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Evaluation of the safety factors of shotcrete linings during the creep stage

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Abstract

The sprayed concrete linings used in the tunnels generally develops secondary deformations over time even in the presence of constant stress levels within it. These deformations influence the loading process on the lining and, therefore, also the stress levels within the support structure. In this work the behaviour of the sprayed concrete linings in the tunnel was investigated, under different possible operating conditions, in order to evaluate the effect of secondary deformations over time on the evolution of stability conditions (safety margins with respect to the possible concrete failure) over time, after the construction of the tunnel has been completed. A parametric analysis has been performed to study 8 different types of tunnels, with variable geometry and rock quality, and 8 different types of sprayed concrete. 64 cases of the parametric analysis cover the vast range of variability of the influential parameters and allow to obtain useful considerations in relation to the effects of secondary deformations over time on the static behaviour of the lining and on the safety factor with reference to the possible failure of the sprayed concrete.

KEY WORDS: Tunnels & tunnelling; Excavation; Mathematical modelling

Notation list

φ_p: peak friction angle of the rock;

c_p: peak cohesion of the rock;

c_r: residual cohesion of the rock;

E_i: elastic modulus of shotcrete at ith-step;

E_{rm}: elastic modulus of the rock;

E_∞: elastic modulus of the shotcrete at infinity, when creep ceased;

E_1: initial elastic modulus of the shotcrete at $t = 0$;

E_2: elastic modulus of the shotcrete in the parallel creep scheme;

M: bending moments;

N: normal forces;

p_0: lithostatic pressure;

R: tunnel radius;

t_i: average time;

t_{sc}: thickness of the shotcrete lining;

φ_r: residual friction angle of the rock;

v: Poisson coefficient of the rock;

v_{sc} : Poisson coefficient of the shotcrete;

σ_{ci}: uniaxial compressive strength;

$\sigma_{max,ci}$: maximum compression stress in the lining, induced by the bending moments and by the normal acting forces, in the i-th relief step;

$\sigma_{max,ti}$: maximum tensile stress in the lining, induced by the bending moments and by the normal acting forces, in the i-th relief step;

σ_{ti}: tensile strength;

η: viscosity of the shotcrete;

Ψ: dilatancy of the rock;

α: rate of evolution of secondary deformations;

β : ratio between the final secondary de-formations and the initial deformations;

k : ratio between the horizontal load and the vertical load applied to the lining;

k_i: average stiffness of the lining;

Kn: normal stiffness of the interaction spring between the lining and the rock (hyperstatic reaction method);

Ks: shear stiffness of the interaction spring between the lining and the rock (hyperstatic reaction method).

Introduction

Sprayed concrete (or shotcrete) is concrete which is conveyed under high pressure through a pneumatic hose and projected into place at high velocity, with simultaneous compaction (DIN 18551, 2005), see Fig. 1. Among the properties of shotcrete used for tunnel design, such as early (compressive) and long-time strength, tensile strength, shrinkage, curing time, cracking, durability, creep is one of the most important factors (Thomas, 2009), because shotcrete linings are loaded at a very early age, therefore the influence of time dependent material properties on the deformation behaviour and bearing capacity is much more significant than in regular concrete structures (Schädlich and Schweiger, 2014). Neville et al. (1983) define creep as the increase in strain with time under a sustained stress, i.e. the material deforms not only due to the stresses which it is subjected to, but also due over a time during which these stresses are applied.

Fig. 1 Application of shotcrete

According to Thomas (2009) the high creep capacity of sprayed concrete can be considered as positive as this can dissipate stress concentrations and avoid overloading. The current simplistic approach to model sprayed concrete linings in numerical simulations assumes a linear elastic material with a stepwise increase of the Young's modulus in subsequent excavation stages in order to simulate the curing effect. While realistic lining deformations may be obtained with this method, lining stresses are usually too high, in particular if the lining is subjected to significant bending (Schädlich and Schweiger 2014). For sprayed concrete, the principle of rheological models are the same as for rock (Thomas 2009). However, in shotcrete creep is significantly higher at an early stage of load as the strength of concrete is lower, as found by Huber (1991). However, it must be kept in mind that some accelerators increase the early strengths (Melbye 1994) therefore creep after 24 or 48 h is close to that at greater ages (Kuwajima, 1999). Concrete reinforcement reduces creep, presumably due to the restrain effect (Ding, 1998). However, reinforcing synthetic fibers sprayed together with the shotcrete have twice the creep capacity than a shotcrete with steel fibres (Thomas, 2009; MacKay and Trottier, 2004).

Numerical models are massively employed to analyse the creep behaviour of shotcrete linings such as some rheological models (Jaeger and Cook, 1979): Kelvin model (Neville et al., 1983; Jaeger and Cook, 1979; Rokahr and Lux, 1987), Burgers model (Yin, 1996), viscoplastic model (Thomas, 2009). Kelvin creep model produces a complete recovery, unlike the Maxwell models where no recovery is produced. The rheological models help to give a better understanding of the visco-elastics and elasto–viscoplastics behavior. However, these models do not account for shear stresses, temperature and intrinsic structure. Regarding the power laws creep model for sprayed concrete, of the three stages of creep, only primary creep is of interest for sprayed concrete linings after construction (Thomas 2009). Several authors used the power laws for sprayed concrete lining tunnels (e.g. Schubert, 1988; Yin, 1996), however according to Thomas (2009) they are not widely used because of their inferior ability to model complex creep behaviour. It has to be pointed out, that real creep behaviour of linings is hard to obtain as the load-bearing system is a composite consisting of the ground and the lining. Therefore, the reduction in the lining stress due to the creep depends on the characteristics of the surrounding ground (Thomas 2009). As observed by Pöttler (1990) and Yin (1996) if the ground is modelled as elastoplastic, the load on the lining can increase following creep.

