

A numerical model to assess the creep of shotcrete linings

*Original*

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25 **Notation list**

26  $p_0$ : lithostatic pressure;

27  $p_{cr}$ : critical pressure;

28  $\varphi_p$ : peak friction angle of the rock mass;

29  $c_p$ : peak cohesion of the rock mass;

30  $R$ : tunnel radius;

31  $R_{pl}$ : plastic radius;

32  $c_r$ : residual cohesion of the rock mass;

33  $\varphi_r$ : residual friction angle of the rock mass;

34  $E_{rm}$ : elastic modulus of the rock mass;

35  $\nu$ : Poisson coefficient of the rock mass;

36  $E_i$ : elastic modulus of shotcrete at  $i$ th-step;

37  $t_{sc}$ : thickness of the shotcrete lining;

38  $\nu_{sc}$ : Poisson coefficient of the shotcrete;

39  $\varepsilon_t$ : total deformation;

40  $\sigma$ : applied load;

41  $E_\infty$ : elastic modulus of the shotcrete at infinity, when creep ceased;

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

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

44  $\eta$ : viscosity of the shotcrete;

45  $\Psi$ : dilatancy.

46

47 **Introduction**

48 Neville et al. (1983) define creep as the increase in strain with time under a sustained stress,  
49 i.e. the material deforms not only due to the stresses which it is subjected to, but also due  
50 over a time during which these stresses are applied. Normally creep strain are not fully re-  
51 covered, thus it is largely plastic deformation (Dusseault and Fordham, 1993). Goodman  
52 (1980) explains the creep as a viscous behavior. There are certain situations where strains  
53 increase with time. This is the case of tunnels excavated in very soft rock or heavily fractured  
54 rock under significant in-situ stresses (Yu, 1998; Dusseault and Fordham, 1993), in rocks of  
55 argillaceous nature (Barla, 2011), rock salts (Goodman,1980; Moghadam et al., 2013) or also  
56 due to the combination of the applied stress and material properties (exceeding a limiting  
57 shear stress), the geological conditions, the in situ stress conditions and the groundwater  
58 flow (Barla, 2001). For rocks containing clay, the phenomenon associated with water migra-  
59 tion (or clay platelets orientation) could be considered as a type of consolidation (Goodman,  
60 1980). However, the time-dependent behavior of rocks is normally not considered during  
61 tunnel design.

62 **Creep phenomenon in sprayed concrete**

63 Creep behavior is also very important in sprayed (or shot)concrete, SC (Thomas, 2009). For  
64 SC the principle of rheological models is the same as for rock (Thomas, 2009). Because SC  
65 linings are loaded at a very early age, the influence of time dependent material properties on  
66 the deformation behavior and bearing capacity is much more significant than in regular con-  
67 crete structures (Schädlich and Schweiger, 2014). Regarding creep of SC, movement of wa-  
68 ter from the adsorbed layers on the cement paste to internal void may be the cause of creep  
69 (Thomas, 2009) and this theory is supported by the fact that creep increases with increasing  
70 porosity (Neville, 1995).

71 Numerical models are massively employed to assess the creep behavior of SC linings (e.g.  
72 Yin, 1996; Schröpfer, 1995; Schädlich and Schweiger, 2014), such as rheological models  
73 (Jaeger and Cook, 1979), Kelvin model (Neville et al., 1983; Jaeger and Cook, 1979; Rokahr

74 and Lux, 1987), Burgers model (Yin, 1996), viscoplastic model (Thomas, 2009). However,  
75 real creep behavior of linings is hard to understand as the load-bearing mechanism is a  
76 composite consisting of the ground and the lining behavior. The current simplistic approach  
77 to model SC linings in numerical simulations considers a linear elastic material with a step-  
78 wise increase of the Young's modulus in subsequent excavation stages. While realistic lining  
79 deformations may be obtained with this method, lining stresses are usually too high, in par-  
80 ticular if the lining is subjected to significant bending (Schädlich and Schweiger, 2014).

81 According to (Huber, 1991, Neville et al., 1993, Thomas, 2009) creep of SC increases with  
82 humidity, cement content, increasing stress and decreasing strength. (Thomas, 2009) ob-  
83 served also that by increasing the proportion of aggregates the magnitude of creep is re-  
84 duced. Besides, the paste is also responsible for the creep. As a matter of fact, aggregate  
85 undergoes very little creep. However, the aggregate influences the creep of concrete through  
86 a restraining effect on the magnitude of creep. The paste which is creeping under load is  
87 restrained by aggregate which do not creep.

88 Cement on the other hand does not have an influence on the creep behavior; however creep  
89 increases with an increase in water/cement ratio (Akroyd, 1962). Concrete reinforcement  
90 (e.g. fibers) reduces creep phenomenon, presumably due to the restraining effect (Ding,  
91 1998).

