Insights on squeezing behavior from Saint-Martín-la-Porte galleries

Y Liu¹, J Sulem¹, D Subrin², H Tran-Manh³ and E Humbert⁴

¹ Laboratoire Navier, Ecole des Ponts, Univ Gustave Eiffel, CNRS, 6-8 Avenue Blaise Pascal, 77455, Marne-la-Vallée, France
² Centre d’études des tunnels (CETU), 25 Avenue François Mitterrand, 69500, Bron, France
³ Itasca Consultants SAS, 29 Avenue Joannes Masset, 69009, Lyon, France
⁴ Tunnel Euralpin Lyon Turin (TELT), 13 Allée du Lac de Constance BP 281, 73375, Le Bourget-du-Lac, France

jean.sulem@enpc.fr

Abstract. In the context of the Saint-Martín-la-Porte survey project of the Lyon-Turin railway link, an access gallery (SMP2) was first excavated across a Carboniferous formation, where tectonized productive Houiller was met at a depth of 300 m. It exhibited a highly squeezing behavior, characterized by large, time-dependent and often anisotropic deformation. Recently, a new survey gallery (SMP4) began to be excavated along the axis of the future base tunnel at a depth of about 600 m. Squeezing conditions have been met again when SMP4 crossed the same Carboniferous formation. Practical problems have been encountered related to the large and anisotropic closure of the cross-section and the instability on the tunnel face. On the basis of previous studies and numerical analyses of carried out for SMP2, the proposed methods are extended to SMP4 conditions. Numerical modeling is performed using FLAC3D code and the various phases of excavation and specific support installation are considered. The efficiency of the compressible elements in reducing the stress in the support system is demonstrated.

1. Introduction

As part of the Trans-European Transport Network (TEN-T) Project, the Lyon-Turin railway is a key element of the Mediterranean Corridor. It will connect France and Italy through a 57.5 km base tunnel under the Alps. In Saint-Martín-la-Porte in France, a survey project is underway to study the geological environment of one of the most complex areas of the Lyon-Turin base tunnel (figure 1a). An access gallery (SMP2) was first excavated to reach the future base tunnel to provide access for the excavation of the base tunnel. A tectonized Carboniferous formation was encountered at a depth of 300-330 m, where productive Houiller was encountered. It presents a very heterogeneous stratified and fractured structure, composed of schist and/or Carboniferous schist, sandstone and a large proportion of clastic rock. Due to the poor mechanical properties of the rock mass, squeezing behavior was observed around the tunnel. It is characterized by large, time-dependent and often anisotropic convergence around the tunnel wall. Observation and convergence measurement show an elliptical deformation of the tunnel section with a high convergence up to 2 m, which produces severe problems for the excavation and support process. On the basis of the intensive field monitoring, a number of studies have been carried out on SMP2 to analyze the response of the rock masses and of the specific support systems during and
after excavation (e.g. Barla et al., 2007; Russo et al., 2009; Vu et al., 2013; Descoeudres et al., 2015; Tran-Manh et al., 2015).

Figure 1. (a) Saint-Martin-la-Porte galleries (b) Occurred collapse at chainage 10303 m in SMP4

Since 2017, another survey gallery (SMP4) has been excavated along the axis of the future base tunnel at a depth of about 600 m. It crossed the same squeezing formation as SMP2. The excavation is first carried out with large section (SMP4-GS) with a radius of about 6.5 m. Due to the existence of a fault zone, collapse occurred in the vicinity of 10303 m (figure 1b) (Liu et al, 2019). After that, the surrounding rock materials were reinforced and the excavation was performed with a reduced section to ensure the safety of tunnel construction and propose operational solutions. From chainage 10310 to 10410 m, the equivalent radius of the tunnel section is about 3.15 m (SMP4-PS), and is enlarged to its full size later (SMP4-RPS).

The geological context of the SMP4-PS is very complex. The rock mass is very heterogeneous both in the longitudinal and radial directions (figure 2). Several discontinuity planes are present. The proportion of Carboniferous shales/coal, which is more deformable, is much higher from chainage 10310 to 10337 m than in the following parts.

Figure 2. Geological context of SMP4-PS
In the present study, we focus on the part of SMP4-PS beyond the collapsed zone after chainage 10310 m. Based on the previous research of SMP2, numerical simulation of SMP4-PS is performed with the finite difference code FLAC3D considering the various excavation and support methods. The constitutive parameters of the rock mass are adjusted.