This research shows a parametric analysis considering a novel model based on the hyperstatic reaction model (HRM) and the convergence-confinement method (CCM), based on the Voigt-Kelvin creep model (Oreste et al. 2019), considering eight types of tunnels, 8 types of concrete and two rock types. CCM (Oreste, 2009; 2015; Spagnoli et al., 2016; 2017) is able to evaluate the initial load on the sprayed concrete lining, through the intersection of the convergence-confinement curve (CCC) with the reaction line of the lining, considering initial elastic modulus of the shotcrete (E_1) before the creep takes place. HRM investigates the behaviour of SC lining under the loads applied by the surrounding rock and considering the correct interaction between the lining and the rock (Oreste, 2007, Do et al., 2014a; 2014b). The HRM considers half of a tunnel section by beam elements connected by nodes. The elements develop bending moments, axial forces and shear forces. The interaction between ground and support is represented by "Winkler" type springs in the normal and tangential direction for each node of the model (Oreste et al., 2018; 2019b).

The numerical model used to study the creep behaviour of a shotcrete lining

The numerical model adopted (Oreste et al., 2019a) permits to consider the secondary deformation behaviour of a sprayed concrete lining in the time following the construction of the tunnel, evaluating in detail the stress transmitted from the rock to the tunnel boundary. The simplification scheme of Voigt-Kelvin was used in the calculation (Figure 2):

$$\varepsilon_t = \frac{\sigma}{E_2} \cdot \left(1 - e^{-\frac{E_2 \cdot t}{\eta}}\right) + \frac{\sigma}{E_1} \qquad (1)$$

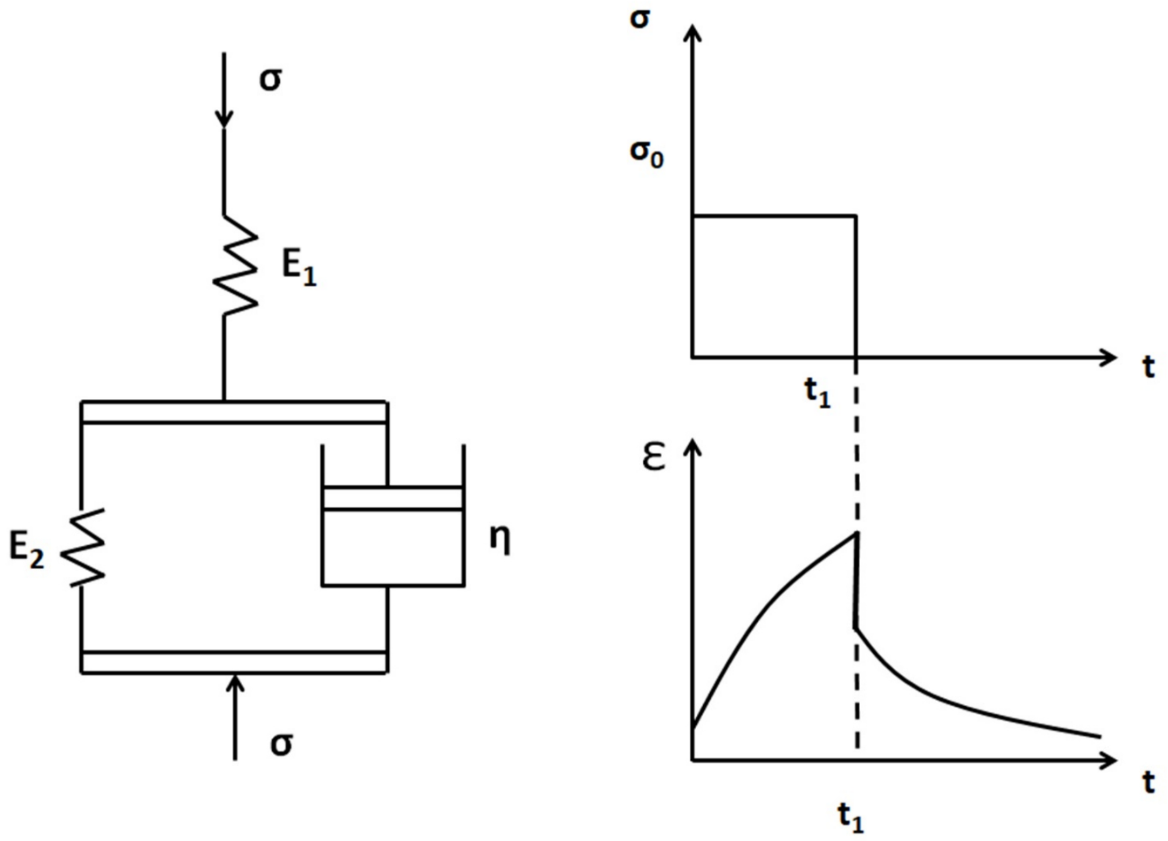

Fig. 2 Voigt-Kelvin creep model (σ is the applied load, E is the elastic modulus and η is the viscosity coefficient, ε is the deformation.

This scheme allows to analyse the evolution of secondary deformations over time (rate depending on the term E_2 and viscosity η) through a progressive reduction of the elastic modulus representative of the sprayed concrete, starting from an initial value E_1 (at the end of the phase tunnel construction) up to a lower value E_∞ which characterizes the support structure at time t=t_∞ after the tunnel construction phase has ended. The following relation applies (Oreste et al., 2019):

$$\frac{1}{E_\infty} = \frac{1}{E_1} + \frac{1}{E_2} \qquad (2)$$

Defining the final secondary deformations, due to the creep, as a certain percentage β of the primary deformations (the initial ones), we have: $E_2 = {}^{E_1}/_{\beta}$, and, therefore: $E_\infty = \frac{E_1}{(1+\beta)}$.

