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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.

27 **KEY WORDS:** Tunnels & tunnelling; Excavation; Mathematical modelling

28

29 **Notation list**

- 30 φ_p : peak friction angle of the rock;
- 31 c_p : peak cohesion of the rock;
- 32 c_r : residual cohesion of the rock;
- 33 E_i : elastic modulus of shotcrete at i -th-step;
- 34 E_{rm} : elastic modulus of the rock;
- 35 E_∞ : elastic modulus of the shotcrete at infinity, when creep ceased;
- 36 E_1 : initial elastic modulus of the shotcrete at $t = 0$;
- 37 E_2 : elastic modulus of the shotcrete in the parallel creep scheme;
- 38 M : bending moments;
- 39 N : normal forces;
- 40 p_0 : lithostatic pressure;
- 41 R : tunnel radius;
- 42 t_i : average time;
- 43 t_{sc} : thickness of the shotcrete lining;
- 44 φ_r : residual friction angle of the rock;
- 45 ν : Poisson coefficient of the rock;
- 46 ν_{sc} : Poisson coefficient of the shotcrete;
- 47 σ_{ci} : uniaxial compressive strength;
- 48 $\sigma_{max,ci}$: maximum compression stress in the lining, induced by the bending moments and by
- 49 the normal acting forces, in the i -th relief step;
- 50 $\sigma_{max,ti}$: maximum tensile stress in the lining, induced by the bending moments and by the
- 51 normal acting forces, in the i -th relief step;
- 52 σ_{ti} : tensile strength;
- 53 η : viscosity of the shotcrete;
- 54 Ψ : dilatancy of the rock;
- 55 α : rate of evolution of secondary deformations;

56 β : ratio between the final secondary de-formations and the initial deformations;
57 k : ratio between the horizontal load and the vertical load applied to the lining;
58 k_i : average stiffness of the lining;
59 K_n : normal stiffness of the interaction spring between the lining and the rock (hyperstatic re-
60 action method);
61 K_s : shear stiffness of the interaction spring between the lining and the rock (hyperstatic reac-
62 tion method).
63

64 **Introduction**

65 Sprayed concrete (or shotcrete) is concrete which is conveyed under high pressure through a
66 pneumatic hose and projected into place at high velocity, with simultaneous compaction (DIN
67 18551, 2005), see Fig. 1. Among the properties of shotcrete used for tunnel design, such as
68 early (compressive) and long-time strength, tensile strength, shrinkage, curing time, cracking,
69 durability, creep is one of the most important factors (Thomas, 2009), because shotcrete lin-
70 ings are loaded at a very early age, therefore the influence of time dependent material proper-
71 ties on the deformation behaviour and bearing capacity is much more significant than in regular
72 concrete structures (Schädlich and Schweiger, 2014). Neville et al. (1983) define creep as the
73 increase in strain with time under a sustained stress, i.e. the material deforms not only due to
74 the stresses which it is subjected to, but also due over a time during which these stresses are
75 applied.



76

77 **Fig. 1 Application of shotcrete**

78 According to Thomas (2009) the high creep capacity of sprayed concrete can be considered
79 as positive as this can dissipate stress concentrations and avoid overloading. The current sim-
80 plistic approach to model sprayed concrete linings in numerical simulations assumes a linear
81 elastic material with a stepwise increase of the Young's modulus in subsequent excavation
82 stages in order to simulate the curing effect. While realistic lining deformations may be obtained
83 with this method, lining stresses are usually too high, in particular if the lining is subjected to
84 significant bending (Schädlich and Schweiger 2014). For sprayed concrete, the principle of
85 rheological models are the same as for rock (Thomas 2009). However, in shotcrete creep is
86 significantly higher at an early stage of load as the strength of concrete is lower, as found by
87 Huber (1991). However, it must be kept in mind that some accelerators increase the early
88 strengths (Melbye 1994) therefore creep after 24 or 48 h is close to that at greater ages (Ku-
89 wajima, 1999). Concrete reinforcement reduces creep, presumably due to the restrain effect
90 (Ding, 1998). However, reinforcing synthetic fibers sprayed together with the shotcrete have
91 twice the creep capacity than a shotcrete with steel fibres (Thomas, 2009; MacKay and Trottier,
92 2004).