2. Tunneling and monitoring of SMP4-PS

2.1. Excavation and support method

SMP4-PS was excavated at a rate of about 0.6 m/day. The yielding support system used in SMP4-PS is presented in figure 3. In the first stage, a horse-shoe section was excavated and a light support system was installed using steel ribs with sliding joints. In the second stage, at about 11 m from the tunnel face, the invert was excavated leading to a circular section and new support elements were added including four to eight compressible concrete (HiDCon) elements depending on the local amount of deformation. No final lining was installed in SMP4-PS as this part will be enlarged to full size later.

![Figure 3. Temporary support structure used in SMP4-PS](image)

2.2. Mean convergence of SMP4-PS

The mean convergence of SMP4-PS has been monitored and analyzed using the convergence law proposed by Sulem et al. (1987a, 1987b) written as:

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

where \(T\) is a characteristic time related to the time-dependent properties of the system, \(X\) is a parameter related to the distance of influence of the tunnel face, \(C_{\infty, x}\) is the instantaneous convergence obtained in the case of an infinite rate of face advance, \(m\) is a parameter related to the ratio between the time-dependent convergence and the instantaneous convergence, \(n\) is a constant, usually taken equal to 0.3.

The average values obtained from SMP2 of 4 parameters of the convergence law are applied considering the tunnel size effect for SMP4-PS: \(T = 20\) days; \(X = 7.6\) m; \(m = 18\) and \(n = 0.3\). The only parameter to fit is the instantaneous convergence \(C_{\infty, x}\) for the two stages of excavation and support installation (Liu, 2020). The average convergence is analyzed by fitting the deformation of the tunnel section with a circle We take into account the two stages of excavation and support installation: (A) excavation of the tunnel section and (B) installation of the yielding support system. The obtained parameters and the predicted final mean convergence of the sections are summarized in table 1.
Table 1. Parameters of convergence law for some sections with high convergence in SMP4-PS and predicted total mean convergence

| Section | $C_{\infty A}$ [m] | $C_{\infty B}$ [m] | $C_{\infty}$ [m] |
|---------|-----------------|-----------------|--------------|
| 10316 T | 0.0237          | 0.0060          | 0.1868       |
| 10321 C | 0.0338          | 0.0034          | 0.1656       |
| 10326 T | 0.0679          | 0.0037          | 0.2376       |

3. Numerical simulation

The in-situ conditions of SMP-PS field works are complex and some simplifications have been considered in the model. In accordance with the assumptions made by the project engineers in the design reports, the in-situ stress in Houiller formation is assumed to be 8.5 MPa for SMP2 and 16.2 MPa for SMP4. We assume that the galleries are circular and opened in one step. The ground is very heterogeneous. Reinforcement system including bolts and anchors is applied to improve the properties of the highly fractured ground. This reinforcement system is not explicitly modeled and the influence of these elements is included in the properties of the equivalent homogenized ground.

3.1. Numerical model

2D numerical modeling is performed (figure 4) based on the analysis of the average circular convergence. Only half of the section is modeled because of the symmetry of the system with respect to the vertical direction. Two stages of tunnel excavation and support installation are considered.

The constitutive models for the ground used here are the same as those used for modeling SMP2 (Tran Manh et al., 2015). The ground response is highly anisotropic because of the heterogeneity of rock mass. As a fixed direction of anisotropy cannot be identified, the average behavior is studied. The rock mass is simulated with the isotropic visco-elastic-plastic model CVISC (Itasca, 2017) with the aim to simulate the average response of the tunnel. This model has been widely used in numerical simulations of rock squeezing behavior (Bonini et al., 2009; Tran-Manh, 2014). The constitutive parameters as calibrated for SMP2 need to be adjusted as the rock is stiffer at greater depth. They are summarized in table 2. The behavior of compressible elements of the temporary support is simulated using the double-yield model available in FLAC3D code.
### Table 2. Constitutive parameters of SMP4-RPS

| Material Type                  | Parameter          | Value   |
|-------------------------------|--------------------|---------|
| Shotcrete                     | Young's modulus    | $E$     | 10 (GPa) |
| Elastic                       | Poisson's ratio    | $\nu$   | 0.2 (-)  |
| Compressible blocks           | Young's modulus    | $E$     | 550 (MPa) |
| Double-yield model            | Poisson's ratio    | $\nu$   | 0 (-)    |
|                               | Cohesion           | $c$     | $10^{20}$ |
|                               | Tension limit      | $\sigma'$| 0 (MPa)  |
|                               | Multiplier         | $R$     | 1000 (-) |
|                               | Cap pressure (with hardening) | $p_c$ | 2.83 (MPa) |