92 Creep is significantly higher at an early stage of load as the strength of SC is lower, as found  
93 by (Huber, 1991) who observed that a sample loaded at 8 days creeps by 25% more than a  
94 similar sample loaded at 28 days. However, it must be kept in mind that some accelerators  
95 increase the early strengths (Melbye, 1994) therefore creep after 24 or 48 h is close to that at  
96 greater ages (Kuwajima, 1999). The stronger the aggregate the more is the restraining effect  
97 and hence the less is the magnitude of creep. However, synthetic fibers reinforced SC have  
98 twice the creep capacity than steel fibers reinforced SC (Thomas, 2009; MacKay and Trotti-  
99 er, 2004).

## 100 **The numerical model**

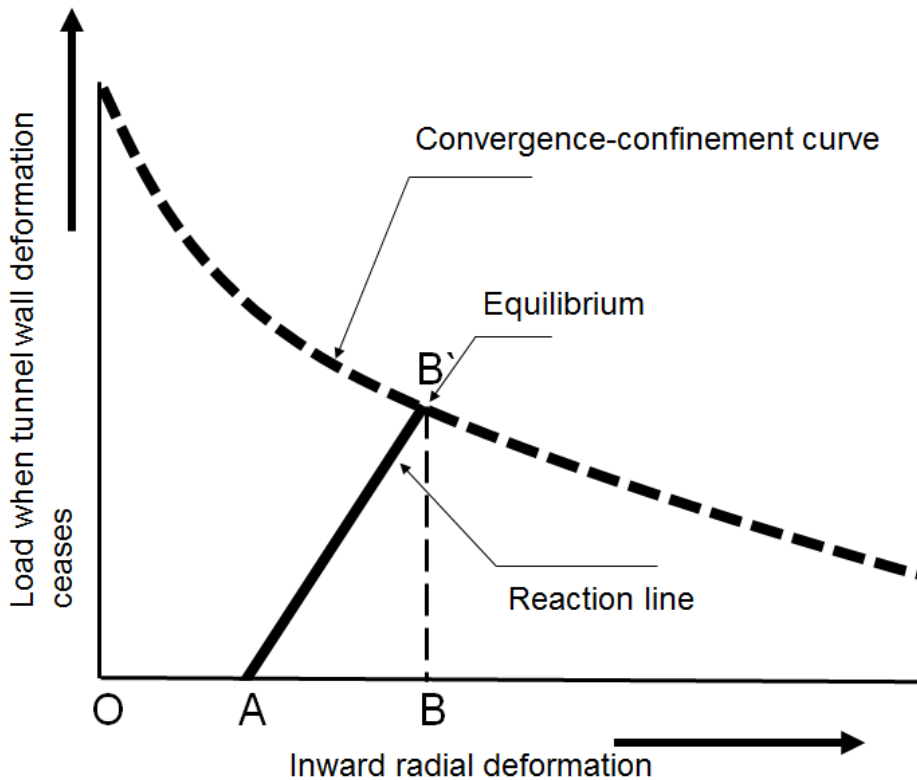
101 To study the behavior of the SC lining during the creep phases, a specific model has been  
102 developed. The method is based on the joint application of the CCM and HRM. With the  
103 CCM (Oreste, 2009; 2015; Spagnoli et al., 2016; 2017) it is possible to evaluate the initial  
104 load on the SC lining, through the intersection of the convergence-confinement curve (CCC)  
105 with the reaction line of the lining (see Fig. 1). To define the reaction line the initial elastic  
106 modulus of the SC ( $E_1$ ) is considered, before the creep starts. Once the initial load is evalu-  
107 ated, it is possible to obtain by means of the HRM the exact path of the stress inside the lin-  
108 ing at the initial condition. HRM investigates the behavior of SC lining under the loads applied  
109 by the rock mass and considering the interaction between the lining and the rock mass  
110 (Oreste, 2007, Do et al., 2014). The HRM models half of a tunnel section by beam elements  
111 connected by nodes. The elements develop bending moments, axial forces and shear forces.  
112 The interaction between ground and support is represented by “Winkler” type springs in the  
113 normal and tangential direction for each node of the model (Oreste et al., 2018).

114 The initial condition represents the situation at the end of the excavation and loading phases  
115 of the SC lining. Once the lining has been installed and is in full and effective contact with the  
116 ground, the support starts to deform as shown in Fig. 1. CCC qualitatively reflects the stress  
117 redistribution of the ground around the opening (Deere et al., 1970). The y-axis of Fig. 1 rep-  
118 resents the load that must be applied to the walls of the opening to prevent any further de-  
119 formation, whilst the x-axis is the tunnel wall convergence. OA represents the deformation  
120 occurring before the lining is installed. OB represents the deformation of the tunnel walls. AB  
121 is the deformation of the lining and BB' is the load in the support.

122 From this moment the analysis of the creep phenomenon starts, which evolve over the time.  
123 With the evolution of creep, SC shows a lower stiffness which implies an increase of the de-  
124 formation in the lining. Therefore, the displacement of the tunnel wall increases. The defor-  
125 mation due to the creep (i.e. secondary deformation), causes a decrease of the applied loads

126 at the lining leading to a great benefit as this can avoid overloading (Thomas, 2009). The  
127 specific model allows to consider two aspects:

- 128 • Higher deformation of the SC lining over time;
- 129 • Reduction of the loads on the lining due to the deformation and increase of the tunnel  
130 wall displacement;



131

132 Fig. 1 Simplified load-deformation diagram at the end of the excavation and loading phase of  
133 the SC lining. Keys: OA represents the deformation occurring before the lining is installed.  
134 OB represents the deformation of the walls of the tunnel; AB represents the deformation of  
135 the lining; BB' represents the load in the support.