Knowing the values E_1 and E_∞ , it is possible to determine the initial (k_{in}) and final (k_{fin}) stiffness of the lining and evaluate, through the Convergence-Confinement Method (CCM), the reduction of the load applied by the rock to the support structure during the evolution of the secondary deformations in the shotcrete (Oreste et al., 2019). The phenomenon of reduction of the applied load is simulated for homogeneous steps and to each of them is associated a value of the average stiffness of the lining, k_i, a value of the average elastic modulus E_i of the sprayed concrete (equation 3), and finally a value of the average time, t_i, following the completion of the tunnel construction in the studied section (equation 4):

$$E_i = \frac{k_i \cdot (1+v_{sc}) \cdot [(1-2 \cdot v_{sc}) \cdot R^2 + (R-t_{sc})^2] \cdot R}{R^2-(R-t_{sc})^2} \tag{3}$$

$$t_i = \frac{-\eta \cdot \ln[\left(\frac{E_2}{E_1}\right)+1-\left(\frac{E_2}{E_i}\right)]}{E_2} \tag{4}$$

Once these parameters have been determined for each unloading step, it is possible to use the Hyperstatic Reaction Method (HRM) to verify the stress in the sprayed concrete produced by secondary deformations over time. More specifically, we start from considering the development of bending moments, normal forces and shear forces in the initial situation (at the end of the tunnel construction phase) and the stress state is modified in relation to the effects produced by the applied relief load steps. Each relief step is applied to a lining that appears with a different elastic module, E_i, gradually decreasing. At the end of the calculation the final load state is obtained, associated with a very large time, t_i, representative of the final phase of the secondary deformation process.

Since shotcrete shows an overall reduction of the elastic modulus (E_i) over time (t_i) due to the development of secondary deformations (creep), it is possible to associate to the value E_i also the unconfined compressive strength of the sprayed projected (σ_{ci}) and the tensile strength (σ_{ti}). In general, the strength values follow the same pattern over time as shown by the elastic modulus and it is therefore possible to assume the constant ratio (E_i/σ_{ci} and E_i/σ_{ti}) over time between the modulus of elasticity and the strength of the shotcrete. This assumption allows to determine over time the safety factor of the lining (FS), considered as the ratio between the maximum acting stress (induced in the shotcrete by the bending moment and the normal force) and the strength of the sprayed concrete. There are two safety factors, one related to the possible cracking of the shotcrete by compression ($FS_{,ci}$), the other related to the possible tensile failure ($FS_{,ti}$), only if the combination of bending moments and normal forces induces (at least in a portion of the lining) tensile stresses:

$$FS_{,ci} = {}^{\sigma_{ci}}/_{\sigma_{max,ci}} \quad (5)$$

$$FS_{,ti} = {}^{\sigma_{ti}}/_{\sigma_{max,ti}} \quad (6)$$

Where:

$\sigma_{max,ci}$ is the maximum compression stress in the lining, induced by the bending moments and by the normal acting forces, in the i-th relief step;

$\sigma_{max,ti}$ is the maximum tensile stress in the lining (if it exists), induced by the bending moments and by the normal acting forces, in the i-th relief step.

Being able to obtain the trend of the safety factors of the shotcrete for each relief step, it is possible to evaluate the stability conditions of the lining over time, during the evolution of the secondary deformation process. This circumstance is very useful for checking the effects of the creep on the stability conditions of the shotcrete tunnel linings.

The parametric analysis on the effect of creep on the behaviour of a shotcrete lining

In order to theoretically analyse the effect of the creep on the mechanical behaviour of a sprayed concrete lining, a parametric study was developed in which 8 different types of circular tunnel were considered, which differ in geometry (diameter), geomechanical quality (RMR) of the rock in which they are excavated and lithostatic stress state (p_0), which depends on the depth of the tunnel. The 8 types of tunnel are obtained by combining this set of pairs of values:

- Tunnel radius, R: 2m and 6m;
- RMR index of the rock: 30 and 60
- Lithostatic stress state, p_0: 2MPa and 7MPa.

RMR of 30 and 60 were considered in order to have a wide range of mechanical parameters of the rock, typical of situations where SC linins are used. Table 1 shows the values of the geomechanical parameters of the rock arbitrary assumed for each of the two values of the RMR quality index. The initial stiffness of the normal and shear springs (Kn and Kn respectively) are usually evaluated from the rock data using very simple relationships (Oreste, 2007):

$$Kn = \frac{2 \cdot E_{rm}}{R} \quad (7)$$

$$Kn = 0.5 \cdot Kn \quad (8)$$

Where E_{rm} is the elastic modulus of the rock and R is the tunnel radius.

Table 1 Geomechanical parameters of the rock assumed in the calculation for the two values of the RMR indices considered in the parametric analysis.

RMR 30		
Rock parameter	**Unity of measure**	**Value**
Elastic modulus (E_{rm})	[MPa]	3160
Coefficient of Poisson (v)	[-]	0.30
Peak cohesion (c_p)	[MPa]	0.15
Residual cohesion (c_r)	[MPa]	0.12
Peak friction angle (φ_p)	[°]	20
Residual friction angle (φ_r)	[°]	16
Dilatancy (ψ)	[°]	16
Kn	[MN/m]	550.82

Ks	[MN/m]	275.41
RMR 60		
Rock parameter	**Unity of measure**	**Value**
Elastic modulus (E_{rm})	[MPa]	17780
Coefficient of Poisson (v)	[-]	0.30
Peak cohesion (c_p)	[MPa]	2
Residual cohesion (c_r)	[MPa]	2
Peak friction angle (φ_p)	[°]	37
Residual friction angle (φ_r)	[°]	37
Dilatancy (ψ)	[°]	16
Kn	[MN/m]	3099.26
Ks	[MN/m]	1549.63

8 different types of sprayed concrete were then considered, in relation to the possibility of developing secondary deformations over time. The types of shotcrete differ in terms of the value of the initial elastic modulus (E_1), the parameter β (ratio between the final secondary deformations and the initial deformations) and the rate with which secondary deformations evolve over time (secondary deformations after 3 years equal to half or one third of the final secondary deformations):

- Initial elastic modulus E_1 of the sprayed concrete: 8000 MPa and 16000 MPa

- Parameter β (ratio between the final secondary deformations and the initial deformations): 0.33 and 1.
- Rate of evolution of secondary deformations: secondary deformations after 3 years from the construction ending of the tunnel equal to α=1/3 or α =1/2 times the final secondary deformations (for a very long time).