### 3.2. Results

As laboratory data are not available to characterize the mechanical properties of the rock mass, the constitutive parameters of the ground can be obtained from back analysis of the convergence data. In order to constrain the model and reduce the number of parameters to calibrate, the elasto-plastic parameters are first determined by fixing the same values for the Poisson’s ratio $\nu$, the friction angle $\phi$, the tension limit $\sigma$, and the dilation angle $\psi$ as those of SMP2. The two remaining parameters (Young’s modulus $E$ and cohesion $c$), which have much greater influence on the convergence magnitude, are fitted by using the time-independent part of the convergence law. For that, 3D time-independent numerical modeling is performed with a Mohr-Coulomb elasto-plastic model. As for example, the numerical simulation of the convergence of the section at chainage 10326 m is shown in figure 5 together with that obtained from the convergence law.

![Figure 5. Calibration of the elasto-plastic parameters ($E = 1625$ MPa, $c = 2.52$ MPa)](image)

The obtained elasto-plastic parameters are used to compute the longitudinal displacement profile (LDP) and thus the evolution of the deconfinement rate $\lambda$ as defined in the convergence-confinement method (Panet and Sulem, 2021) (figure 6). The deconfinement rate at the tunnel face is about 0.4 while at 1 m from the face, it reaches values above 0.8.

Once the deconfinement rate and the elasto-plastic parameters are obtained, the time-dependent parameters of the CVISC model can be identified as shown in the following. The constitutive parameters values for the elements introduced in the numerical modeling of SMP4-PS are summarized in table 3. The average convergence of the sections is well reproduced by the numerical simulation up to 250 days and the hoop stress in the temporary deformable support system shows the efficiency of the HiDCon elements in reducing the stress (figure 7).
Figure 6. (a) Longitudinal displacement profile and (b) computed deconfinement rate for the section at chainage 10326 m of SMP4-PS

Table 3. Constitutive parameters of the ground of SMP2 and SMP4.

| Gallery  | Chainage | $E$  | $\nu$ | $G^K$ | $\eta^K$ | $\eta^M$ | $c$  | $\phi$ | $\sigma_t$ | $\psi$ |
|----------|----------|-----|------|------|---------|---------|-----|------|---------|-------|
|          | (m)      | (MPa) | (*)  | (MPa) | (GPa.day) | (GPa.day) | (MPa) | (◦)  | (kPa) | (◦)    |
| SMP2     | 1383     | 650 | 0.3  | 550  | 2.2      | 13.75    | 1.2  | 26   | 8.5    | 0      |
| SMP4-PS  | 10316 T  | 1625| 0.3  | 825  | 13.2     | 550      | 3.12 | 26   | 8.5    | 0      |
|          | 10321 C  | 1625| 0.3  | 715  | 2.64     | 412.5    | 3.84 | 26   | 8.5    | 0      |
|          | 10326 T  | 1625| 0.3  | 605  | 1.375    | 275      | 2.52 | 26   | 8.5    | 0      |

4. Conclusions
In the previous studies of SMP2 (Vu et al., 2013; Tran-Manh et al., 2015), a procedure of field data processing of the cross-section convergence and a numerical model have been proposed to analyze the large time-dependent and anisotropic deformation observed in the squeezing Carboniferous formation. In the present work, the numerical model and the values of the constitutive parameters used in SMP2 have been applied and adjusted to SMP4-PS. Numerical modeling has been performed using FLAC3D for the sections exhibiting high convergence. The specific excavation and support installation process has been considered and the constitutive parameters of the ground have been adjusted in order to account for the different stiffness of the rock mass at greater depth. CVISC model permits to well reproduce the time-dependent convergence and stress state in the support. The different values of the constitutive parameters in the different zones of the gallery reflect the high heterogeneity of the ground. The performance of the HiDCon elements is demonstrated. They permit a significant reduction of the stress in the support system and prove to be highly efficient for tunneling in squeezing ground.