136 In order to determine the stress and strain evolution of the lining over time (i.e. during the  
137 creep), it is important to define the apparent elastic modulus of the SC lining at the infinity  $E_{\infty}$ ,  
138 i.e. at the end of the creep. This value permits to draw a reaction line of the lining at the infini-  
139 tity, and therefore, to obtain the final load acting on the lining (i.e. lower than the initial load)

140 from the intersection of the new reaction line with CCC. The stiffness  $k$  of the circular lining is  
141 function of the elastic modulus of the SC and therefore (Fig. 2):

$$142 \quad k_{in} = \frac{R^2 - (R - t_{sc})^2}{(1 + \nu_{sc}) \cdot [(1 - 2 \cdot \nu_{sc}) \cdot R^2 + (R - t_{sc})^2]} \cdot \frac{1}{R} \cdot E_1 \quad (1)$$

$$143 \quad k_{fin} = \frac{R^2 - (R - t_{sc})^2}{(1 + \nu_{sc}) \cdot [(1 - 2 \cdot \nu_{sc}) \cdot R^2 + (R - t_{sc})^2]} \cdot \frac{1}{R} \cdot E_\infty \quad (2)$$

144 where:

145  $t_{sc}$  is the shotcrete lining thickness;

146  $\nu_{sc}$  is the Poisson coefficient of the SC;

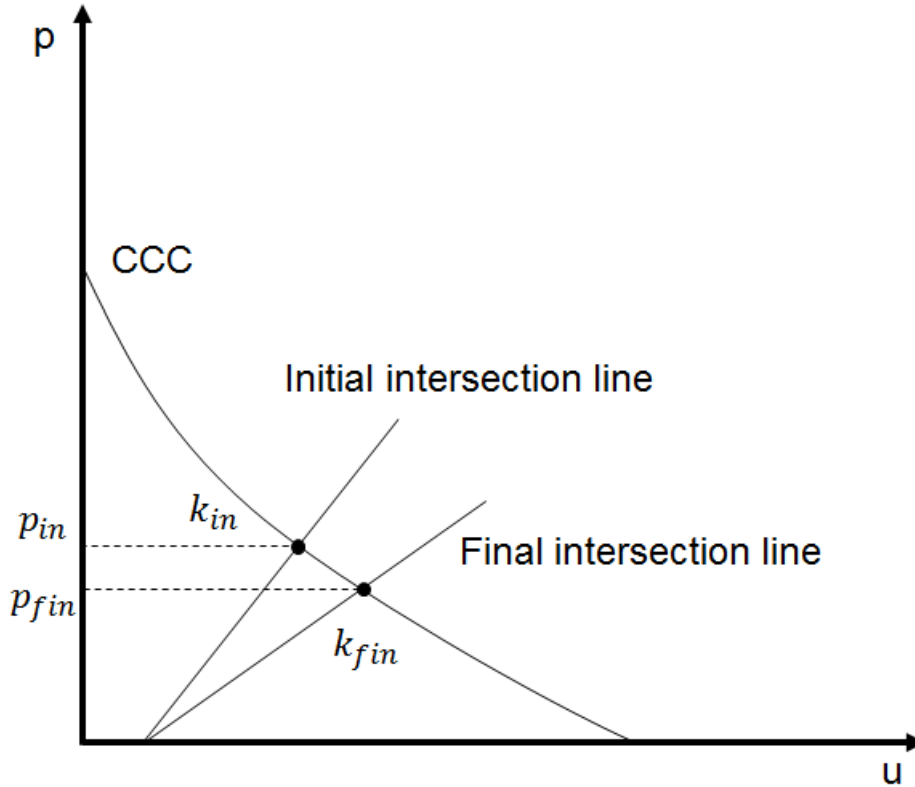
147  $E_1$  is the initial elastic modulus of the SC;

148  $E_\infty$  is the elastic modulus of the shotcrete at infinity, i.e. the creep ceased;

149  $k_{in}$  is the initial stiffness of the SC lining;

150  $k_{fin}$  is the final stiffness of the SC lining;

151  $R$  is the tunnel radius.