93 Numerical models are massively employed to analyse the creep behaviour of shotcrete linings
94 such as some rheological models (Jaeger and Cook, 1979): Kelvin model (Neville et al., 1983;
95 Jaeger and Cook, 1979; Rokahr and Lux, 1987), Burgers model (Yin, 1996), viscoplastic model
96 (Thomas, 2009). Kelvin creep model produces a complete recovery, unlike the Maxwell models
97 where no recovery is produced. The rheological models help to give a better understanding of
98 the visco-elastics and elasto-viscoplastics behavior. However, these models do not account
99 for shear stresses, temperature and intrinsic structure. Regarding the power laws creep model
100 for sprayed concrete, of the three stages of creep, only primary creep is of interest for sprayed
101 concrete linings after construction (Thomas 2009). Several authors used the power laws for
102 sprayed concrete lining tunnels (e.g. Schubert, 1988; Yin, 1996), however according to
103 Thomas (2009) they are not widely used because of their inferior ability to model complex
104 creep behaviour. It has to be pointed out, that real creep behaviour of linings is hard to obtain
105 as the load-bearing system is a composite consisting of the ground and the lining. Therefore,

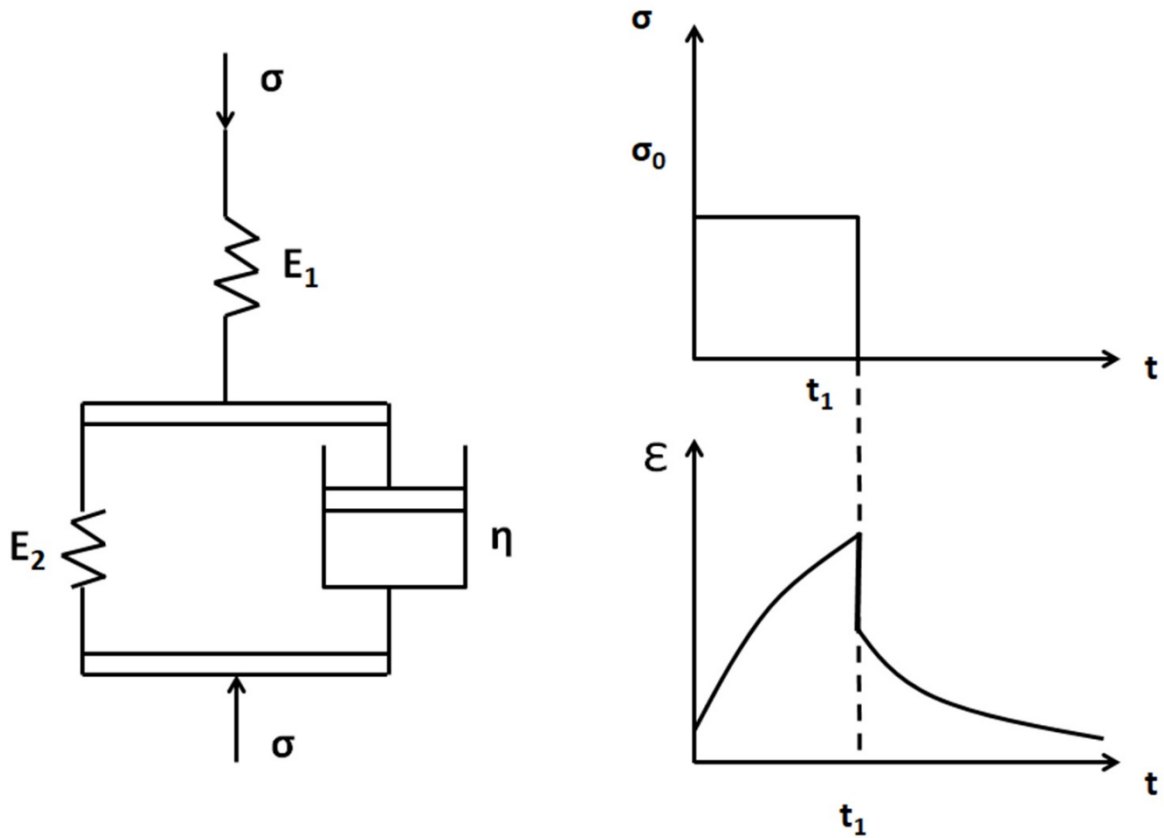
106 the reduction in the lining stress due to the creep depends on the characteristics of the sur-
107 rounding ground (Thomas 2009). As observed by Pöttler (1990) and Yin (1996) if the ground
108 is modelled as elastoplastic, the load on the lining can increase following creep.