The combination of three pairs of values leads to 8 different types of concrete. Each of these ones was considered in each of the 8 tunnel types mentioned above. In total, therefore, 64 different cases were analysed.

Table 2 and 3 summarize the characteristic values of the 8 types of tunnel considered and the 8 types of shotcrete hypothesized in the calculation, respectively. The viscosity η is calculated using equation 1 which describes the path of the deformations over time:

$$\eta = -\frac{E_2 \cdot (3 \cdot 3600 \cdot 24 \cdot 365)}{ln(1-\alpha)} \tag{9}$$

Table 2 Types of tunnel considered in the developed parametric analysis.

Sequence	RMR	Tunnel radius, R (m)	Lithostatic stress state, p_0 (MPa)
A	30	2	2
B	30	2	7
C	30	6	2
D	30	6	7
E	60	2	2
F	60	2	7
G	60	6	2

H	60	6	7

Table 3 Types of sprayed concrete considered in the developed parametric analysis.

Case	Initial elastic modulus of the shotcrete at $t = 0, E_1$ (MPa)	Elastic modulus of the shotcrete in the parallel creep scheme, E_2 (MPa)	Viscosity η (MPa·s)	α parameter	β parameter
1	8000	24000	2.067×10^{12}	0.5	0.33
2	8000	24000	3.276×10^{12}	0.33	0.33
3	8000	8000	6.889×10^{11}	0.5	1
4	8000	8000	1.092×10^{12}	0.33	1
5	16000	48000	4.134×10^{12}	0.5	0.33
6	16000	48000	6.552×10^{12}	0.33	0.33
7	16000	16000	1.378×10^{12}	0.5	1
8	16000	16000	2.184×10^{12}	0.33	1

The thickness of the sprayed concrete lining, t_{sc}, was set at 0.2 m and the Poisson ratio, v_{sc}, was 0.15. The ratio k between the horizontal load and the vertical load applied to the lining was considered equal to 0.5. The time associated with the decrease of the elastic modulus corresponding to the midpoint of each of the 10 steps is thus obtained. With the proposed model it is possible to conduct studies in terms of variations of normal and shear forces, rotation and bending moments. For each of the 64 cases studied it was possible to obtain the trend of the bending moments M and of the normal forces N along the development of the lining in a transverse section of the tunnel. Figures 3 and 4 show, as an example, respectively the values of the trend of the bending moment and of the normal force along the support structure (for half of its development in the cross section, starting from the centre of the reverse arc of the tunnel) for the case D1 (type D tunnel, type 1 shotcrete-see Tab. 2 and 3).