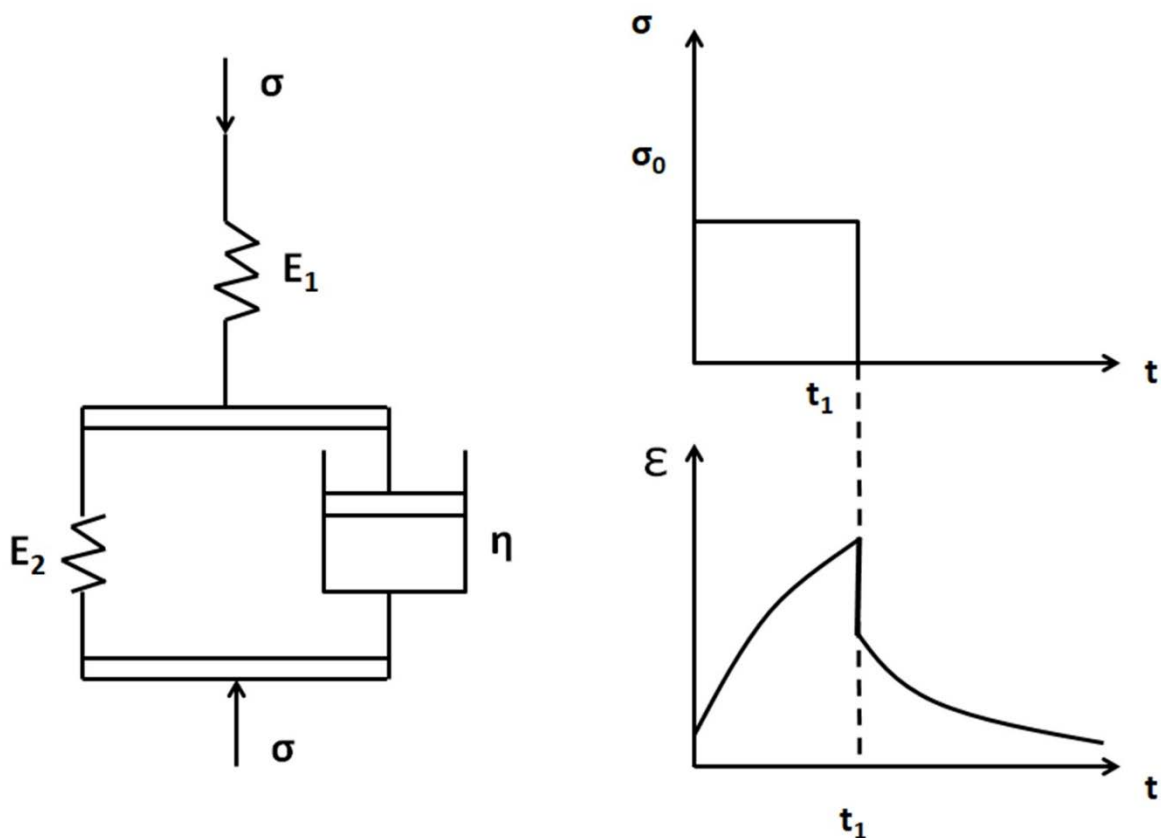
152

153 **Fig. 2 Evaluation of the initial and final load on the lining through the convergence-**  
 154 **confinement method. Key:  $p$  internal pressure of the tunnel;  $u$  radial displacement of**  
 155 **the tunnel wall;  $k_{in}$  and  $k_{fin}$  initial and final stiffness of the SC lining;  $p_{in}$  and  $p_{fin}$  initial**  
 156 **and final load on the SC lining; CCC convergence-confinement curve.**

157 The stress-strain analysis of the lining from the initial ( $t = 0$ ) to the final condition  $t = \infty$ ) is  
 158 performed, through different calculation steps, with the HRM. Each step considers the appli-  
 159 cation of a negative load  $\Delta p$  on the lining ( $\Delta p = (p_{fin} - p_{in})/n$ , where  $n$  is the step number) con-  
 160 nected to a particular value of the elastic modulus of the SC. The results of each calculation  
 161 steps, in terms of stress and strains in the SC, add to the situation resulting at the end of the  
 162 previous step. Knowing the value  $\Delta p$ , it is possible to graphically obtain the mean path of the  
 163 reaction line at each step (i) and the stiffness  $k_i$ . As the elastic modulus of the SC and the  
 164 stiffness of the lining are depending on each other, it is possible to obtain the mean elastic  
 165 modules  $E_i$  at each step:

166 
$$E_i = \frac{k_i \cdot (1 + \nu_{sc}) \cdot [(1 - 2 \cdot \nu_{sc}) \cdot R^2 + (R - t_{sc})^2] \cdot R}{R^2 - (R - s_{sc})^2} \quad (3)$$

167 For the determination of the time associated with the reduction of the elastic modulus of the  
 168 SC corresponding to each step, the viscosity  $\eta$  comes into play. To take into account the ef-  
 169 fect of the viscosity due to the creep phenomenon, the Voigt-Kelvin model, consisting of two  
 170 springs and a viscous damper, was used (see Fig. 3). Among the creep-models, the Voigt-  
 171 Kelvin model is one of the three most commonly used rheological models, along with Max-  
 172 well model and the Burgers model, for SC linings (Thomas, 2009). It exhibits an exponential  
 173 strain creep, i.e. it predicts very good creep and it assumes an uniform distribution of strain.  
 174 The material is modelled with a viscous-elastic response. It consists of a spring in series with  
 175 a parallel of another spring and a viscous damper.



