-4} / C_{\infty x 1-4}$ ) larger than 4 cannot be properly simulated (sections 19, 20 and 45).

**Fig15.** Back analysis of convergence data of sections within zone A (from chainage 1905 to chainage 2723)

**Tab1.** Fitted values of  $\alpha$  and  $c_j$  for each section within zone A

A linear correlation can be found between the variability index  $\alpha$  (fitted along direction 1-4) and a parameter  $\xi$  as defined in equation 4.  $\xi$  is a function of the instantaneous convergence evaluated in the semi-empirical convergence law along direction 1-4 ( $C_{\infty x 1-4}$ ) (see section 3.1) (Fig16.).  $C_{\infty x 1-4 min}$  is the instantaneous convergence along direction 1-4 for section 29 (showing the smallest convergences) and  $C_{\infty x 1-4 max}$  is the instantaneous convergence along direction 1-4 for section 12 (showing the largest convergences).

$$\xi = \left( \frac{C_{\infty x 1-4} - C_{\infty x 1-4 min}}{C_{\infty x 1-4 max} - C_{\infty x 1-4 min}} \right)^{\frac{1}{3}} \tag{4}$$

1  
2 **Fig16. Linear correlation between  $\alpha$  (variability index introduced in the model parameters)**  
3 **and  $\xi$  (variability index evaluated on convergence measurements)**  
4

#### 5 **4.4 Prediction of the long-term response of the Fréjus road tunnel**

6

7 We have shown above that the proposed constitutive model is able to correctly reproduce the  
8 field data. It is always a challenging question to assess the performance of a model that has  
9 been calibrated on data recorded during few months for predicting the very long-term  
10 behavior of a structure. It is however an interesting point to test the predictive capacity of the  
11 model. Therefore, a numerical prediction of the average long-term behavior (40 years) of the  
12 Fréjus road tunnel has been carried out. We first identify a typical section (section 23 in  
13 chainage 2267) showing an average response within zone A. The values of the mechanical  
14 parameters which govern section 23 short-term behavior are:  $\alpha = 0.6$  and  $c_j = 0.2$  MPa. With  
15 this set of parameters, we extrapolate the long-term convergences of section 23 at 40 years,  
16 assuming that the final support is not installed and by using the empirical convergence law  
17 fitted in the previous chapter ( $X = 10.5$  m,  $m = 4.5$ ,  $n = 0.3$ ,  $C_{\infty x 2-4} = 26.1$  mm,  $C_{\infty x 1-4} =$   
18  $11.0$  mm,  $T_{2-4} = 3.3$  days,  $T_{1-4} = 1.9$  days). Finally, we perform a numerical analysis of  
19 section 23, using the proposed constitutive model and without the final support (Fig17). It was  
20 obtained that with the chosen constitutive model, it is not possible to find a single set of  
21 parameters able to reproduce short-term convergences and mid and long-term convergences at  
22 the same time. This is due to the linear Maxwell element in the rheological model which leads  
23 to constant deformation rate in the long-term and therefore cannot reproduce the decreasing  
24 convergence rate of the empirical convergence law. For this reason, in an attempt to keep the  
25 model as simple as possible, two sets of parameters are used in the same numerical  
26 simulation. The first set of parameters ( $\alpha = 0.65$  and  $c_j = 0.2$  MPa) is used to fit short-term  
27 convergences on the average behavior of the road tunnel. The short-term convergences are  
28 considered to be the ones that occur before the installation of the final concrete lining (107  
29 days after the excavation of the section). The blue vertical line shown in Fig17. (a) separates  
30 the short-term convergences from the mid and long-term convergences. A second set of  
31 parameters is used to reproduce the long-term convergences. Only parameter  $\eta_M$  of the  
32 second set is modified as compared to the first one,  $\eta_M$  is multiplied by 23 (Fig17.).  
33

34 **Fig17. Medium-term (a) and long-term (b) back analysis of convergence data of section 23**  
35 **within zone A (chainage 2267)**  
36

37 Finally, we use the identified parameters of the model for the simulation of the Fréjus road  
38 tunnel with the installation of the final lining system in order to study the long-term  
39 ground/lining interaction, Fig18. The installation of the final lining is carried out in two steps:  
40 installation of the invert at 350 m from the excavation face and installation of the final lining  
41 at 600 m from the excavation face (107 days after the excavation of the section). In  
42 consequence, the activation of the second set of parameters coincides with the installation of  
43 the final lining. With this approach, the effect of the installation of the final lining on the  
44 ground behavior is explicitly taken into account (the final lining exerts a pressure on the rock  
45 mass that can lead to the progressive closure of the existing joints of the ground which will  
46 therefore affect the time-dependent behavior of the rock mass). A long-term Young's  
47 modulus for the concrete of 11 GPa is used in the numerical simulations. This modulus

1 corresponds to one third of the secant Young's modulus ( $E_{cm}$ ) after 28 days of a C35/45  
2 concrete after Eurocode 2 as considered in common practice.

#### 4 **Fig18. Geometry of the model: Fréjus road tunnel and its final lining**

6 Fig19. (a) shows the computed maximal (in absolute value) principal stress in the vault of  
7 the road tunnel after 40 years. One of the highest value takes place in the West side of the  
8 vault where the strongest convergence occurs. This stress reaches 13 MPa after 40 years  
9 (Fig19. (b)). This value is slightly smaller than the designed uniaxial compression strength of  
10 a C35/45 concrete estimated at 17 MPa. Measurements of stresses in the lining have been  
11 carried out in the road tunnel with a flat-jack test (between chainages 1800 and 2200) in  
12 recent years. In the East side of the vault values ranging from 5 to 32 MPa with an average of  
13 16 MPa have been retrieved. These data are thus in accordance with the numerical  
14 predictions. From the numerical simulations, we obtain a constant convergence rate of 0.25  
15 mm/year in the lining. The in-situ monitoring convergence rates of the lining range from 0.15  
16 to 0.3 mm/year (data retrieved between chainages 1800 and 2200 from year 1980 to year  
17 1997). The computed results and the *in situ* data are thus in a rather acceptable accordance.

#### 19 **Fig19. Plot of the computed maximal principal stress in the vault of the road tunnel after 40** 20 **years (a). Highest computed stress in the vault as a function of time (b)**

## 23 **5. Prediction of the behavior of the Fréjus safety gallery**

### 25 **5.1 Interpretation of stress data retrieved from the segmental lining**

27 Monitoring data from pairs of strain gauges embedded in the segmental lining of the safety  
28 gallery is first analyzed. The stress state in the lining can be obtained from strain data by  
29 assuming an elastic behavior of the concrete. A mid-term Young's modulus of 20 GPa is  
30 considered for the concrete.

32 The segmental lining is submitted to a loading which is the result of the combination of  
33 two mechanisms that take place during the excavation of the tunnel:

- 35 • Instantaneous buckling: Schistosity planes that are tangent to the tunnel wall tend to  
36 buckle during the excavation. This buckling mechanism takes place projecting rock  
37 blocks that are detached from the tunnel wall and impact the TBM and the installed  
38 lining. Within the first meters after the TBM passage (9 m to 20 m from the tunnel  
39 face), the annular gap is not completely filled up with the backfilling material. As a  
40 consequence, the segmental lining is not protected and the detached rock blocks  
41 impact the lining favoring the generation of cracks in the concrete.
- 42 • Time-dependent convergence of the ground: The time-dependent behavior of the  
43 ground results in a time-dependent loading of the lining during and well after the  
44 tunnel excavation.

46 These two mechanisms are generally combined and difficult to separate. However, in the  
47 present work, an attempt to identify the main mechanisms acting in each monitored section is  
48 carried out. From the stress data, the instantaneous buckling effect is identified and separated



1 from the effect of a time-dependent response of the ground which is the main topic addressed  
2 in this paper.

3  
4 Fig20. shows stress data in function of time in ring 1257 (chainage 2902). Measurements  
5 resulting from instantaneous buckling can be identified in those pairs of gauges (one at the  
6 intrados and one at the extrados) showing an opposite behavior (one gauge is compressed  
7 while the other one exhibits tensile stresses). In Fig20. (a), dotted lines represent stress  
8 measurements from those pairs of gauges embedded in a segmental lining which is affected  
9 by the impact of instantaneous buckling. In Fig20. (a), the stress measurements recorded by  
10 the other sensors and mainly controlled by the time-dependent convergence of the ground are  
11 also plotted. Some tensile stresses are nevertheless observed on data plotted in Fig20 (a).  
12 They may be due to the efforts induced by the longitudinal support of the TBM which is  
13 jacked against the segmental lining in order to advance. Within the first meters after the TBM  
14 passage, the annular gap is not completely filled up with the backfilling material and as a  
15 consequence the thrust cylinders of the machine may induce important tensile efforts in the  
16 segmental lining.

17  
18 **Fig20.** Evolution of the stress state in function of time in section 1257 (chainage 2902) **(a)**  
19 schematic representation of the position of the strain gauges within the concrete ring **(b)** (the  
20 evolution of the time-dependent convergence of the ground is in solid line whereas the  
21 evolution of convergence originated from instantaneous buckling is in dashed line)  
22  
23

## 24 **5.2 Prediction of the short-term response of the Fréjus safety gallery**

25  
26 A 3D numerical simulation has been carried out with FLAC<sup>3D</sup> software in order to simulate  
27 the behavior of the Fréjus safety gallery. Fig21. shows the geometry of the numerical model.  
28 Far field boundaries are placed at a distance of 36 radii (considering an outer radius of the  
29 gallery R of 4.5 m) in order to minimize boundary effects. The length of the model is 90 m.  
30 An average value of 190 mm is assumed for the overcutting and an eccentricity of the lining  
31 (0.095 m) with respect to the TBM cutting head is considered. The size of the elements at the  
32 tunnel wall is of 0.6 m. The in-situ stress state is initially imposed everywhere in the domain  
33 (average depth of 1067 m and average specific weight of the ground of 27 kN/m<sup>3</sup>). Gravity  
34 gradient effects are disregarded. The step of excavation is 1.8 m which corresponds to the  
35 transversal length of a segmental lining. An advancing rate of 12.9 m/day is considered in  
36 accordance with the average advancing rate observed during the excavation of the safety  
37 gallery. In order to simplify the model and to focus on long-term behavior it was chosen not  
38 to explicitly simulate the TBM excavation process.

39  
40 **Fig21.** Scheme of the geometry of the lining and the backfilling in the safety gallery **(a)**  
41 geometry of the numerical model of the safety gallery **(b)**  
42

43 Buckling phenomena are not considered in the present study. The unsupported span is  
44 taken equal to 19.8 m. It is assumed that the annular gap is completely filled up with the  
45 backfilling material only at this distance of 19.8 m. A “sandwich” type backfilling composed  
46 of gravel and mortar is considered in the simulations. The gravel and the mortar are assumed  
47 to have an elastic response with a Young’s modulus of 100 and 500 MPa respectively. The  
48 installed elastic lining has a thickness of 40 cm and its Young’s modulus is 20 GPa. The  
49 choice of this value has been made as it corresponds to a commonly use mid-term Young’s

1 modulus in civil engineering practice for the case of a C45/55 concrete. The backfilling and  
2 the lining are active since their installation at a distance of 19.8 m from the tunnel face.