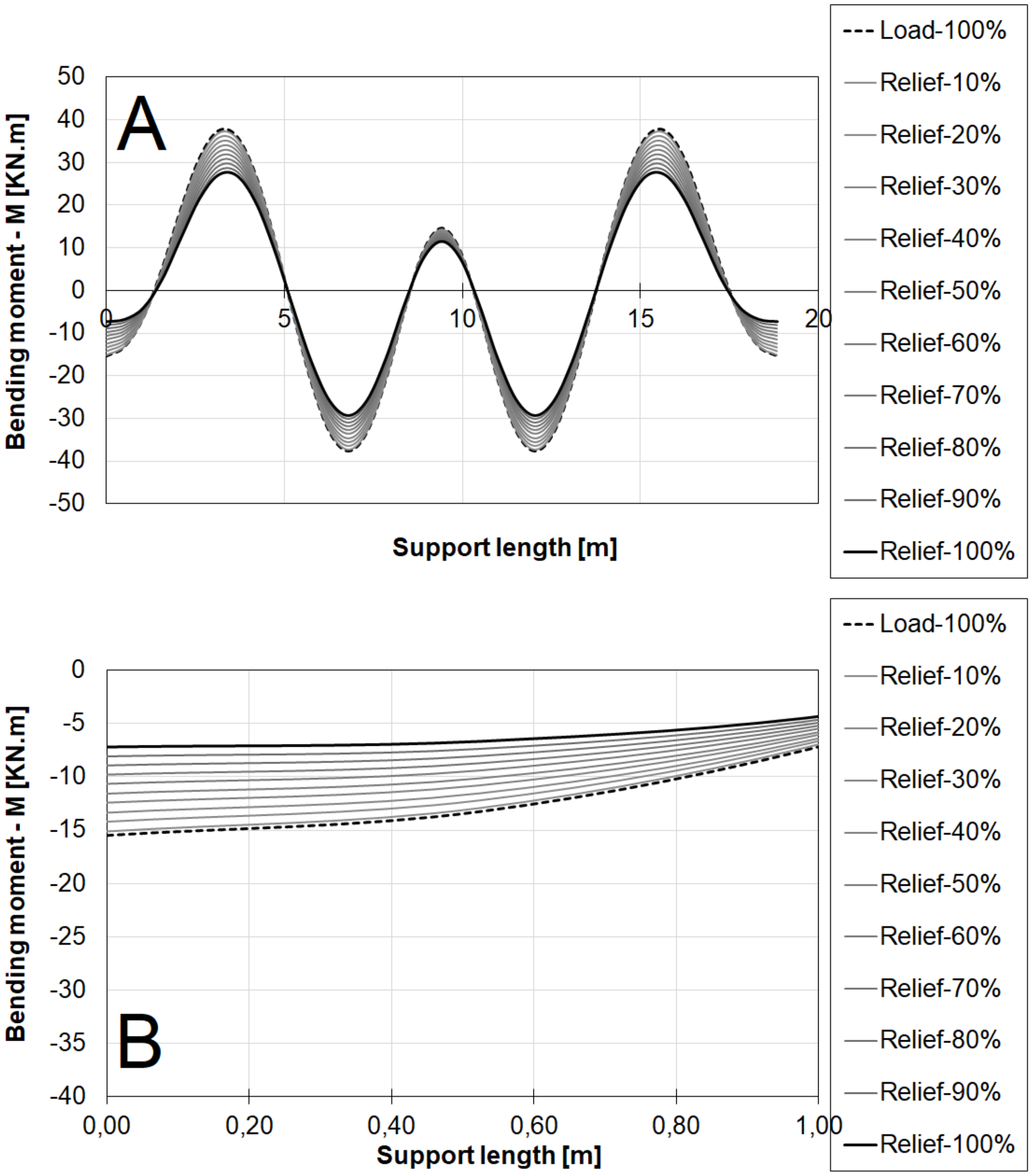

Fig. 3 Trend of bending moments along the development of the shotcrete lining, in a tunnel cross section, for the D1 case studied in the parametric analysis (A). Detail for the first meter of support length (B). The origin of the lines refers to the centre of the

reverse arc and the diagrams consider half of the development of the supporting structure. The diagram shows the trend at the end of the tunnel construction phase (t = 0), with the dotted line, and for the 10 stress relief steps considered, until reaching a very high time value (for which $E_i \approx E_\infty$, $t \approx \infty$), shown with the continuous black line.

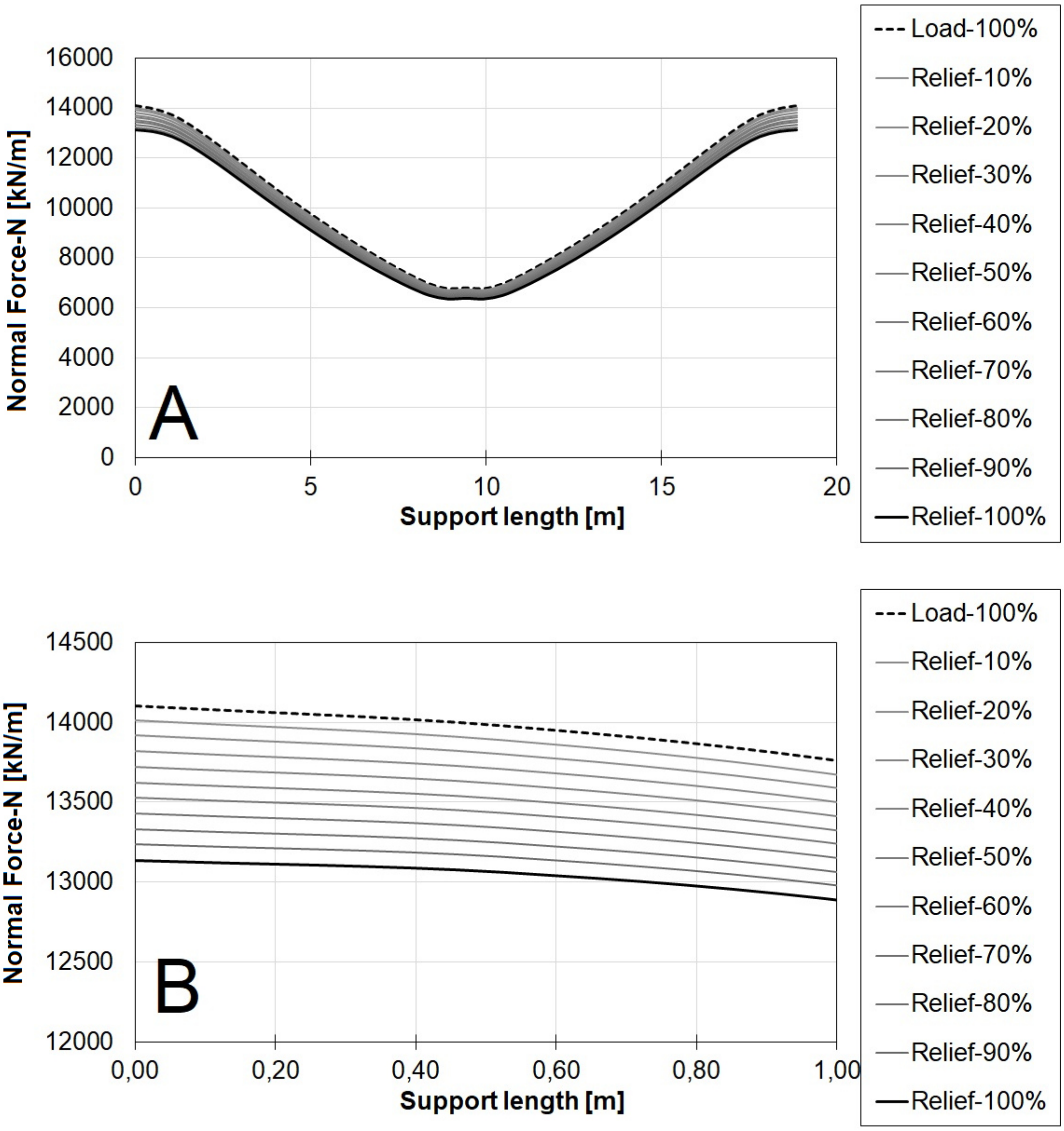

Fig. 4 Trend of normal forces along the development of the shotcrete lining, in a tunnel cross section, for the D1 case studied in the parametric analysis (A). Detail for the first meter of support length (B). The origin of the lines refers to the centre of the reverse arc and the diagrams consider half of the development of the supporting structure. The diagram shows the trend at the end of the tunnel construction phase (t = 0), with the

dotted line, and for the 10 stress relief steps considered, until reaching a very high time value (for which E_i ≈E_∞, t ≈∞), shown with the continuous black line.