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

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

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

$$127 \quad \varepsilon_t = \frac{\sigma}{E_2} \cdot \left(1 - e^{-\frac{E_2 \cdot t}{\eta}}\right) + \frac{\sigma}{E_1} \quad (1)$$



128

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

131 This scheme allows to analyse the evolution of secondary deformations over time (rate de-
 132 pending on the term E_2 and viscosity η) through a progressive reduction of the elastic modulus
 133 representative of the sprayed concrete, starting from an initial value E_1 (at the end of the phase
 134 tunnel construction) up to a lower value E_∞ which characterizes the support structure at time
 135 $t=t_\infty$ after the tunnel construction phase has ended. The following relation applies (Oreste et
 136 al., 2019):

$$137 \quad \frac{1}{E_\infty} = \frac{1}{E_1} + \frac{1}{E_2} \quad (2)$$

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

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

$$148 \quad E_i = \frac{k_i \cdot (1 + v_{sc}) \cdot [(1 - 2 \cdot v_{sc}) \cdot R^2 + (R - t_{sc})^2] \cdot R}{R^2 - (R - t_{sc})^2} \quad (3)$$

$$149 \quad t_i = \frac{-\eta \cdot \ln\left[\left(\frac{E_2}{E_1}\right) + 1 - \left(\frac{E_2}{E_i}\right)\right]}{E_2} \quad (4)$$

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

159 Since shotcrete shows an overall reduction of the elastic modulus (E_i) over time (t_i) due to the
 160 development of secondary deformations (creep), it is possible to associate to the value E_i also
 161 the unconfined compressive strength of the sprayed projected (σ_{ci}) and the tensile strength
 162 (σ_{ti}). In general, the strength values follow the same pattern over time as shown by the elastic
 163 modulus and it is therefore possible to assume the constant ratio (E_i/σ_{ci} and E_i/σ_{ti}) over time
 164 between the modulus of elasticity and the strength of the shotcrete. This assumption allows to
 165 determine over time the safety factor of the lining (FS), considered as the ratio between the

166 maximum acting stress (induced in the shotcrete by the bending moment and the normal force)
167 and the strength of the sprayed concrete. There are two safety factors, one related to the
168 possible cracking of the shotcrete by compression ($FS_{,ci}$), the other related to the possible
169 tensile failure ($FS_{,ti}$), only if the combination of bending moments and normal forces induces
170 (at least in a portion of the lining) tensile stresses:

$$171 \quad FS_{,ci} = \sigma_{ci} / \sigma_{max,ci} \quad (5)$$

$$172 \quad FS_{,ti} = \sigma_{ti} / \sigma_{max,ti} \quad (6)$$

173 Where:

174 $\sigma_{max,ci}$ is the maximum compression stress in the lining, induced by the bending moments and
175 by the normal acting forces, in the i-th relief step;

176 $\sigma_{max,ti}$ is the maximum tensile stress in the lining (if it exists), induced by the bending moments
177 and by the normal acting forces, in the i-th relief step.

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

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

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

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

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

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

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

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

197 **Table 1 Geomechanical parameters of the rock assumed in the calculation for the two**
 198 **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 (ν)	[-]	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
K_n	[MN/m]	550.82

K_s	[MN/m]	275.41
RMR 60		
Rock parameter	Unity of measure	Value
Elastic modulus (E_{rm})	[MPa]	17780
Coefficient of Poisson (ν)	[-]	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
K_n	[MN/m]	3099.26
K_s	[MN/m]	1549.63

199

200 8 different types of sprayed concrete were then considered, in relation to the possibility of
201 developing secondary deformations over time. The types of shotcrete differ in terms of the
202 value of the initial elastic modulus (E_1), the parameter β (ratio between the final secondary de-
203 formations and the initial deformations) and the rate with which secondary deformations evolve
204 over time (secondary deformations after 3 years equal to half or one third of the final secondary
205 deformations):

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

- 207 • Parameter β (ratio between the final secondary deformations and the initial defor-
- 208 mations): 0.33 and 1.
- 209 • Rate of evolution of secondary deformations: secondary deformations after 3 years
- 210 from the construction ending of the tunnel equal to $\alpha=1/3$ or $\alpha =1/2$ times the final sec-
- 211 ondary deformations (for a very long time).