3  
4 The ground behavior as identified from the study of the road tunnel is extrapolated for the  
5 simulation of the safety gallery. From preliminary computations, it was obtained that  
6 assuming the same values for the constitutive parameters as those calibrated on the road  
7 tunnel leads to an overestimation of the stresses in the lining. As the lining is placed at a  
8 distance of more than two diameters to the tunnel face, its response is mainly controlled by  
9 the time-dependent behavior of the rock mass. Therefore, the instantaneous constitutive  
10 parameters are kept the same in both tunnels and the time-dependent parameters ( $\eta_M$ ,  $\eta_k$ ,  $G_k$ )  
11 are adjusted. In the sake of keeping the model as simple as possible, these time-dependent  
12 ground parameters are simply multiplied by a factor  $F$  for simulating the response with TBM  
13 excavation. The observation that with TBM excavation, the time-dependent deformation of  
14 the ground is reduced is attributed to the fact that, when tunneling with a TBM, the ground is  
15 less damaged than when tunneling by drilling and blasting. In order to assess how the time  
16 dependent parameters of the rock should be adjusted for the safety gallery, some preliminary  
17 numerical tests have been performed. Parameters  $G_k$  and  $\eta_k$  control the short-term response.  
18 It was obtained that if  $G_k$  is adjusted with a larger value of  $F$  than  $\eta_k$ , short-term  
19 convergences will be overestimated. On the other hand, mid-term and long-term response are  
20 mostly controlled by parameter  $\eta_M$ . Here again, it was obtained that by taking of the same  
21 value of  $F$  as the one applied to short-term creep parameters gives the best results to simulate  
22 mid-term and long-term ground convergences. Consequently, the same value of  $F$  was  
23 adopted for all the time-dependent parameters for obtaining numerical results in good  
24 accordance with monitoring data. It is found that the Fréjus safety gallery response can be  
25 correctly reproduced by taking a value of  $F$  equal to 15. If  $F$  is taken equal to 1, the average  
26 maximal hoop stress obtained with the model parameters describing the average behavior of  
27 the road tunnel ( $\alpha = 0.65$  and  $c_j = 0.2$  MPa) clearly overestimates the state of stresses in the  
28 lining (Fig22.).

29  
30 **Fig22.** Fitting of the parameter  $F$  with the average maximal hoop stress obtained with the  
31 model parameters describing the average behavior of the road tunnel ( $\alpha = 0.65$  and  $c_j = 0.2$   
32 MPa)

33  
34 Fig23. shows the envelope of the predicted maximal hoop stresses (dotted lines) in the  
35 lining. This maximal stress state corresponds to the zone of stress concentration in the lining  
36 (Fig24.). Following the sign convention of FLAC<sup>3D</sup>, compressions are taken negative, thus  
37 compressive stresses correspond to the minimal principal stresses as plotted in Fig24. We can  
38 observe that the maximal compression is located at the invert as the mortar injected in the  
39 annular gap tends to lead to stress concentration in this area (see Fig24.). These computations  
40 are performed by taking the constitutive parameters calibrated on the sections of the road  
41 tunnel which exhibits the highest and the lowest convergence. We can observe that the  
42 maximal hoop stresses (resulting only from the time-dependent behavior of the ground)  
43 retrieved from the different sections of the safety gallery in zone A fall within the predicted  
44 envelope. The average maximal hoop stress obtained with the model parameters describing  
45 the average behavior of the road tunnel ( $\alpha = 0.65$  and  $c_j = 0.2$  MPa) is also plotted in Fig23.  
46 (black thick solid line).

47  
48 **Fig23.** Predicted envelope of maximal hoop stress in the safety gallery and retrieved maximal  
49 hoop stress from sections within zone A

1  
2 **Fig24. Minimal principal stress (maximal compression) in the lining after 3 months (maximal**  
3 **constitutive parameters for the ground are assumed in the computation)**  
4

5 Similarly, Fig25. shows the predicted envelope of the minimal hoop stresses in the lining.  
6 We observe that the minimal hoop stresses retrieved from the safety gallery are predicted with  
7 less accuracy than the retrieved maximal stresses. The numerical results tend to overestimate  
8 the minimal stresses and tensile stresses are not obtained.  
9

10 **Fig25. Predicted envelope of minimal hoop stress in the safety gallery and retrieved minimal**  
11 **hoop stress from sections within zone A**  
12

### 13 **5.3 Prediction of the long-term response of the Fréjus safety gallery** 14

15 The above numerical simulations show an accurate short-term prediction of the safety  
16 gallery response as a good approximation of field data has been achieved. However, the  
17 question arises concerning the long-term predictive capacity of the numerical model as  
18 applied to the safety gallery. Obviously no long-term data are available at the moment,  
19 therefore only blind predictions can be performed. A numerical prediction of the average  
20 long-term behavior (40 years) of the Fréjus safety gallery has been carried out. For this  
21 purpose, we consider the constitutive parameters of the model corresponding to the average  
22 behavior (see Fig23.) as used for the short-term predictions. For the segmental lining, we take  
23 a constant Young modulus of 12 GPa corresponding to the long-term behavior of the  
24 concrete. This modulus corresponds to one third of the secant Young's modulus ( $E_{cm}$ ) after 28  
25 days of a C45/55 concrete after Eurocode 2 as considered in common practice. The  
26 mechanical properties of the mortar and the gravel are kept unchanged. The numerical  
27 computations lead to a maximal compressive stress located at the invert of about 25 MPa in  
28 the lining after 40 years (see Fig26.). This prediction looks reasonable and gives confidence to  
29 the predictive capability of the proposed approach, however, it can only be confirmed when  
30 long-term data will be available.  
31

32 **Fig26. Highest computed compressive stress as a function of time**  
33

## 34 **6. Conclusion** 35

36 The present work aimed at studying the behavior of tunnels excavated under squeezing  
37 conditions. Particular attention has been paid to the effect of the method of excavation on the  
38 response of the tunnel. For that, we have referred to the case study of the Fréjus road tunnel  
39 and of its safety gallery which are an example of two parallel tunnels excavated in complex  
40 conditions but with different methods. The Fréjus tunnel response which was excavated by  
41 drill and blast methods is compared to that of its safety gallery which was excavated with a  
42 TBM.  
43

44 The instantaneous and the time-dependent behavior of the rock mass of the Fréjus road  
45 tunnel has been studied by means of a numerical back-analysis of the convergence  
46 measurements of the road tunnel. The constitutive model of the rock mass is visco-elasto-  
47 plastic with weakness planes (ubiquitous joints model) in the direction of the schistosity of the  
48 ground in order to account for its anisotropy. A calibration method has been developed in  
49 order to properly fit most of the sections in one of the most complicated areas of the road

1 tunnel. This method consists in the identification and in the back-analysis of the sections of  
2 the road tunnel showing the smallest and the largest convergences. The rest of the sections of  
3 the studied area can be fitted by adjusting the joints cohesion and a variability parameter  
4 which represents the magnitude of the convergences of the matrix. The limitations of the  
5 model in terms of anisotropy have been studied with this work as sections showing an  
6 anisotropy factor larger than 4 cannot be properly simulated.

7  
8 Based on the extrapolation of the convergence law of Sulem et al. (1987) a prediction of  
9 the long-term convergences of the ground in an hypothetical unlined road tunnel has been  
10 carried out. These long-term convergences have been back-analyzed with the numerical  
11 model by using two set of parameters within the same numerical simulation: a first set of  
12 parameters used in order to back-analyze the short-term convergences and a second set of  
13 parameters used in the back-analysis of the long-term convergences. This is a first step to  
14 account for the evolution in time of the rock behavior and further development will enrich the  
15 constitutive model in the near future by considering non-linear viscous elements.  
16 Nevertheless, reasonable predictions of the stress state developed in the lining after 40 years  
17 have been obtained following this methodology.

18  
19 An attempt to predict the response of the Fréjus safety gallery has been presented in this  
20 study. The behavior of the ground identified with the study of the road tunnel has been  
21 extrapolated to the parallel zones of the safety gallery. From the numerical results, it is  
22 observed that although instantaneous parameters can be assumed the same in both tunnels, the  
23 time-dependent constitutive parameters of the rock mass to be considered in the numerical  
24 model depend upon the excavation process. In practice, the shear modulus and the viscosity of  
25 the Kelvin element and the viscosity of the Maxwell element need to be multiplied by a factor  
26  $F=15$  for the modelling of the TBM excavation (Fréjus safety gallery) as compared to drilling  
27 and blasting excavation process (Fréjus road tunnel). The reason for that stems from the fact  
28 that the damage induced in the rock by blasting effects is more important than the one induced  
29 by a mechanized excavation and the blocking of the ground by the rigid lining occurs in a  
30 very short time. The results of the prediction are very good in terms of the maximal hoop  
31 stress if compared to the retrieved field data (3 months of monitoring). However, the minimal  
32 hoop stress is slightly overestimated. With the same set of model parameters (except the  
33 consideration of a long-term Young's modulus of the concrete of the lining), the computations  
34 are pursued up to 40 years. It is obtained that the proposed model leads to reasonable long-  
35 term predictions which however cannot be confirmed in absence of long-term field data.

### 36 37 38 **Conflict of interest**

39  
40 The authors declare they have no conflict of interest.

### 41 42 43 **References**

- 44  
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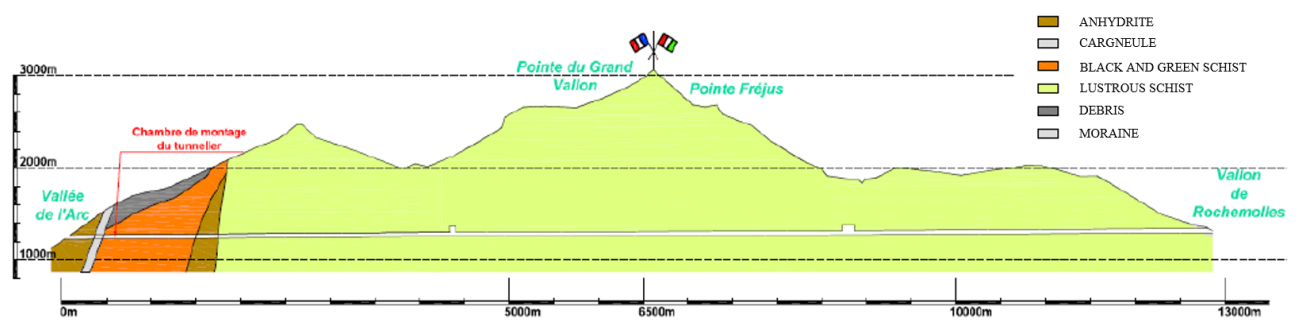
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**Tab1.** Fitted values of  $\alpha$  and  $c_j$  for each section within zone A

Section	Chainage	$\alpha$	$c_j$	$C_{\infty x 1-4}$	$\beta$
8	1905	0.97	0.28	18.2	2.24
11	1965	0.95	0.24	20.72	2,22
<b>12</b>	<b>1976</b>	<b>1.00</b>	<b>0.15</b>	<b>23.28</b>	<b>2,51</b>
13	1998	0.85	0.30	20.38	1,73
14	2018	0.70	0.33	14.75	1,83
16	2063	0.75	0.00	13.64	3,85
18	2136	0.60	0.00	10.66	3,84
19	2157	<b>Anisotropy ratio &gt; 4</b>		7.18	<b>6.42</b>
20	2184,5	<b>Anisotropy ratio &gt; 4</b>		11.28	<b>4.29</b>
23	2267	0.60	0.20	11.01	2,37
24	2287	0.20	0.07	6.98	2,60
25	2289	0.50	0.28	8.93	2,12
26	2292,5	0.30	0.35	7.60	1,92
28	2296	0.45	0.52	8.11	1,74
<b>29</b>	<b>2322</b>	<b>0.00</b>	<b>0.15</b>	<b>6.34</b>	<b>1,89</b>
30	2341	0.45	0.00	8.88	3,41
33	2438	0.70	1.40	9.72	1,29
36	2509	0.77	0.15	13.05	2,81
37	2531	0.70	0.00	11.84	3,83
41	2626	0.70	0.15	11.60	2,57
43	2682	0.65	0.09	10.91	3,12
44	2723	0.70	0.15	11.30	2,73
45	2745	<b>Anisotropy &gt; 4</b>		8.03	<b>4.65</b>