From the analysis of the results shown in Figs. 3 and 4 it can be seen how the creep phenomenon can lead, depending on the type of tunnel (diameter, depth and quality of the rock) and the type of sprayed concrete (initial stiffness, entity final of secondary deformations and viscosity), to significant changes in the trend of bending moments and normal forces induced along the development of the lining. The variation of the maximum bending moment along the lining and of the normal force at the point of maximum moment is interesting. Starting from the values of M and N, the stress induced in the sprayed concrete at each point of the lining and, therefore, the maximum value of stress, among those present was determined. In the following, reference will be made only to the analysis with respect to the compression stress, since no tensile stresses were detected within the lining in any of the examined cases. Because the failure of the sprayed concrete linings can occur in compression or traction, it is useful to evaluate the maximum compressive stresses and the maximum tensile stresses reached at each stage during the creep phase and compare them with the compressive and tensile strength. While the compression stress is always present in a tunnel support, it is not always possible to detect the traction stress, or the traction stress does not always reach levels such as to be close to the tensile strength of the shotcrete. The evaluation of the maximum compression tension $\sigma_{max,ci}$ (equation 5) in the shotcrete lining referred to the combined compressive and bending stress:

$$\sigma_{max,ci} = max\left(6 \cdot \frac{|M|}{1 \cdot t^2} + \frac{|N|}{1 \cdot t}\right) \tag{10}$$

where M and N are the values of bending moment and normal force which are present at the same point along the circumferential development of the supporting structure.

Starting from $\sigma_{max,ci}$, it was then possible to determine the safety factor FS , (equation 5), in order to evaluate the compressive strength σ_{ci} variable over time and linked to the value of the elastic modulus E_i determined at each single relief step considered. For the determination of σ_{ci} reference was made to the Chang and Stille equation (1993):

$$\sigma_{ci} = \left(\frac{E_i}{3.86}\right)^{\frac{5}{3}} \tag{11}$$

where E_i is the elastic modulus in GPa and σ_{ci} is uniaxial compressive strength of the shotcrete in MPa.

In the specific case, 10 stress relief steps were considered and, therefore, for each of them the load reduction value (vertical and horizontal) applied to the lining, the elastic modulus E_i reached by the shotcrete in that specific step and, consequently, the strength σ_{ci} of the shotcrete were determined.

For each of the 64 cases studied the safety factor of the lining at the time variation t_i was determined. In all cases a reduction in the safety factor over time was found, starting from the value found at the end of the tunnel construction phase, when the time t was conventionally set to 0. The minimum value of the factor safety is always reached at the end of the creep phase, for very long times, t. During the design of the lining, it is possible to keep the attention on the value of the safety factor for a time t = t_∞, when its minimum value is reached.

Fig. 5 (A-H) shows the results obtained for the safety factor of the lining during the creep phase for the 8 considered tunnels (A-H, see Tab. 2).

The trends referring to the 8 types of shotcrete considered are illustrated for each tunnel. The analysis of the graphs shows how the initial safety factor (at the end of the tunnel construction phase) depends for each tunnel on the elastic form E_1 of the sprayed concrete only. The other parameters characterizing the shotcrete (E_2 and η) have no role. The percentage reduction of the final safety factor (at the end of the creep phase), with respect to the initial value, on the other hand, depends on the elastic modulus E_2, i.e. on the elastic modulus indicating the overall entity of the secondary deformations. The reduction of the safety factor due to the phenomenon of creep can be very consistent, especially for low values of the geomechanical quality index of the rock and for shallow tunnels.

The viscosity only influences the rate with which the final condition with minimum safety factor is reached in time: obviously, with increasing viscosity, the time necessary to reach the minimum safety factor increases.