176  
 177 **Fig. 3 Voigt-Kelvin creep model ( $\sigma$  is the applied load,  $E$  is the elastic modulus and  $\eta$  is**  
 178 **the viscosity coefficient,  $\epsilon$  is the deformation.**

179 Gradual recovery of elastic deformation occurs. The total deformation will be:

180  $\varepsilon_t = \frac{\sigma}{E_2} \cdot (1 - e^{-\frac{E_2 \cdot t}{\eta}}) + \frac{\sigma}{E_1}$  (4)

181 where:

182  $\varepsilon_t$  is the deformation over time;

183  $\sigma$  is the applied load;

184  $E$  is the elastic modulus;

185 In this case two different configurations have been adopted regarding secondary deformation.  
186

187 •  $\varepsilon_2 = \frac{1}{2} \frac{\sigma}{E_2}$  after t=3 years ( $\varepsilon_2$ , secondary deformation due to the parallel. After 3 years  
188 is half of the total secondary deformation);

189 •  $\varepsilon_2 = \frac{1}{3} \frac{\sigma}{E_2}$  after t=3 years ( $\varepsilon_2$ , secondary deformation due to the parallel. After 3 years  
190 is one-third of the total secondary deformation).

191 The law of the Voigt-Kelvin model is as follows:

192  $\varepsilon_t = \frac{\sigma}{E_2} \cdot (1 - e^{-\frac{E_2 \cdot t}{\eta}}) + \frac{\sigma}{E_1}$  (5)

193  $E_2$  is obtained as:

194  $\frac{1}{E_\infty} = \frac{1}{E_1} + \frac{1}{E_2}$  (6)

195 Therefore:

196  $E_2 = \frac{E_1 \cdot E_\infty}{E_1 - E_\infty}$  (7)

197 Considering:

198  $\varepsilon_2 = \frac{\sigma}{E_2} \cdot (1 - e^{-\frac{E_2 \cdot t}{\eta}})$  (8)

199 From the two different assumptions, i.e.  $\varepsilon_2$  half and one-third of the total secondary deformation,  
200 the viscosity value,  $\eta$ , can be obtained. For example, considering the case in which it

201 is assumed that the  $\varepsilon_2$  reaches half of the total value (at infinity) after a time  $t = 3$  years, it will  
 202 be:

$$203 \quad \varepsilon_{2(t=3)} = \frac{1}{2} \frac{\sigma}{E_2} = \frac{\sigma}{E_2} \cdot \left(1 - e^{-\frac{E_2 \cdot t}{\eta}}\right) \quad (9)$$

204 therefore:

$$205 \quad e^{-\frac{E_2 \cdot 3}{\eta}} = \frac{1}{2} \quad (10)$$

206 The viscosity,  $\eta$ , will be:

$$207 \quad \eta = \frac{-3 \cdot E_2}{\ln\left(\frac{1}{2}\right)} \quad (11)$$

208 For the model the value of the elastic modulus will be:

$$209 \quad E_t = \frac{1}{\frac{1}{E_1} + \frac{(1 - e^{-\frac{E_2 \cdot t}{\eta}})}{E_2}} \quad (12)$$

210 therefore:

$$211 \quad t = \frac{-\eta \cdot \ln\left[\left(\frac{E_2}{E_1} + 1 - \frac{E_2}{E_t}\right)\right]}{E_2} \quad (13)$$

212 The time associated with the decrease of the elastic modulus corresponding to the midpoint  
 213 of each of the 10 steps is thus obtained. With the proposed method it will be possible to con-  
 214 duct studies in terms of variations of normal and shear forces, rotation and bending mo-  
 215 ments. It is also possible to evaluate the decreases of the SC elastic modulus in each of the  
 216 10 calculation steps and the times associated to each step.

## 217 Numerical example

218 In the following examples, the calculation procedure previously explained was performed, in  
 219 order to verify creep effects on the static conditions over time of the SC lining. 10 calculation  
 220 steps ( $n=10$ ) were considered in order to describe the stress and strain state in the creep  
 221 phase. Each of the 10 calculation steps considers a decrease of the applied load  $\Delta p$ . For

222 each of them, a reaction line of the SC lining was obtained and from it the elastic modulus  
 223  $E_i$  and the corresponding time.

224 Five cases were considered to calculate the creep in SC linings. Cases 1, 2, 4 and 5 refer to  
 225 a rock with RMR = 30, whereas case 3 is for RMR = 60. These values were arbitrary select-  
 226 ed to have a broader range of rock types. For case 1,  $E_\infty = 75\% E_1$ , assumed with a second-  
 227 ary deformation after 3 years being one-half of the total deformation. The viscosity was cal-  
 228 culated as per equation 18. For case 2,  $E_\infty = 50\% E_1$  however the secondary deformation is  
 229 the same as for case 1. In case 3,  $E_\infty$  and the viscosity were the same as per case 1, how-  
 230 ever the rock was assumed to have better characteristics. In case 4,  $E_\infty$  is the same as per  
 231 case 1 and case 3, however viscosity was calculated as per equation 16 (i.e. secondary de-  
 232 formation after 3 years being one-third of the total deformation). Finally, in case 5,  $E_\infty$  is the  
 233 same as per case 2 but the secondary deformation is the same as per case 4.