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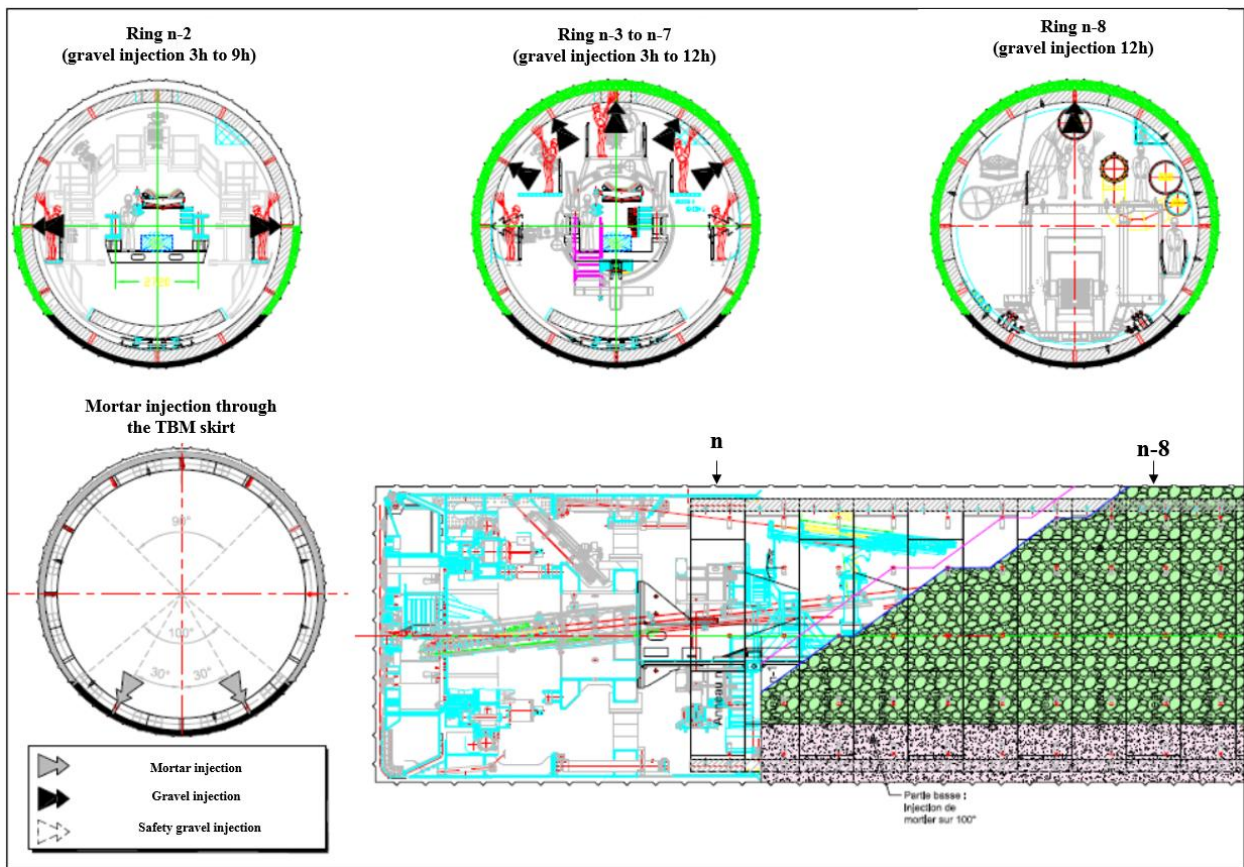


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**Fig1.** Geological profile of the alignment



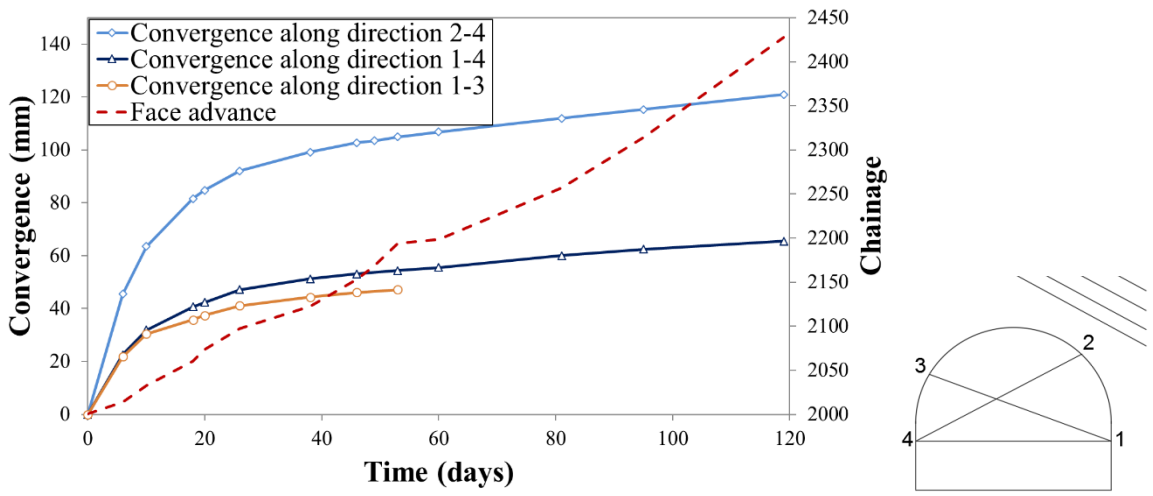
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**Fig2.** Backfilling technique of the annular gap after Vinnac (2012)

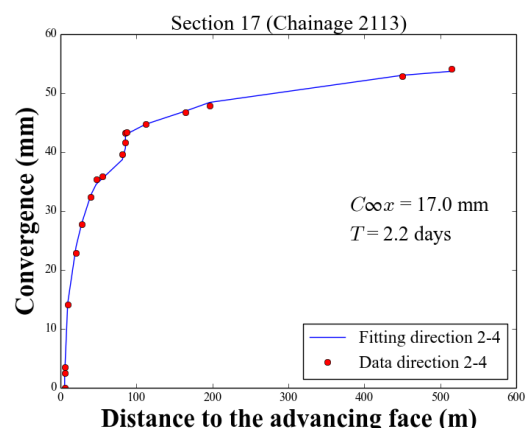
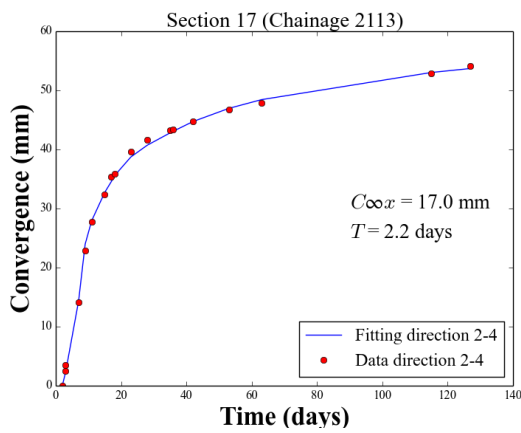
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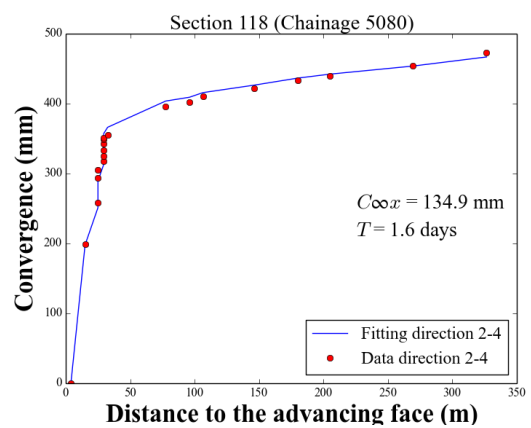
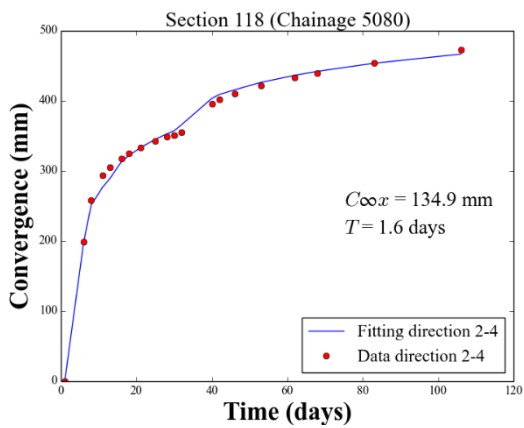
**Fig3.** Convergence curves and schematic position of the targets in section 13 (chainage 1998)

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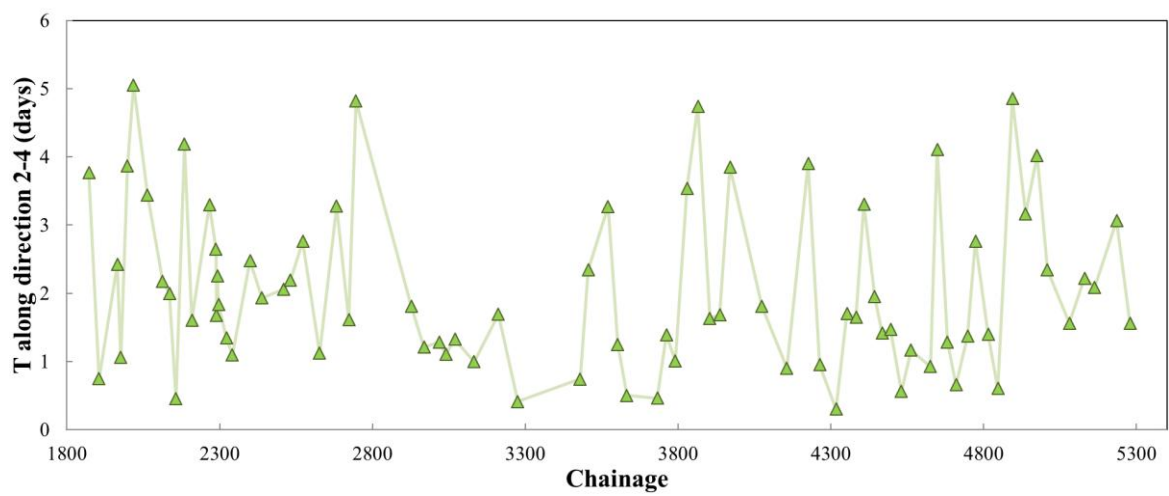


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**Fig4.** Convergence evolution along direction 2-4 and fit with the law of de Sulem et al. (1987) for section 17 at chainage 2113 (a) and section 118 at chainage 5080 (b). On the left in function of time and on the right in function of the distance to the advancing face

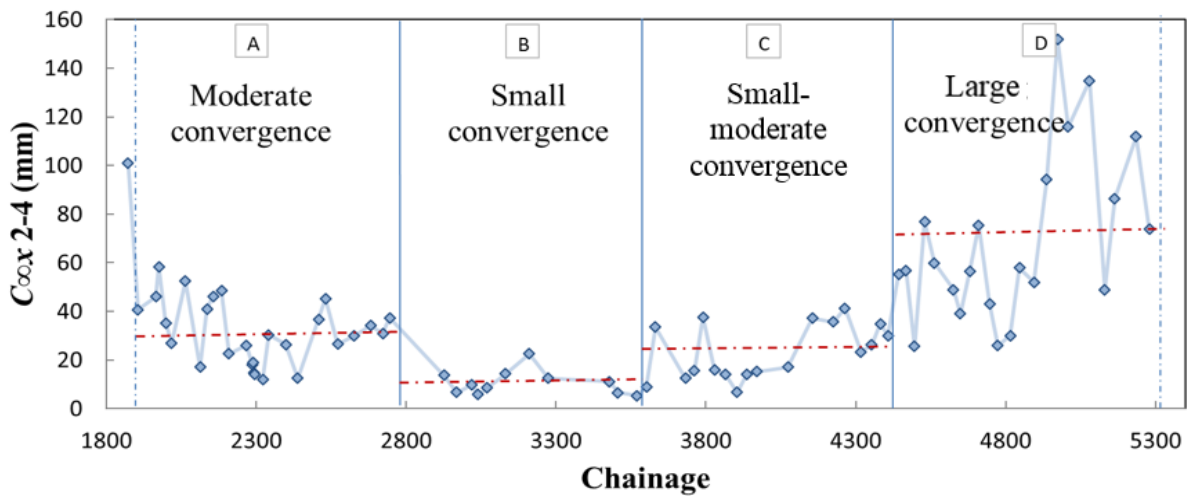
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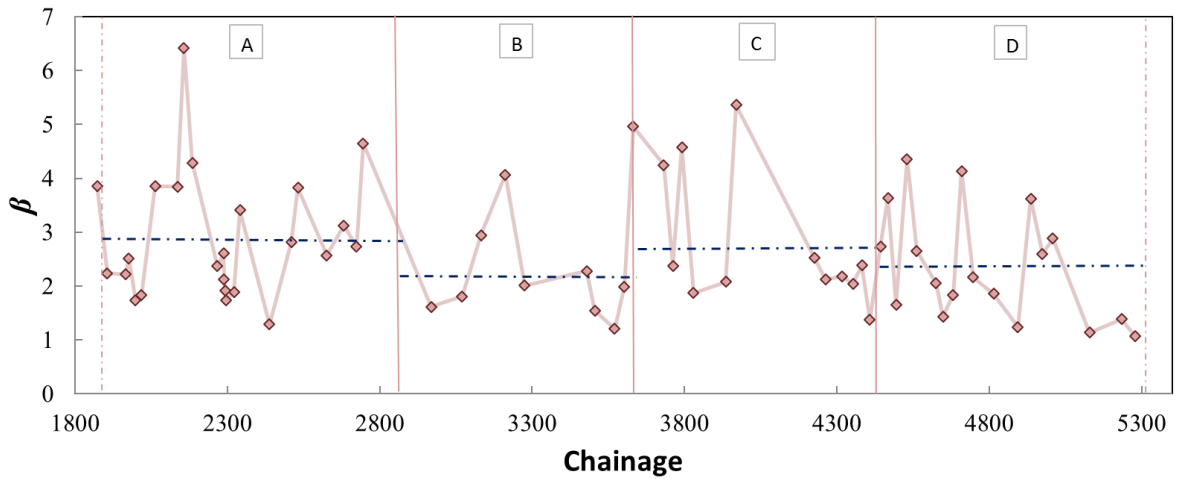
**Fig5.** Evolution of  $T$  along direction 2-4 along the road tunnel after De la Fuente et al., (2017)