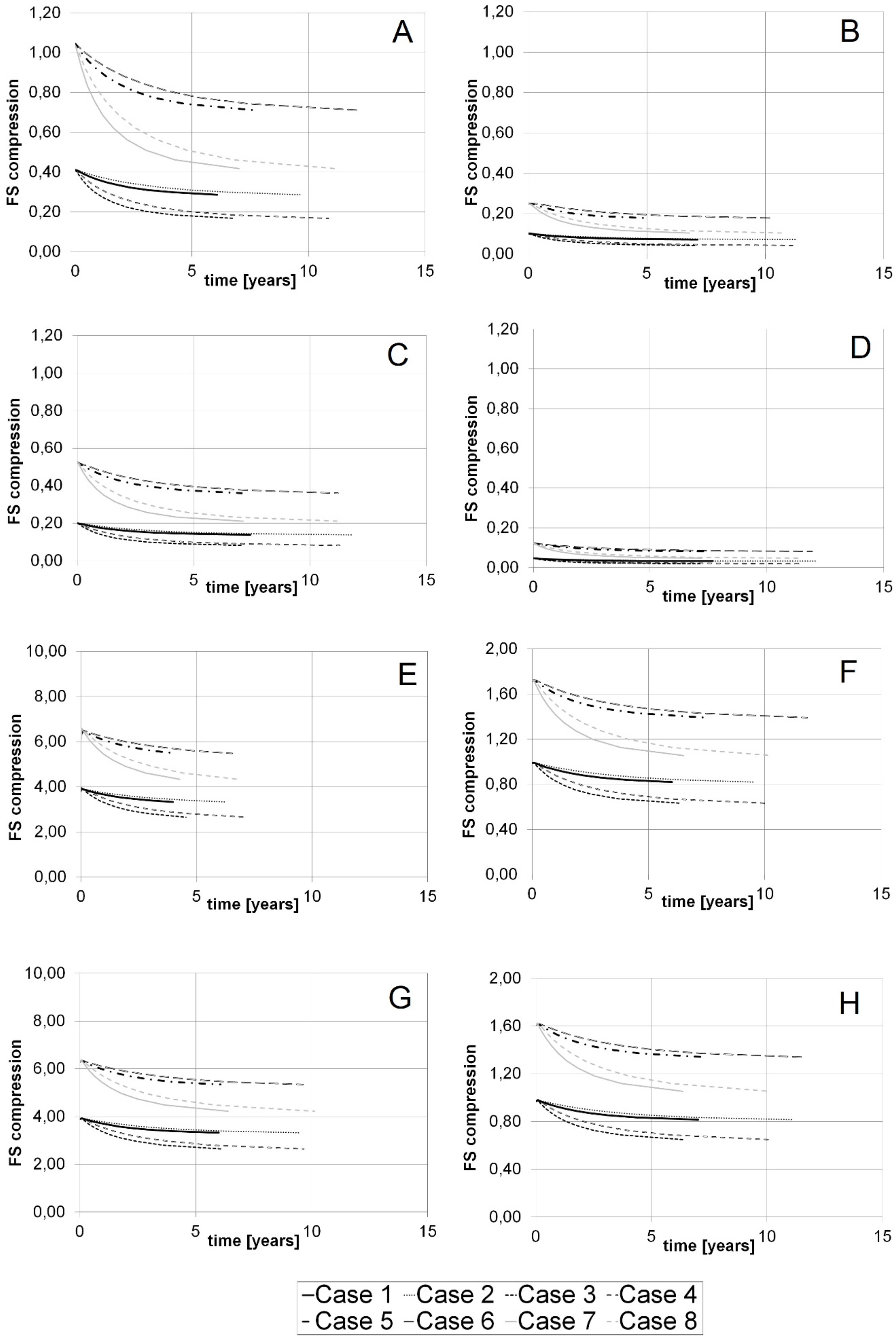
A
B
C
D
E
F
G
H
FS compression
time [years]
0
5
10
15
0,00
0,20
0,40
0,60
0,80
1,00
1,20
1,60
2,00
2,00
4,00
6,00
8,00
10,00
Case 1
Case 2
Case 3
Case 4
Case 5
Case 6
Case 7
Case 8

Fig. 5 Trend of safety factors over time at the tunnels type A to H, for the 8 types of sprayed concrete considered.

From the analysis of the results of the parametric analysis it is possible to note, therefore, how the creep phenomenon can be very important for the behaviour of the sprayed concrete lining of a tunnel and, therefore, cannot be neglected in the design phase. The determination of the minimum safety factor, at the end of the creep phase is interesting. In fact, this value influences the design of the supporting structure and must be determined during calculation. In order to correctly evaluate the minimum safety factor, it is necessary to estimate the elastic modulus E_2 of the shotcrete in the simplified Voigt-Kelvin model. This parameter is determined starting from the estimate of the final entity of the secondary deformations of the sprayed concrete with respect to the initial deformations obtained at the end of the tunnel construction phase. In order to have an estimate of E_2, it is therefore useful to evaluate the evolution of secondary deformations for a certain period of time for a specimen of shotcrete in laboratory.

Conclusions

In this work, after having framed the problem of creep in shotcrete, the result of a parametric study obtained using a specific calculation tool, developed to study this particular mechanical phenomenon, is presented. This calculation tool uses the convergence-confinement method and the hyperstatic reaction method and allows to evaluate the evolution of the stresses and deformations of the sprayed concrete lining over time, in order to determine its safety factor conditions with respect to stability. A simplified model of creep, i.e. the Voigt-Kelvin model, was considered to represent the behaviour of the sprayed concrete. The parametric analysis has considered different types of tunnels, different in diameter, depth and type of rock, and different types of shotcrete. In all the cases analysed a reduction in the safety factor over time was noted, showing the importance of the creep study for the correct design of the thickness of the sprayed concrete lining. The final value of the safety factor is therefore fundamental for the design phase of the tunnel support. This value depends in particular on the elastic modules which the sprayed concrete has in the initial phase and during the evolution of the secondary deformations. The percentage reduction of the final safety factor (at the end of the creep phase), with respect to the initial value, depends on the elastic modulus indicating the overall entity of the secondary deformations. The reduction of the safety factor due to the phenomenon of creep can be very consistent, especially for low values of the geomechanical quality index of the rock and for shallow tunnels. The viscosity is useful only to predict the time necessary to reach the final condition in which the secondary deformations can be considered accomplished. For the correct design of the sprayed concrete lining it is essential to define some parameters influencing the creep behaviour of the material: in particular, in addition to the initial elastic modulus, which influences the initial deformations of the lining, it is necessary to evaluate the final entity secondary deformations and in particular the ratio between the final secondary deformations and the initial deformations obtained at the end of the tunnel construction phase.

References

Chang Y, Stille H (1993) Influence of early age properties of shotcrete on tunnel construction sequences. In Wood, D.F., Morgan, D.R. (Eds.), Shotcrete for Underground Support VI, American Society of Civil Engineers, Reston, pp. 110-117.

DIN 18551-01 (2005) Spritzbeton - Anforderungen, Herstellung, Bemessung und Konformität. Beuth Verlag GmbH, Berlin.

Ding Y (1998) Technologische Eigenschaften von jungen Stahlfaserbeton und Stahlfaserspritzbeton. PhD thesis, University of Innsbruck (Austria).

Do, N.A., Dias, D., Oreste, P., and Djeran-Maigre, I (2014a) The behavior of the segmental tunnel lining studied by the hyperstatic reaction method. European Journal of Environmental and Civil Engineering 18(4), 489–510.

Do, N.A., Dias, D., Oreste, P., and Djeran-Maigre, I (2014b) The Influence of the Simplified Excavation Method on Tunnel Behaviour. Geotechnical and Geological Engineering 32(1), 43-58.