212 The combination of three pairs of values leads to 8 different types of concrete. Each of these

213 ones was considered in each of the 8 tunnel types mentioned above. In total, therefore, 64

214 different cases were analysed.

215 Table 2 and 3 summarize the characteristic values of the 8 types of tunnel considered and the

216 8 types of shotcrete hypothesized in the calculation, respectively. The viscosity η is calculated

217 using equation 1 which describes the path of the deformations over time:

218
$$\eta = -\frac{E_2 \cdot (3 \cdot 3600 \cdot 24 \cdot 365)}{\ln(1-\alpha)} \quad (9)$$

219 **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
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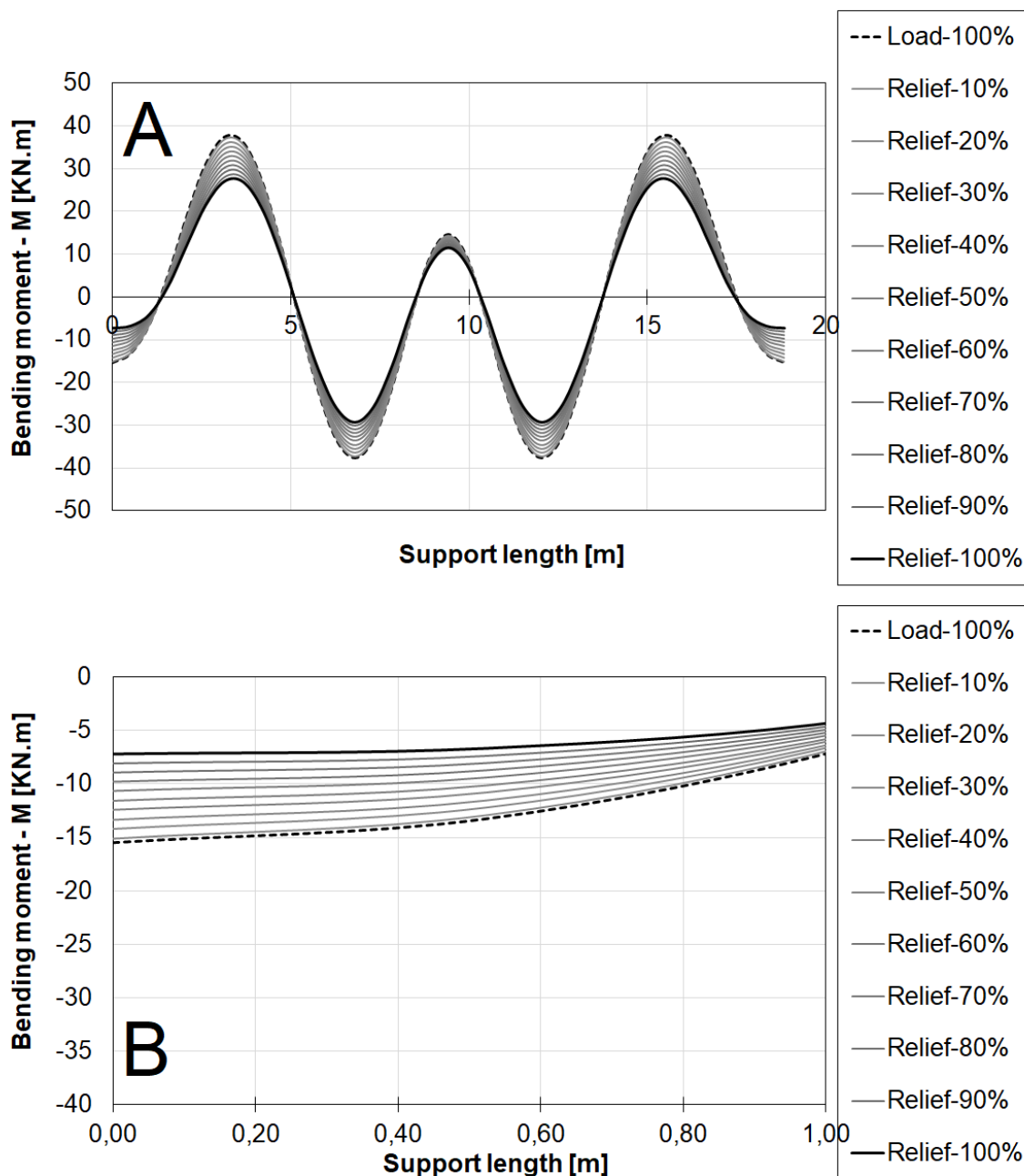
221 **Table 3 Types of sprayed concrete considered in the developed parametric analysis.**