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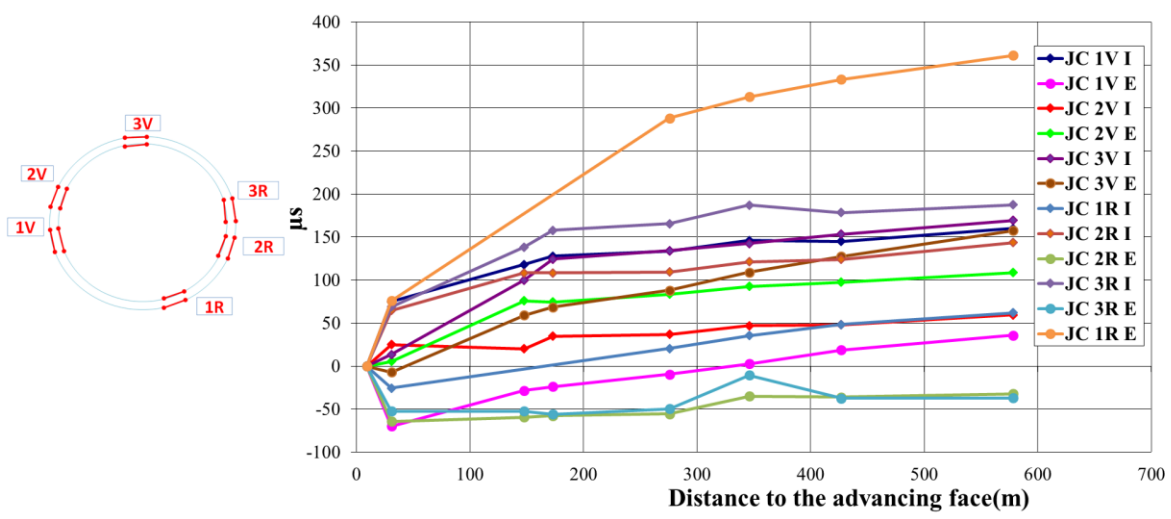


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**Fig6.** Evolution of  $C_{\infty x}$  along direction 2-4 along the road tunnel (the red dotted lines represent the average convergence value for each zone) (a). Evolution of  $\beta$  along the road tunnel (the blue dotted lines represent the average convergence value for each zone) (b). After De la Fuente et al., (2017)

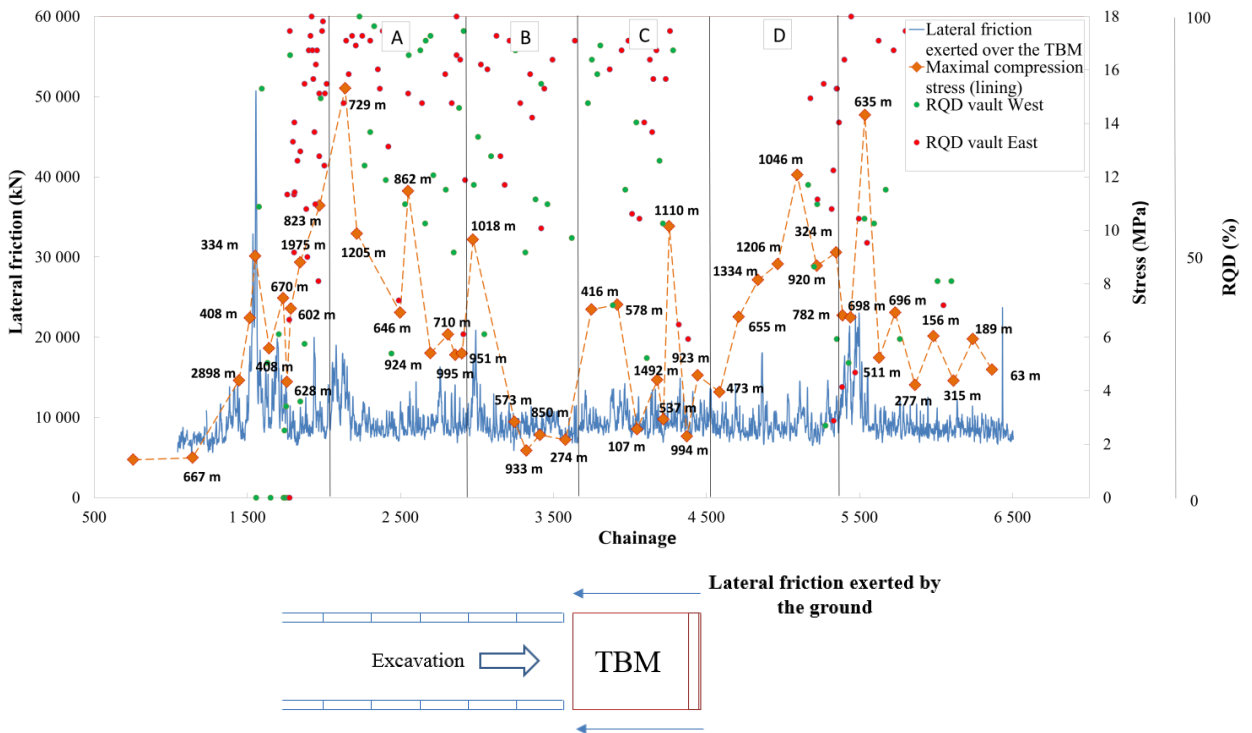
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**Fig7.** Distribution of the strain gauges in the ring 1821, Chainage 3917 (raw data)

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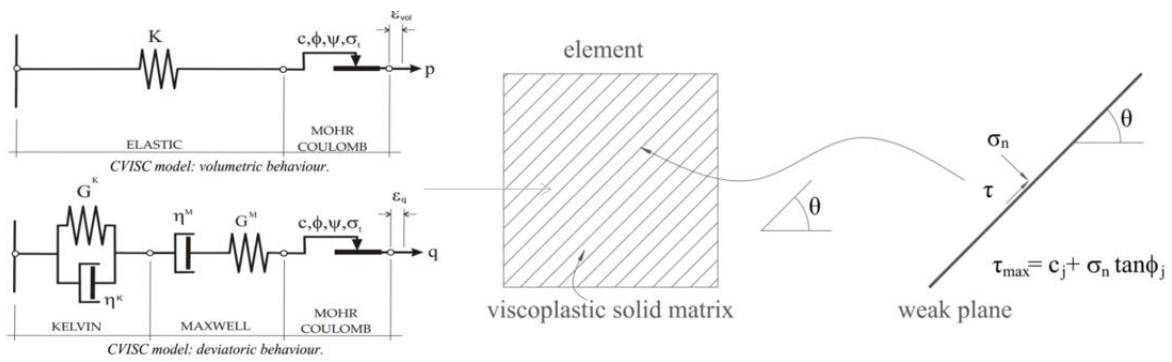


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**Fig8.** Lateral friction exerted by the ground over the TBM skirt, maximal compression stress measured in the lining (the distance to the excavation face at which the stress has been retrieved can be found next to each point representing the stress state) and RQD values of the ground retrieved from the East or the West side of the vault during the excavation, as a function of chainage in the safety gallery (De la Fuente et al., 2017)

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### CVISC Model

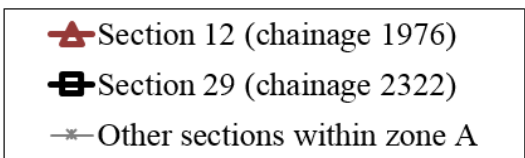
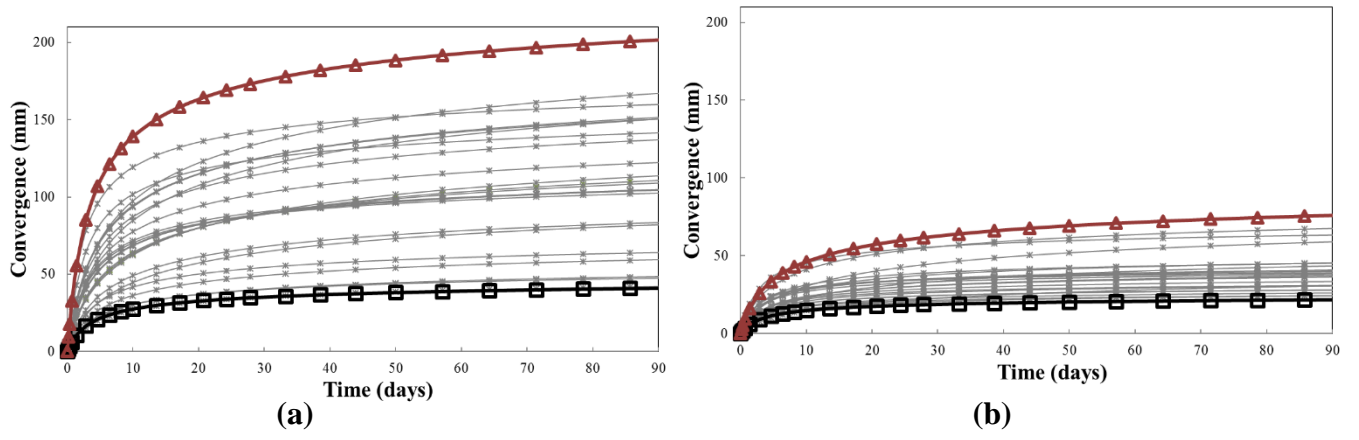
### Ubiquitous joints model

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**Fig9.** Ubiquitous joint model in a viscoplastic matrix