234 *Case 1*

235 For the first four cases the rock mass properties are shown in Tab. 1.

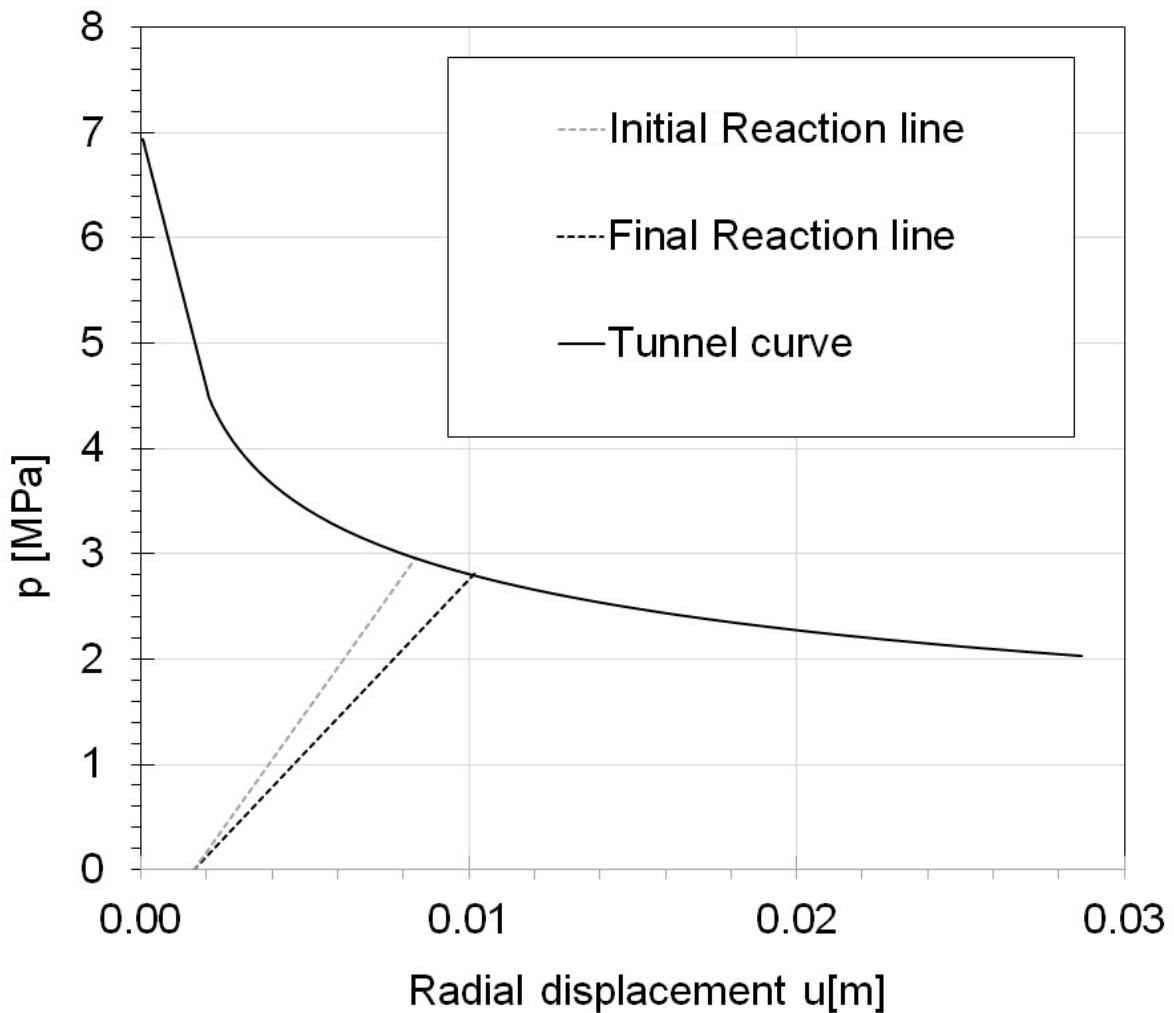
Rock parameter	Unity of measure	Value
Elastic modulus ( $E_{rm}$ )	[MPa]	3160
Coefficient of Poisson ( $\nu$ )	[-]	0.30
Peak cohesion ( $c_p$ )	[MPa]	0.15
Residual cohesion ( $c_r$ )	[MPa]	0.12
Peak friction angle ( $\varphi_p$ )	[°]	20
Residual friction angle ( $\varphi_r$ )	[°]	16

Dilatancy ( $\psi$ )	[°]	16
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236 **Tab. 1 Geomechanical parameters arbitrary assumed for the rock with RMR=30.**

237 For the construction of the characteristic curve and of the reaction lines of the initial and final  
 238 support (Fig. 4), the following assumptions were considered:

- 239 • the elastic module of the concrete  $E_1 = 8000 \text{ MPa}$ ;
- 240 • the elastic modulus of the concrete at infinity,  $E_\infty$ , for which in this first case a value  
 241 equal to  $E_\infty = 75\% E_1$  was adopted.