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

222

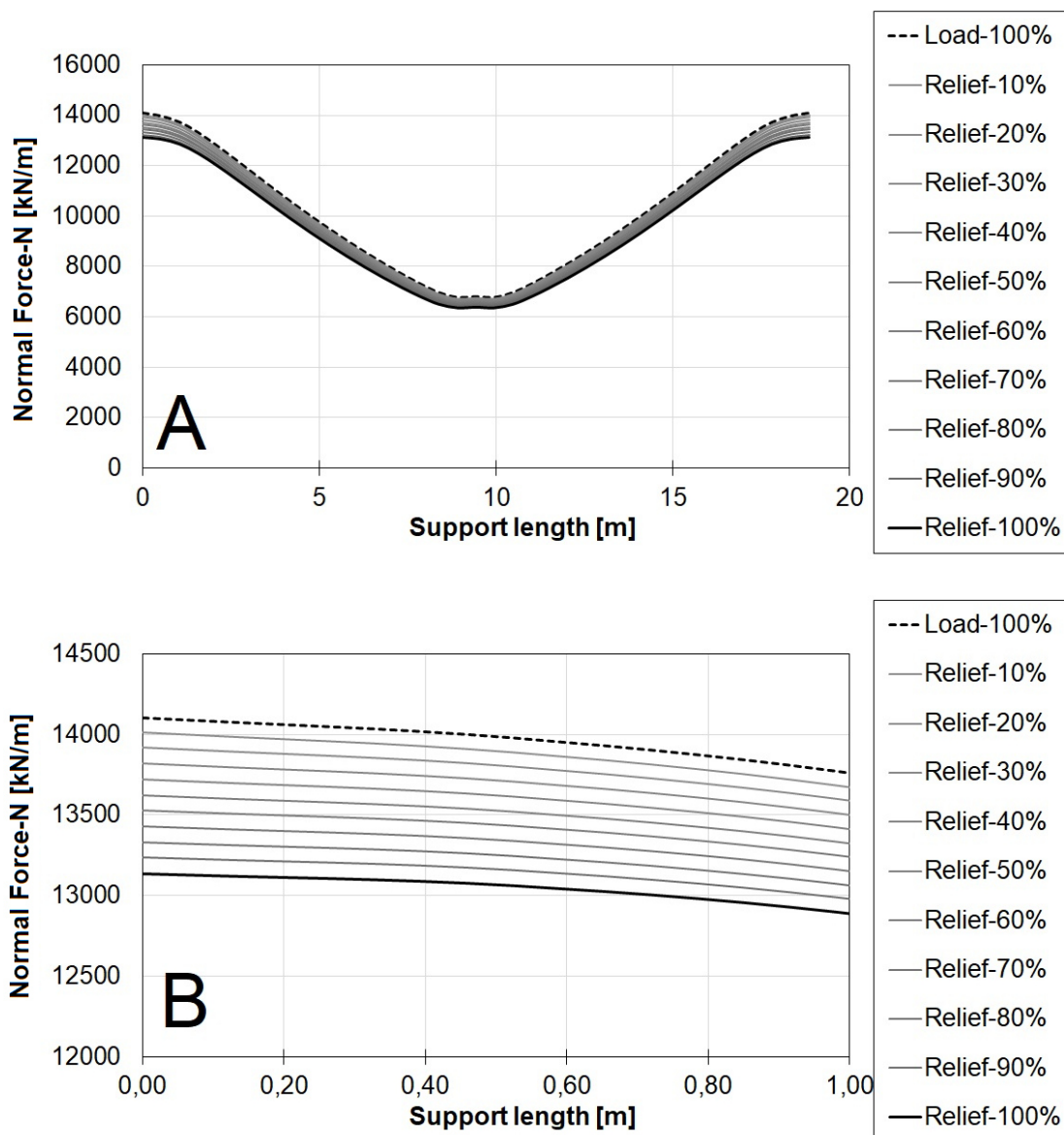
223 The thickness of the sprayed concrete lining, t_{sc} , was set at 0.2 m and the Poisson ratio, ν_{sc} ,
 224 was 0.15. The ratio k between the horizontal load and the vertical load applied to the lining
 225 was considered equal to 0.5. The time associated with the decrease of the elastic modulus
 226 corresponding to the midpoint of each of the 10 steps is thus obtained. With the proposed
 227 model it is possible to conduct studies in terms of variations of normal and shear forces, rota-
 228 tion and bending moments. For each of the 64 cases studied it was possible to obtain the trend
 229 of the bending moments M and of the normal forces N along the development of the lining in