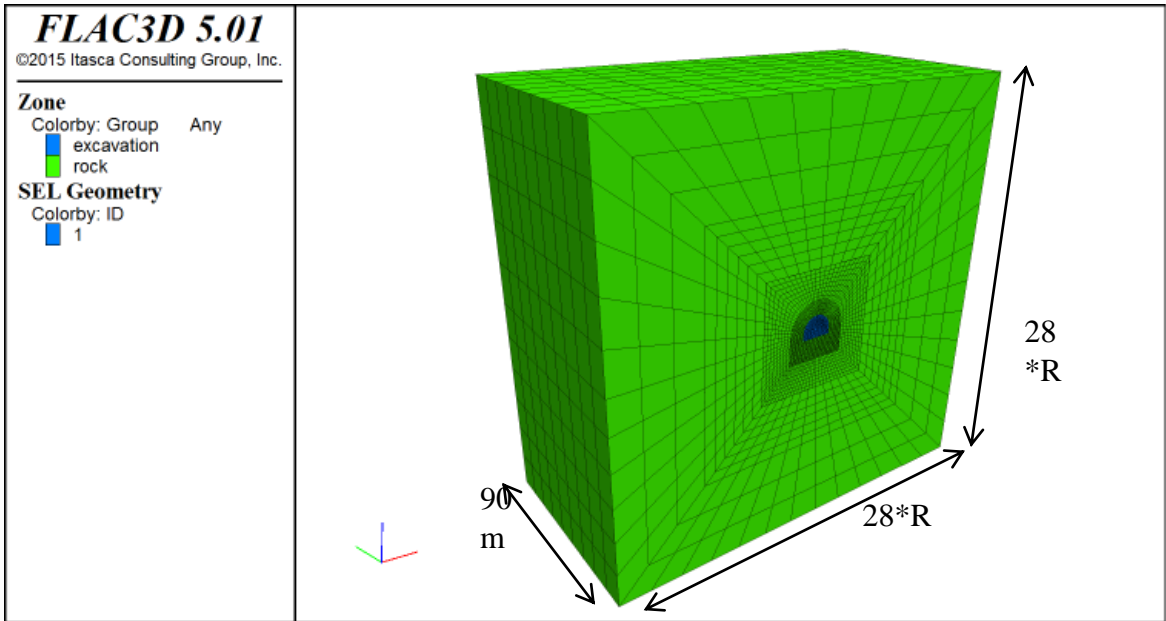


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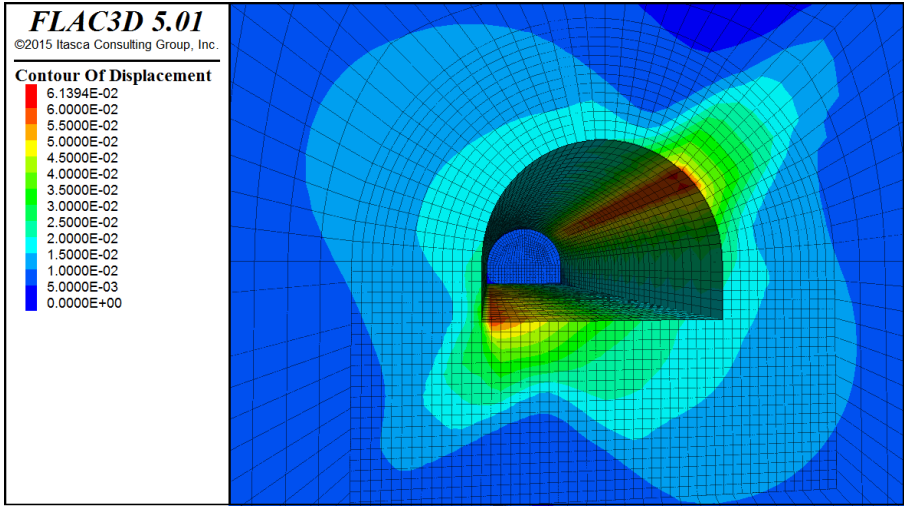


**Fig10.** Convergence curves in the “homogeneous zone A” along direction 2-4 (a) and along direction 1-4 (b)

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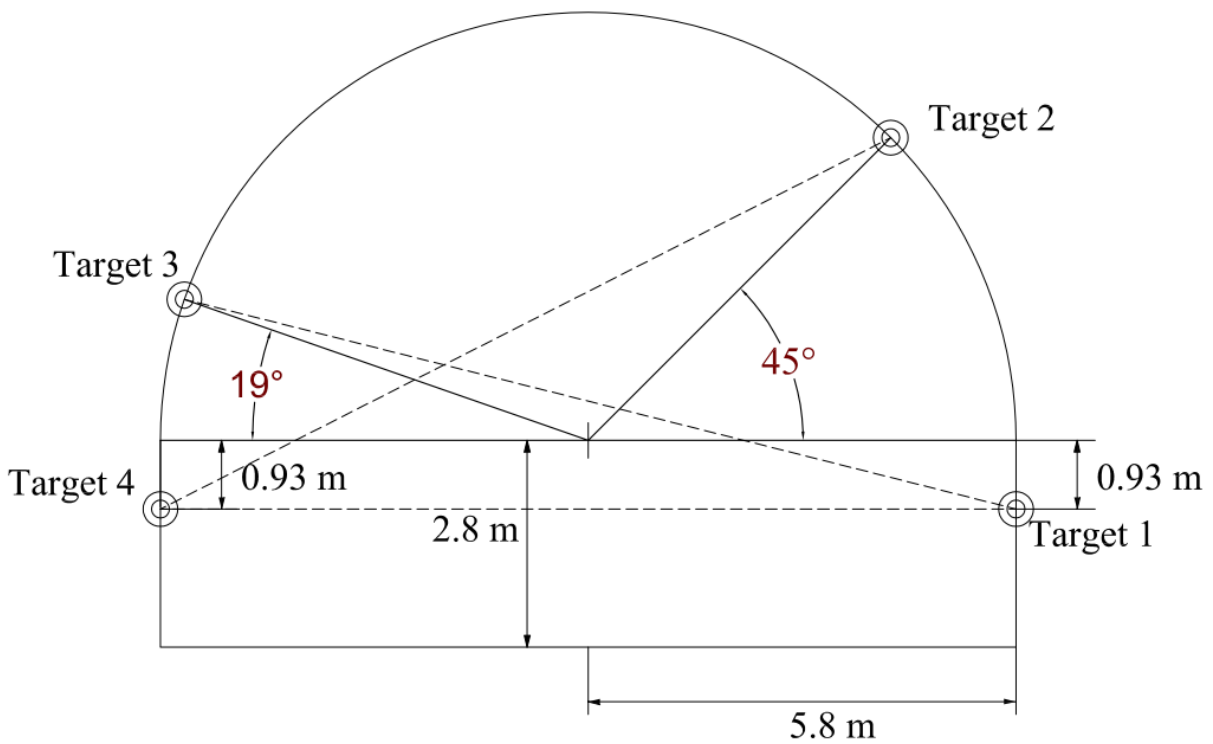
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**Fig11.** Geometry of the model (a). Detail of the displacements around the tunnel during its excavation for section 12 (chainage 1976) (b). R is the radius of the vault of the excavated tunnel (5.8 m)

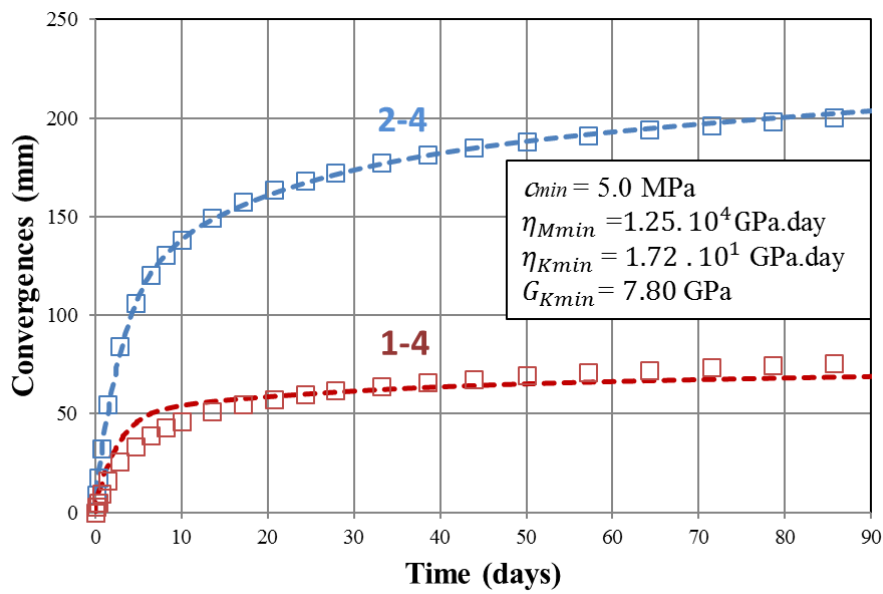


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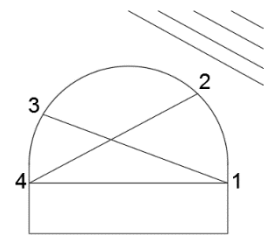
**Fig12.** Geometry of the tunnel and average position of the targets considered in the simulations

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**Section 12 (chainage 1976)**

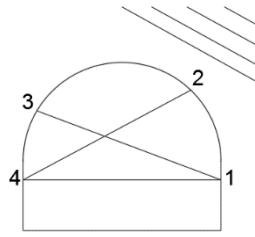
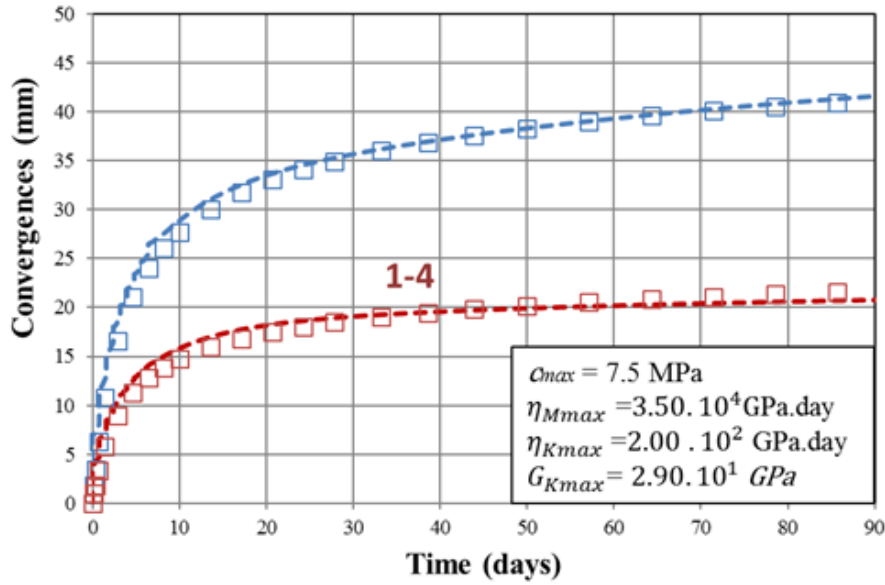


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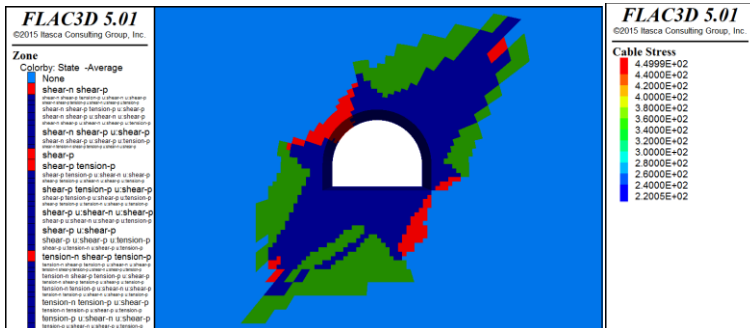
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**Section 29 (chainage 2322)**

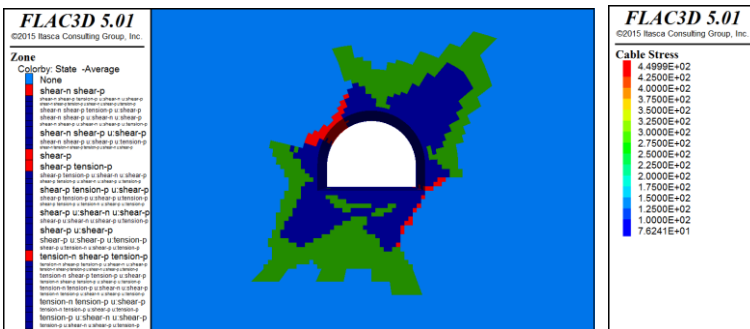


(b)

**Fig13.** Back analysis of convergence data of section 29 (chainage 2322) ( smallest convergence) and schematic average distribution of the targets (right) in the section (a) back analysis of convergence data of section 12 (chainage 1976) (largest convergence) and schematic average position of the targets (right) in the section (b)