242

243 **Fig. 4 Case 1: Convergence-confinement curve of the tunnel and the initial and final**  
 244 **reaction line of the shotcrete lining.**

245 The characteristic curve thus obtained shows displacements in the order of centimeters.

246 Considering equations 6 and 7, we obtain:

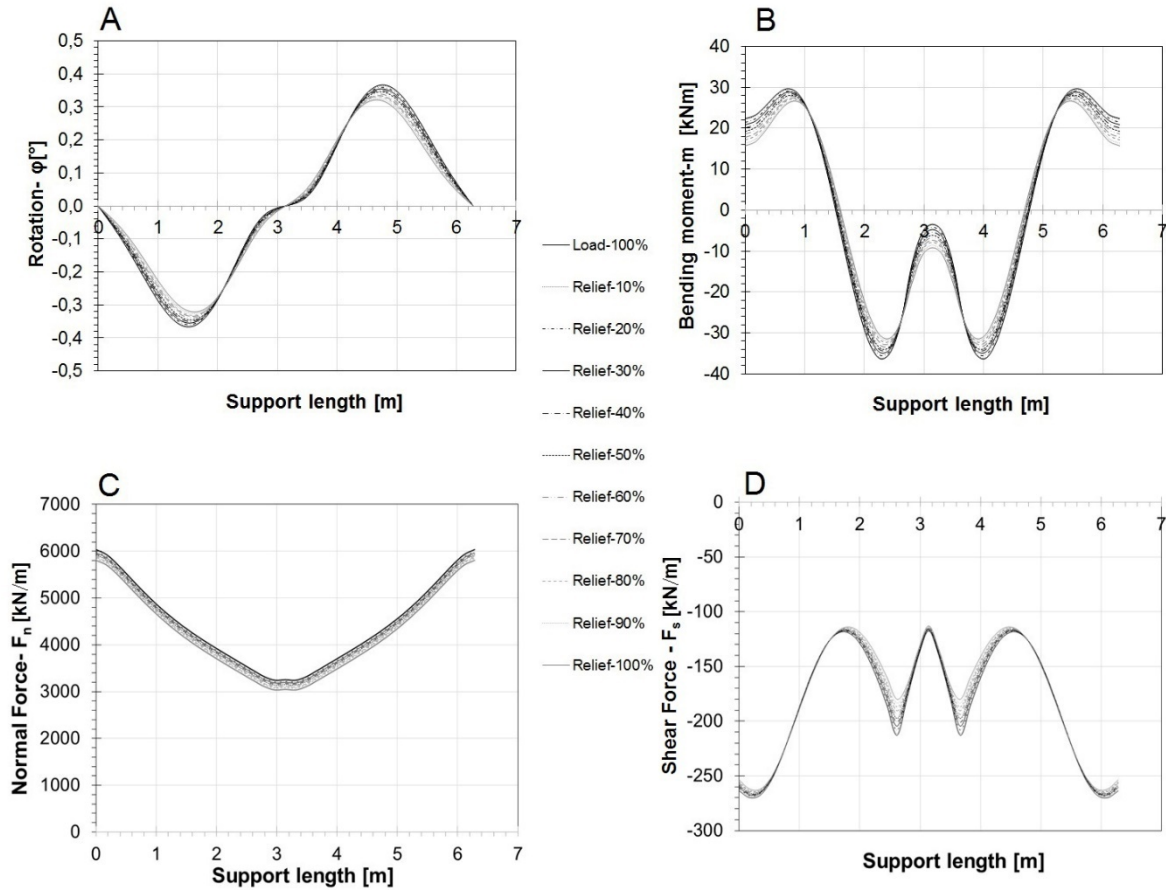
$$247 \quad E_{\infty} = \frac{3}{4} \cdot E_1 \quad (14)$$

248 Therefore,  $E_2 = 3 \cdot E_1 = 24000 \text{ MPa}$ .

249 To take into account the viscosity, it was assumed that after 3 years the secondary deformation is equal to one-third of the total deformation, and we will obtain:

$$251 \quad \eta = \frac{-3 \cdot E_2}{\ln(\frac{1}{2})} [\text{MPa/year}] \quad (15)$$

252 Results are obtained using described procedure with the hyperstatic reaction method, in  
253 terms of variations from the initial condition (when the tunnel is completed,  $t=0$ ), with black  
254 color, to the final condition (step  $i=10$ ,  $t=\infty$ ), with grey color, for rotation, bending moments,  
255 shear and normal forces along the tunnel profile inside the shotcrete lining (see Fig. 5). For  
256 reasons of simplicity, only half of the covering is shown, starting from the center of the invert  
257 up to the center of the cap crown.



258

259 **Fig. 5 Case 1: Results of rotation (A), bending moments (B), normal (C) and shear**  
 260 **forces (D) for case 1 along the lining profile.**

261 From case 1 it is possible to observe:

- 262 • Rotation tends to fade over time due to creep as well as bending moments that re-
- 263 duce more than normal forces. The resulting reductions, in terms of maximum in ab-
- 264 solute value, are the following:
- 265 ○ rotation: 12.33%;
- 266 ○ bending moments: 14.82%;
- 267 ○ normal forces: 3.83%;
- 268 ○ shear forces: 2.88%.