Acknowledgments
This work is carried out at Ecole des Ponts ParisTech (ENPC) in partnership with Tunnel Euralpin Lyon Turin (TELT) and Centre d’Etudes des tunnel (CETU). The authors wish to thank TELT for financing the research work and for providing monitoring data of SMP galleries, and ITASCA for supporting the first author through the Itasca Educational Partnership (IEP) program.
Figure 7. Numerical simulation of the mean response of SMP4-PS (left) and of the minimum principal stress of the temporary structure 200 days after support installation (right).

References

[1] Barla, G., Barla, M., Bonini, M., and Debernardi, D. (2007). Lessons learned during the excavation of the Saint Martin La Porte access gallery along the Lyon-Turin Base tunnel. In: Schneider et al. (Eds.), BBT 2007 – Internationales Symposium Brenner Basistunnel und Zulaufstrecken, 1:45–52. Innsbruck University Press. ISBN-10:3–902571-05-5.

[2] Bonini, M., Debernardi, D., Barla, M., and Barla, G. (2009). The mechanical behaviour of clay shales and implications on the design of tunnels. Rock Mechanics and Rock Engineering, 42(2), 361–388. doi: 10.1007/s00603-007-0147-6

[3] Debernardi, D., and Barla, G. (2009). New viscoplastic model for design analysis of tunnels in...
squeezing conditions. Rock Mechanics and Rock Engineering, 42(2), 259–288.

[4] Descoeudres, F., Giani, G., and Brino, L. (2015). Il tunnel di base del Moncenisio per la nuova linea ferroviaria Torino-Lione: aspetti geomeccanici e confronto con i grandi trafori svizzeri. Gallerie e Grandi Opere Sotterranee(115), 21–31.

[5] Itasca. (2017). Fast lagrangian analysis of continua (FLAC3D v6.00) [Computer software manual]. Itasca Consulting Group Inc., USA.

[6] Liu, Y. (2020). Modeling of time-dependent and anisotropic behavior of highly squeezing ground Application to the Saint-Martin-la-Porte exploratory galleries of the Lyon-Turin link. PhD Thesis, Université Paris-Est.

[7] Liu, Y., Sulem, J., Subrin, D., and Humbert, E. (2019). Anisotropic convergence of tunnels in squeezing ground: The case of Saint-Martin-la-Porte survey gallery. Tunnels and Underground Cities. Engineering and Innovation Meet Archaeology, Architecture and Art. Proceedings of the WTC 2019 ITA-AITES World Tunnel Congress, May 3-9, 2019, Naples, Italy.

[8] Russo, G., Repetto, L., Piraud, J., and Laviguerie, R. (2009). Back-analysis of the extreme squeezing conditions in the exploratory adit to the Lyon-Turin base tunnel. In: ROCKENG09, Proceedings of the 3rd CANUS Rock Mechanics Symposium.

[9] Panet, M., Sulem, J. (2021). Le calcul des tunnels par la méthode convergence-confinement. (2ème édition) Presses des Ponts.

[10] Sulem, J., Panet, M., and Guenot, A. (1987a). An analytical solution for time-dependent displacements in a circular tunnel. International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts, 24(3), 155–164.

[11] Sulem, J., Panet, M., and Guenot, A. (1987b). Closure analysis in deep tunnels. International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts, 24(3), 145–154.

[12] Tran-Manh, H., Sulem, J., Subrin, D., and Billaux, D. (2015). Anisotropic Time-Dependent Modeling of Tunnel Excavation in Squeezing Ground. Rock Mechanics and Rock Engineering, 48(6), 2301–2317. doi: 10.1007/s00603-015-0717-y

[13] Triclot, J., Rettighieri, M., and Barla, G. (2007). Large deformations in squeezing ground in the Saint-Martin-la-Porte gallery along the Lyon-Turin base tunnel. Underground space—the 4th Dimension of Metropolises. Taylor & Francis Group, London.

[14] Vu, T. M., Sulem, J., Subrin, D., Monin, N., and Lascols, J. (2013). Anisotropic closure in squeezing rocks: The example of Saint-Martin-La-Porte access gallery. Rock Mechanics and Rock Engineering, 46(2), 231–246. doi: 10.1007/s00603-012-0320-4