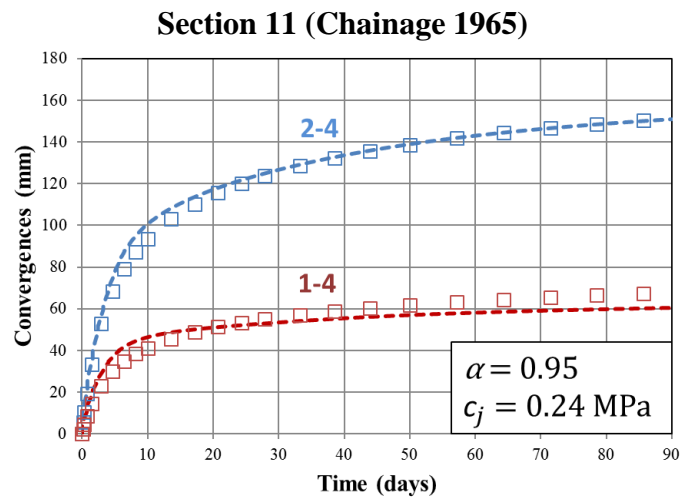
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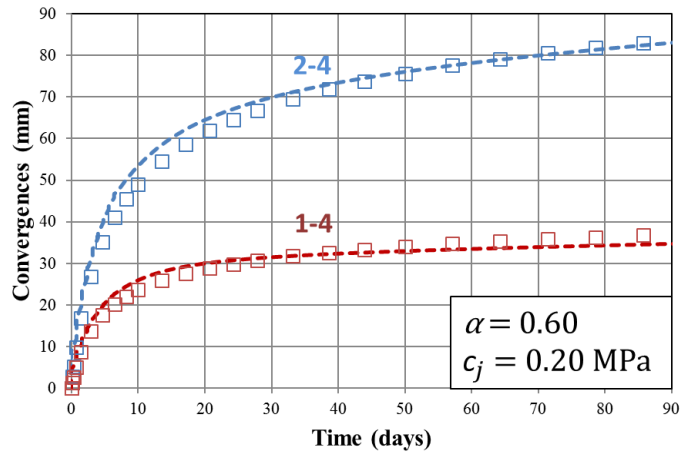
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1 **Fig14.** Plastic areas around the tunnel excavation and stress state in the rockbolts in section 12  
 2 (chainage 1976) (largest convergence) **(a)** and plastic areas around the tunnel excavation and  
 3 stress state in the rockbolts in section 29 (chainage 2322) (smallest convergence) **(b)** .  
 4 Red zones are the areas where the matrix is in plastic state, green zones are the areas where  
 5 joints are in plastic state and blue zones are the areas where matrix and joints are in plastic  
 6 state at the same time. Rockbolts drawn in red have reached the elastic limit.

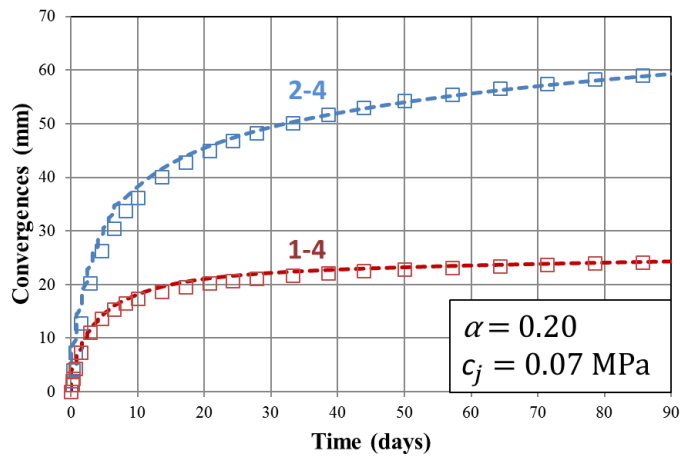
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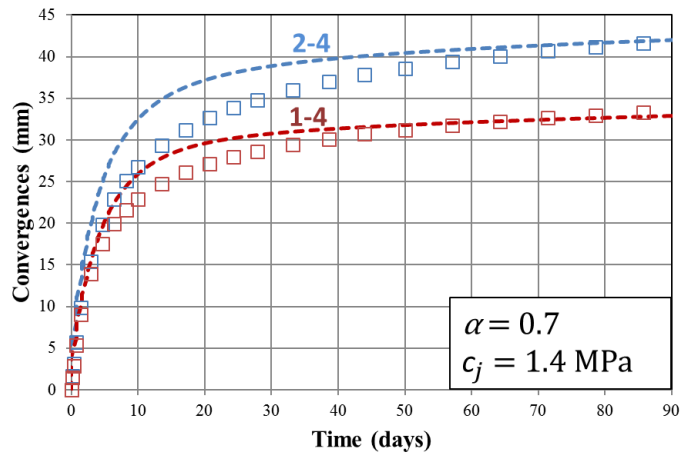
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Section 24 (Chainage 2287)



Section 33 (Chainage 2438)



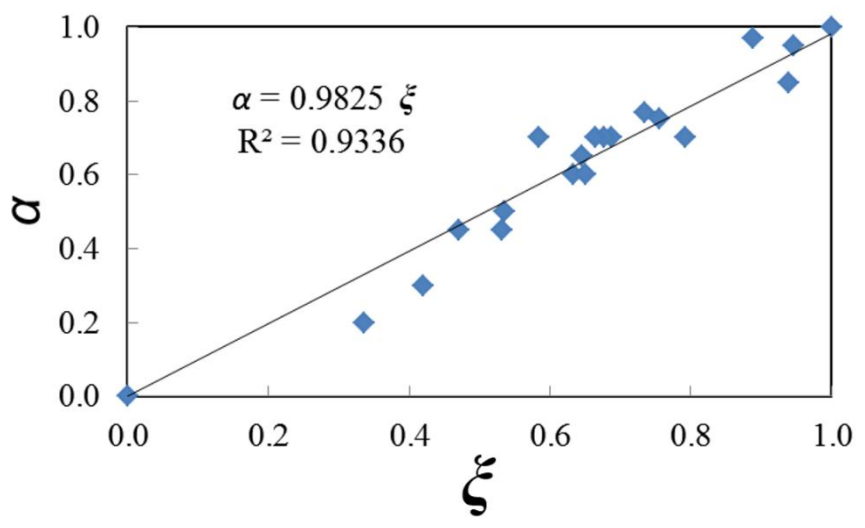
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**Fig15.** Back analysis of convergence data of sections within zone A (from chainage 1905 to chainage 2723)

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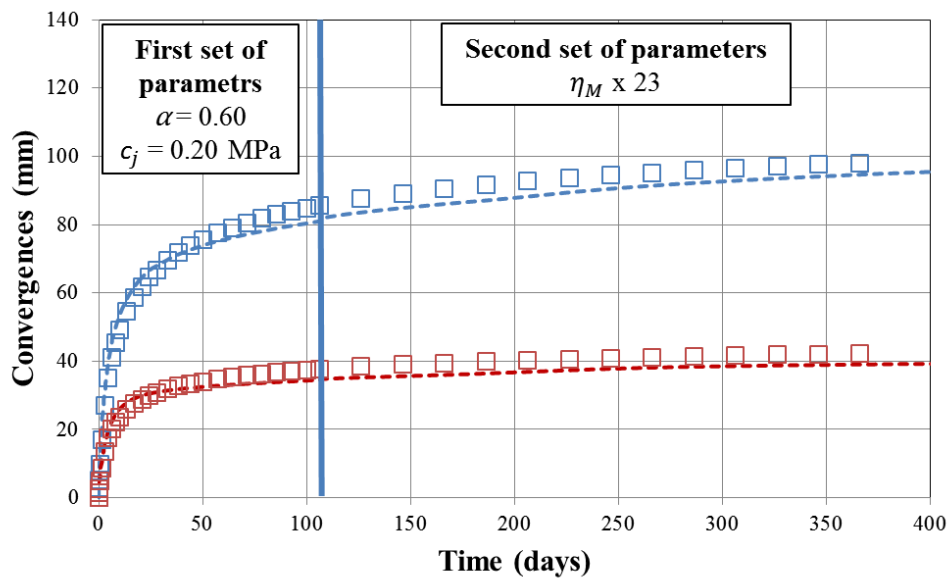


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**Fig16.** Linear correlation between  $\alpha$  and  $\zeta$

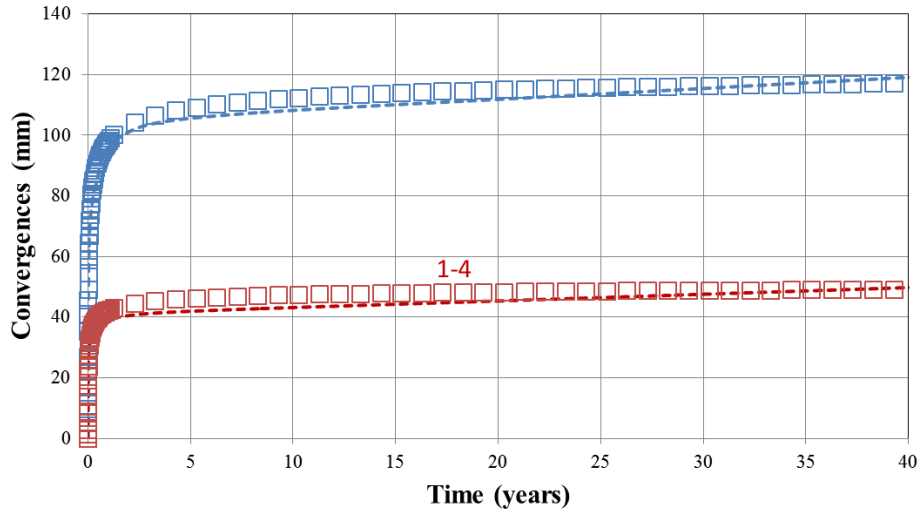


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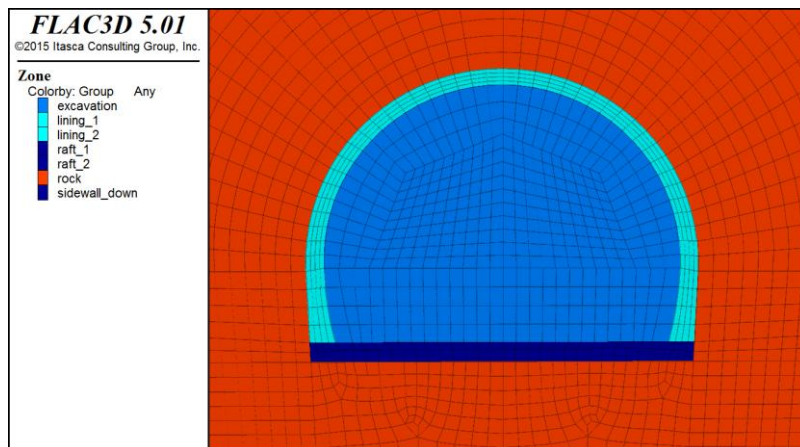
(a)



(b)

**Fig17.** Medium-term (a) and long-term (b) back analysis of convergence data of section 23 within zone A (chainage 2267)

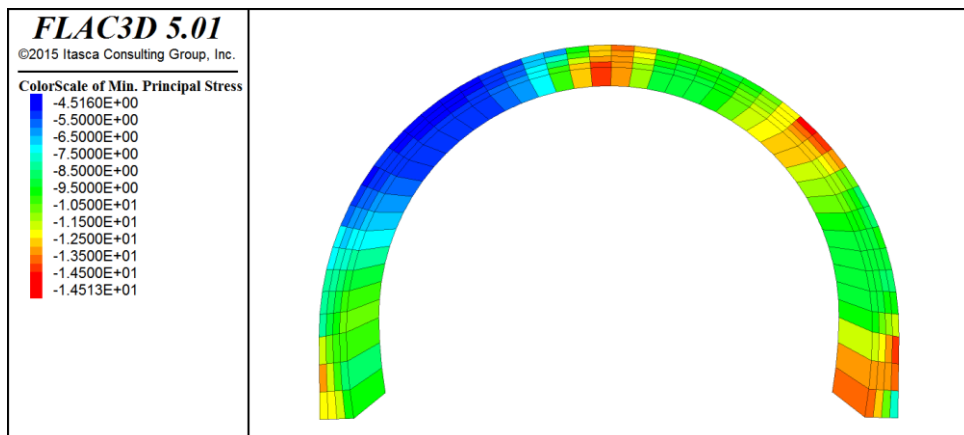
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**Fig18.** Geometry of the model: the Fréjus road tunnel and its final lining