230 a transverse section of the tunnel. Figures 3 and 4 show, as an example, respectively the
 231 values of the trend of the bending moment and of the normal force along the support structure
 232 (for half of its development in the cross section, starting from the centre of the reverse arc of
 233 the tunnel) for the case D1 (type D tunnel, type 1 shotcrete-see Tab. 2 and 3).



234
 235 **Fig. 3 Trend of bending moments along the development of the shotcrete lining, in a**
 236 **tunnel cross section, for the D1 case studied in the parametric analysis (A). Detail for**
 237 **the first meter of support length (B). The origin of the lines refers to the centre of the**

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



242
 243 **Fig. 4** Trend of normal forces along the development of the shotcrete lining, in a tunnel
 244 cross section, for the D1 case studied in the parametric analysis (A). Detail for the first
 245 meter of support length (B). The origin of the lines refers to the centre of the reverse arc
 246 and the diagrams consider half of the development of the supporting structure. The
 247 diagram shows the trend at the end of the tunnel construction phase ($t = 0$), with the

248 **dotted line, and for the 10 stress relief steps considered, until reaching a very high time**
249 **value (for which $E_t \approx E_\infty$, $t \approx \infty$), shown with the continuous black line.**

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

$$268 \sigma_{max,ci} = \max \left(6 \cdot \frac{|M|}{1 \cdot t^2} + \frac{|N|}{1 \cdot t} \right) \quad (10)$$