Hellmich C, Mang HA (1999) Influence of the dilation of soil and shotcrete on the load bearing behaviour of NATM-Tunnels. Felsbau 17:35-43.

Huber HG (1991) Untersuchung zum Verformungsverhalten von jungem Spritzbeton im Tunnelbau. Master thesis, University of Innsbruck (Austria).

Jaeger JC, Cook NGW (1979) Fundamentals of Rock Mechanics. London: Chapman and Hall.

Kuwajima FM (1999) Early age properties of the shotcrete. In Celestino T, Parker, H, eds. Shotcrete for Underground, Sao Paulo, Brazil, 153–173.

MacKay J, Trottier JF (2004) Post-crack creep behaviour of steel and synthetic FRC under flexural loading. In Bernard ES, ed. Shotcrete: More Engineering Developments. London: Taylor & Francis, 183-192.

Melbye T (1994) Sprayed Concrete for Rock Support. Switzerland: MBT Underground Construction Group.

Neville AM, Dilger WH, Brooks JJ (1983) Creep of plain and structural concrete, Harlow: Construction Press.

Oreste P (2007) A numerical approach to the hyperstatic reaction method for the dimensioning of tunnel supports. Tunnelling and Underground Space Technology 22(2):185–205, *https://doi.org/10.1016/j.tust.2006.05.002*.

Oreste P (2009) The Convergence-Confinement Method: Roles and limits in modern geomechanical tunnel design. American Journal of Applied Sciences 6(4):757-771.

Oreste P (2015) Analysis of the Interaction between the Lining of a TBM Tunnel and the Ground Using the Convergence-Confinement Method. American Journal of Applied Sciences 12(4):276-283. DOI: 10.3844/ajassp.2015.276.283.

Oreste P, Spagnoli G, Luna Ramos CA, Sebille L (2018) The Hyperstatic Reaction Method for the Analysis of the Sprayed Concrete Linings Behavior in Tunneling. Geotechnical and Geological Engineering, 36(4): 2143–2169, *https://doi.org/10.1007/s10706-018-0454-6*.

Oreste P, Spagnoli G, Ceravolo LA (2019a) A numerical model to assess the creep of shotcrete linings. Proceedings of the Institution of Civil Engineers – Geotechnical Engineering, 172(4), 344-354, https://doi.org/10.1680/jgeen.18.00089.

Oreste P, Spagnoli G, Luna Ramos CA (2019b) The Elastic Modulus Variation During the Shotcrete Curing Jointly Investigated by the Convergence-Confinement and the Hyperstatic Reaction Methods. Geotechnical and Geological Engineering, 37(3): 1435–1452, *https://doi.org/10.1007/s10706-018-0698-1*.

Pöttler R (1990) Green shotcrete in tunnelling: stifness-strength-deformation. Shotcrete for Underground support, 4:83-81.

Rokahr RB, Lux KH (1987) Einfluss des rheologischen Verhaltens des Spritzbetons auf den Ausbauwiderstand. Felsbau 5:11-18.

Schädlich B, Schweiger HF (2014) A new constitutive model for shotcrete. In Hicks MA, Brinkgreve RBJ, Rohe A, eds. Numerical Methods in Geotechnical Engineering. Boca Raton: CRC Press, 103-108.

Schubert P (1988) Beitrag zum rheologischen Verhalten von Spritzbeton. Felsbau, 6, 150-153.

Spagnoli G, Oreste P, Lo Bianco L. (2016). New equations for estimating radial loads on deep shaft linings in weak rocks. International Journal of Geomechanics 16(6): 06016006, DOI: *10.1061/(ASCE)GM.1943-5622.0000657*.

Spagnoli G, Oreste P, Lo Bianco L. (2017) Estimation of shaft radial displacement beyond the excavation bottom before installation of permanent lining in nondilatant weak rocks with a novel formulation. International Journal of Geomechanics, 17(9): 04017051 https://doi.org/10.1061/(ASCE)GM.1943-5622.0000949.

Thomas A (2009) Sprayed Concrete Lined Tunnels. Oxon: Taylor and Francis.

Yin J (1996) Untersuchungen zum zeitabhängigen Tragverhalten von tiefliegenden Hohlraumen im Fels mit Spritzbeton. PhD thesis, Clausthal University of Technology (Germany).

FIGURE CAPTION

Fig. 1 Application of shotcrete

Fig. 2 Voigt-Kelvin creep model (σ is the applied load, E is the elastic modulus and η is the viscosity coefficient, ε is the deformation.

Fig. 3 Trend of bending moments along the development of the shotcrete lining, in a tunnel cross section, for the D1 case studied in the parametric analysis (A). Detail for the first meter of support length (B). The origin of the lines refers to the centre of the reverse arc and the diagrams consider half of the development of the supporting structure. The diagram shows the trend at the end of the tunnel construction phase (t = 0), with the dotted line, and for the 10 stress relief steps considered, until reaching a very high time value (for which $E_i \approx E_\infty$, $t \approx \infty$), shown with the continuous black line.

Fig. 4 Trend of normal forces along the development of the shotcrete lining, in a tunnel cross section, for the D1 case studied in the parametric analysis (A). Detail for the first meter of support length (B). The origin of the lines refers to the centre of the reverse arc and the diagrams consider half of the development of the supporting structure. The diagram shows the trend at the end of the tunnel construction phase (t = 0), with the dotted line, and for the 10 stress relief steps considered, until reaching a very high time value (for which $E_i \approx E_\infty$, $t \approx \infty$), shown with the continuous black line.

Fig. 5 Trend of safety factors over time at the tunnels type A to H, for the 8 types of sprayed concrete considered.

TABLE CAPTION

Table 1 Geomechanical parameters of the rock assumed in the calculation for the two values of the RMR indices considered in the parametric analysis.

Table 2 Types of tunnel considered in the developed parametric analysis.

Table 3 Types of sprayed concrete considered in the developed parametric analysis.