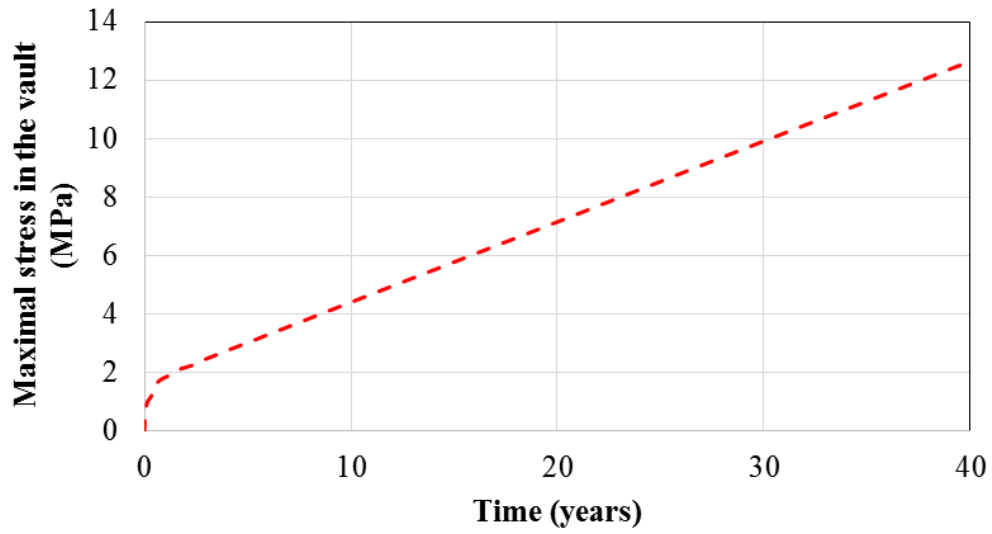
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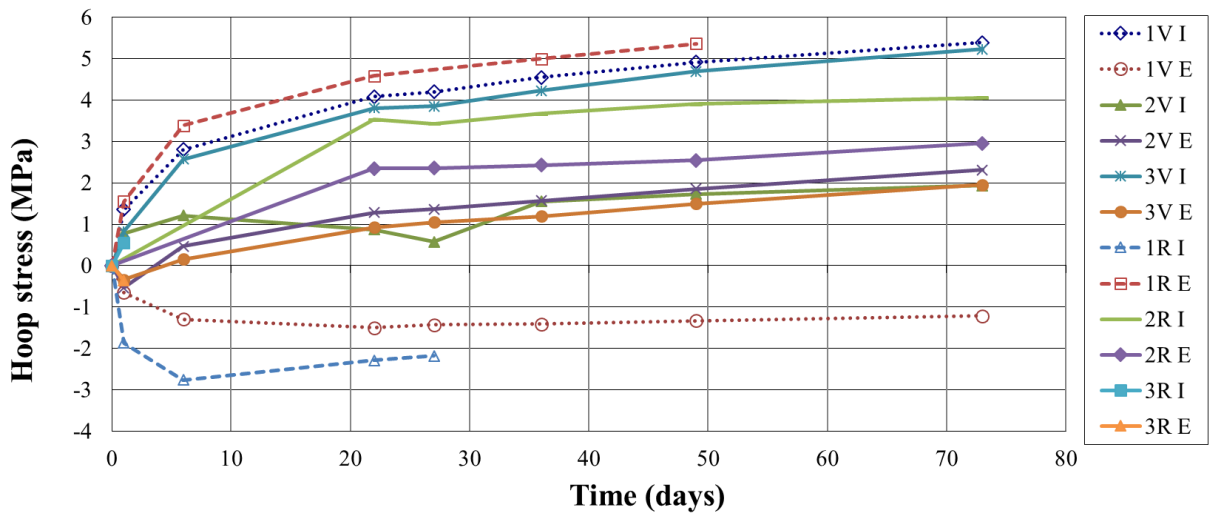
(a)



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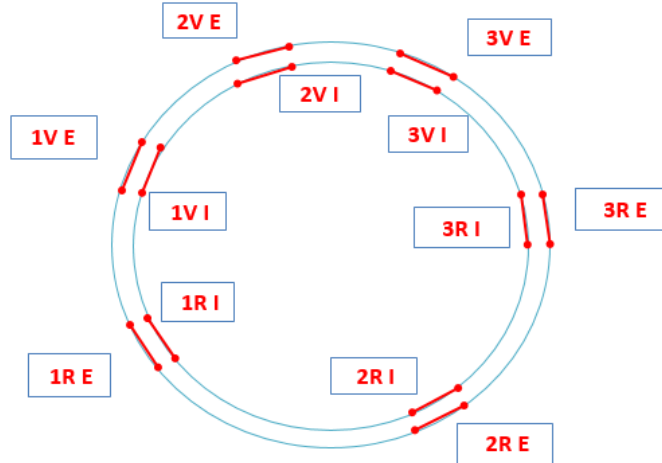
(b)

**Fig19.** Plot of the computed maximal principal stress in the vault of the road tunnel after 40 years (a). Computed stress in the West side of the vault as a function of time (b)



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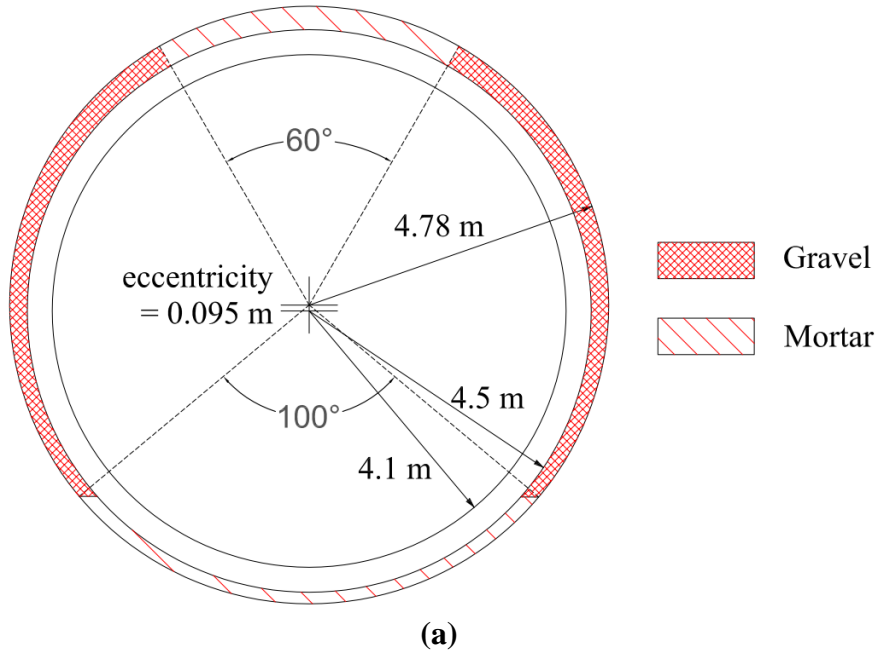
(a)



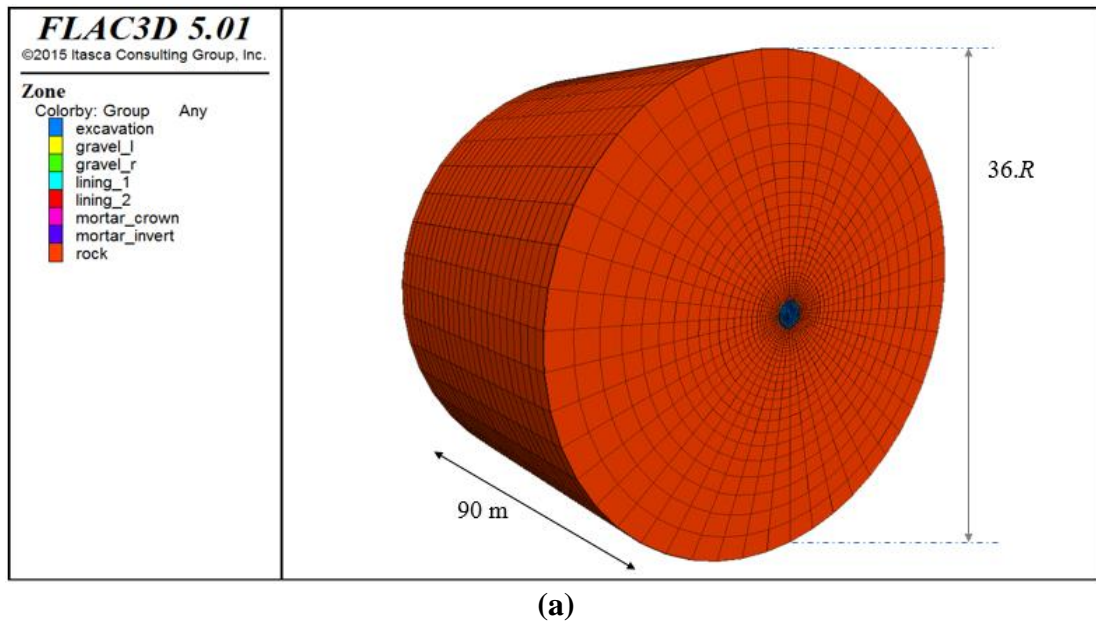
(b)

**Fig20.** Evolution of the stress state in function of time in section 1257 (chainage 2902) (a) schematic representation of the position of the strain gauges within the concrete ring (b) (the evolution of the time-dependent convergence of the ground is in solid line whereas the evolution of convergence originated from instantaneous buckling is in dashed line)

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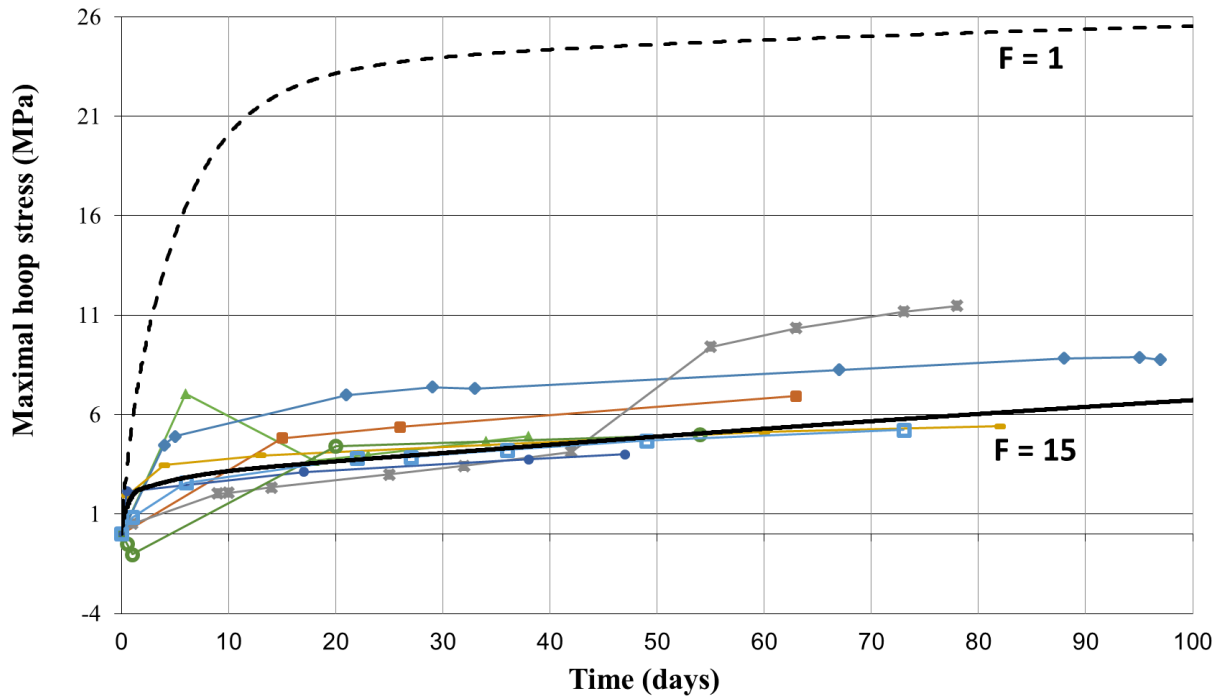