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

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

275
$$\sigma_{ci} = \left(\frac{E_i}{3.86} \right)^{\frac{5}{3}} \quad (11)$$

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

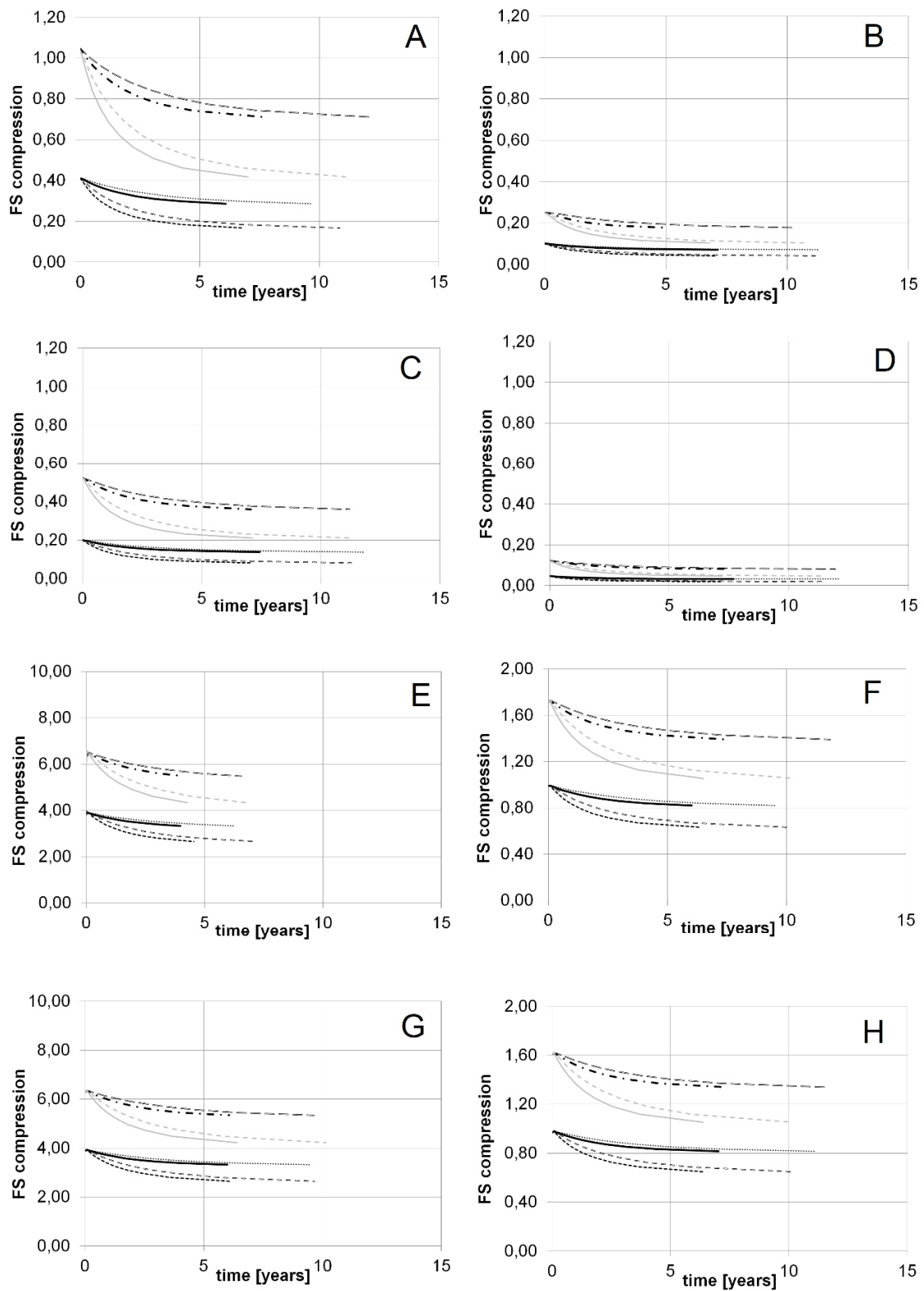
278 In the specific case, 10 stress relief steps were considered and, therefore, for each of them the
279 load reduction value (vertical and horizontal) applied to the lining, the elastic modulus E_i
280 reached by the shotcrete in that specific step and, consequently, the strength σ_{ci} of the shot-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

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

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

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

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



-Case 1 -Case 2 -Case 3 -Case 4
 -Case 5 -Case 6 -Case 7 -Case 8

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

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

317 **Conclusions**

318 In this work, after having framed the problem of creep in shotcrete, the result of a parametric
319 study obtained using a specific calculation tool, developed to study this particular mechanical
320 phenomenon, is presented. This calculation tool uses the convergence-confinement method
321 and the hyperstatic reaction method and allows to evaluate the evolution of the stresses and
322 deformations of the sprayed concrete lining over time, in order to determine its safety factor
323 conditions with respect to stability. A simplified model of creep, i.e. the Voigt-Kelvin model, was
324 considered to represent the behaviour of the sprayed concrete. The parametric analysis has
325 considered different types of tunnels, different in diameter, depth and type of rock, and different
326 types of shotcrete. In all the cases analysed a reduction in the safety factor over time was
327 noted, showing the importance of the creep study for the correct design of the thickness of the
328 sprayed concrete lining. The final value of the safety factor is therefore fundamental for the
329 design phase of the tunnel support. This value depends in particular on the elastic modules
330 which the sprayed concrete has in the initial phase and during the evolution of the secondary

331 deformations. The percentage reduction of the final safety factor (at the end of the creep
332 phase), with respect to the initial value, depends on the elastic modulus indicating the overall
333 entity of the secondary deformations. The reduction of the safety factor due to the phenomenon
334 of creep can be very consistent, especially for low values of the geomechanical quality index
335 of the rock and for shallow tunnels. The viscosity is useful only to predict the time necessary
336 to reach the final condition in which the secondary deformations can be considered accom-
337 plished. For the correct design of the sprayed concrete lining it is essential to define some
338 parameters influencing the creep behaviour of the material: in particular, in addition to the initial
339 elastic modulus, which influences the initial deformations of the lining, it is necessary to eval-
340 uate the final entity secondary deformations and in particular the ratio between the final sec-
341 ondary deformations and the initial deformations obtained at the end of the tunnel construction
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407

408 **FIGURE CAPTION**

409 **Fig. 1 Application of shotcrete**

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

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

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

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

428

429 **TABLE CAPTION**

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

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

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