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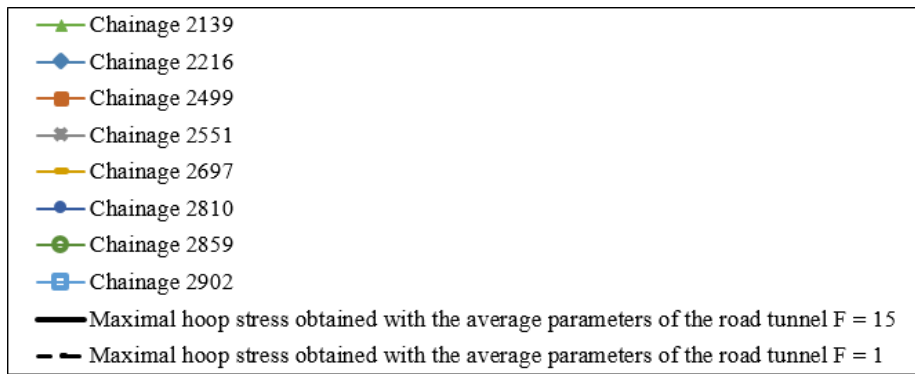


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**Fig21.** Scheme of the geometry of the lining and the backfilling in the safety gallery (a)  
geometry of the numerical model of the safety gallery (b)



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4 **Fig22.** Fitting of the parameter F with the average maximal hoop stress obtained with the  
 5 model parameters describing the average behavior of the road tunnel ( $\alpha = 0.65$  and  $c_j = 0.2$   
 6 MPa)

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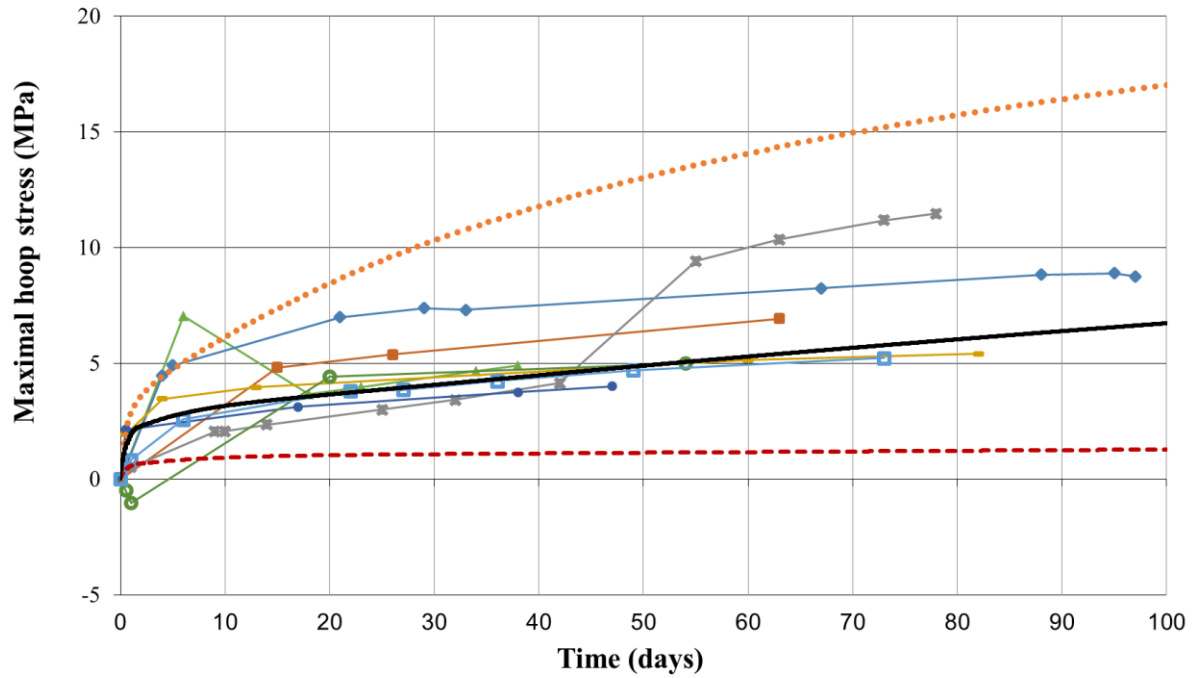
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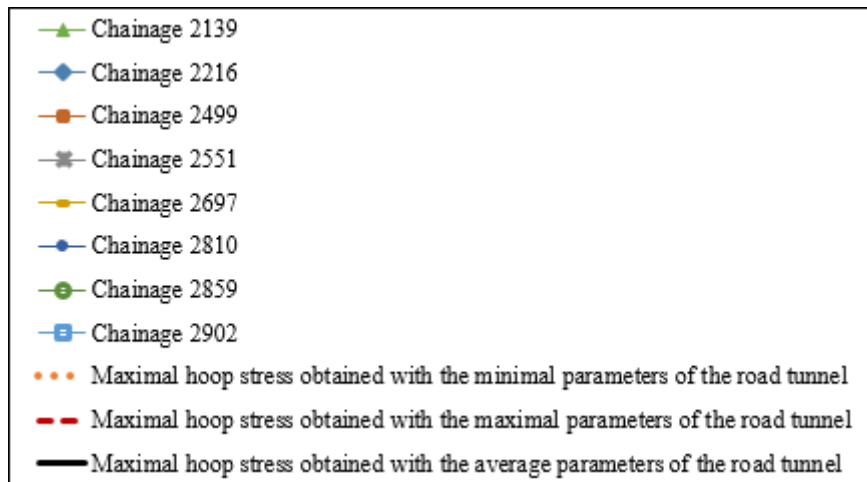
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**Fig23.** Predicted envelope of maximal hoop stress in the safety gallery and retrieved maximal hoop stress from sections within zone A

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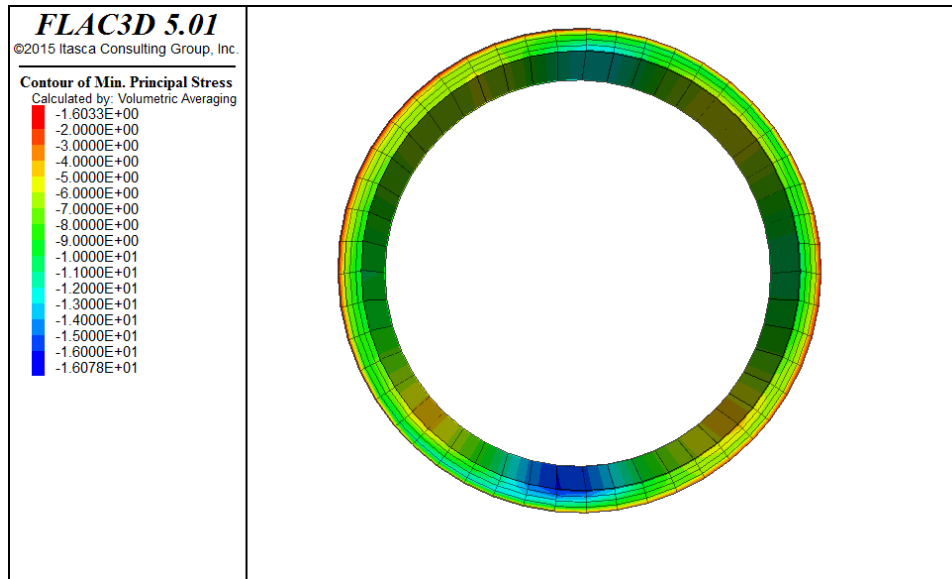
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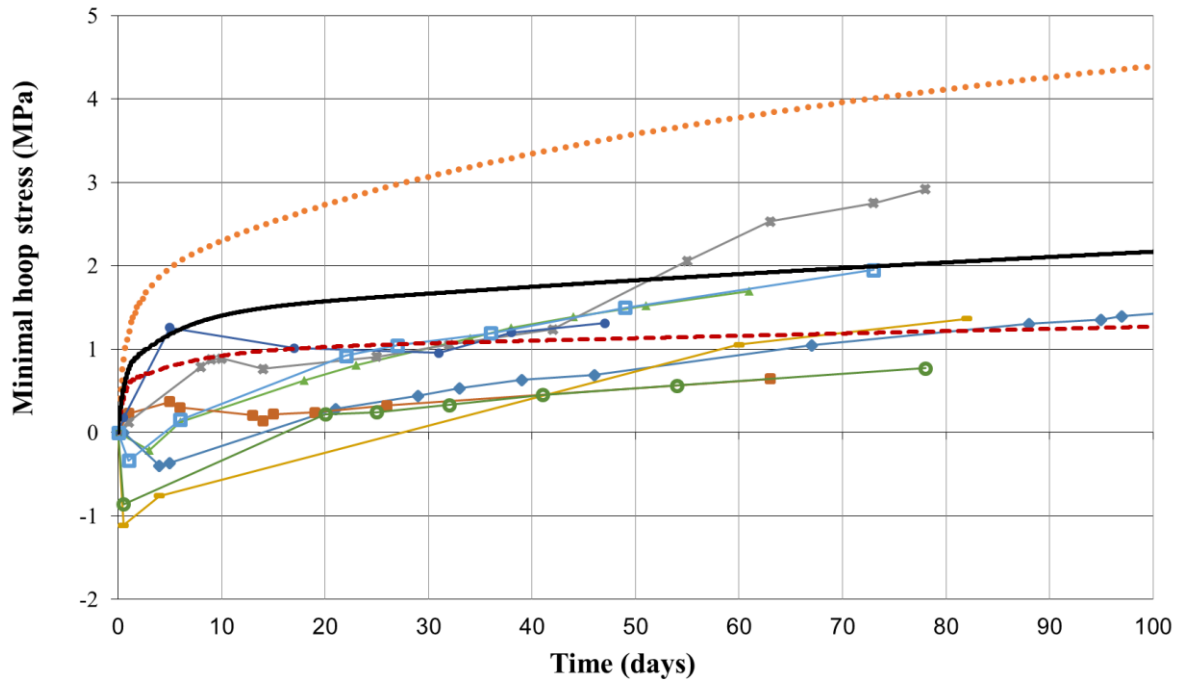
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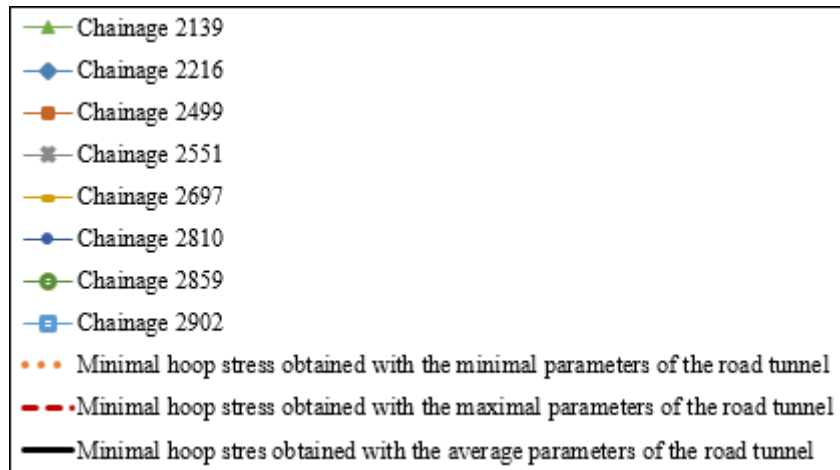


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**Fig24.** Minimal principal stress (maximal compression) in the lining after 3 months (maximal constitutive parameters for the ground are assumed in the computation)



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**Fig25.** Predicted envelope of minimal hoop stress in the safety gallery and retrieved minimal hoop stress from sections within zone A

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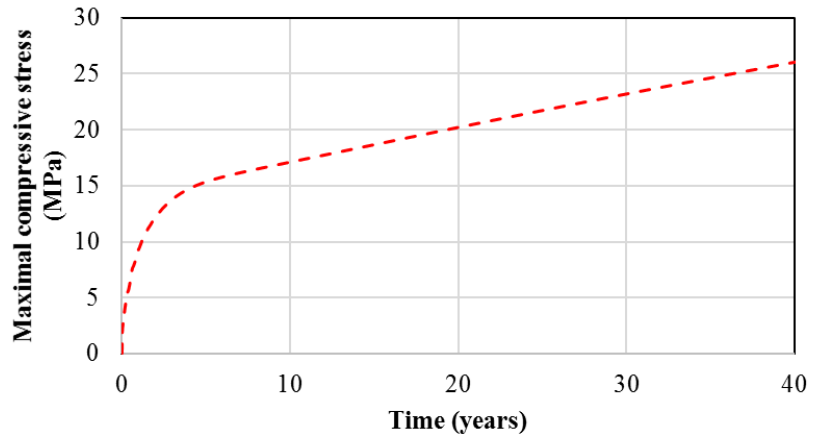
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