269 As regards the variations of the elastic modulus corresponding to each step and the respec-

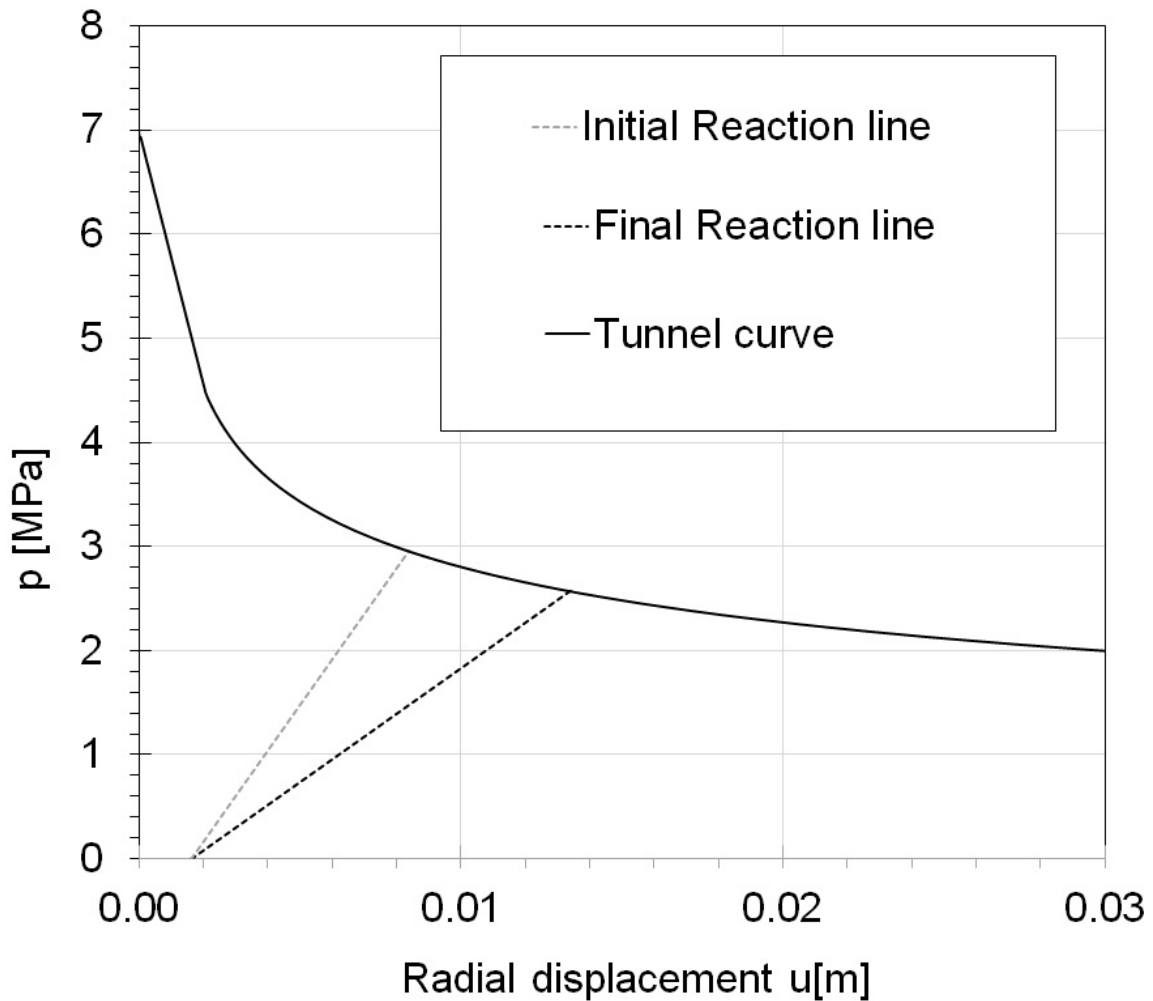
270 tive associated times, the results reported in Tab. 2 have been obtained.

Step	E shotcrete [MPa]	t [year]
1	7934.03	0.11
2	7763.18	0.42
3	7555.00	0.84
4	7347.53	1.34
5	7140.76	1.94
6	6934.70	2.67
7	6729.35	3.62
8	6524.72	4.91
9	6320.80	6.90
10	6117.59	11.10

271 **Tab. 2 – Case 1: variation of the elastic modulus of the SC over time during the creep**  
272 **process, according to the adopted mechanical scheme; time associated to each step,**  
273 **after the construction phase (initial condition).**

274 *Case 2*

275 In case 2, a different hypothesis was made regarding the value of  $E_{\infty}$ . It was assumed  
276  $E_{\infty} = 50\%E_1$ . The characteristic curve and the reaction lines of the lining will be different (Fig.  
277 6). The displacements will be slightly higher than for case 1 and the difference between the  
278 initial and final reaction lines will be more evident with respect to case 1.



279

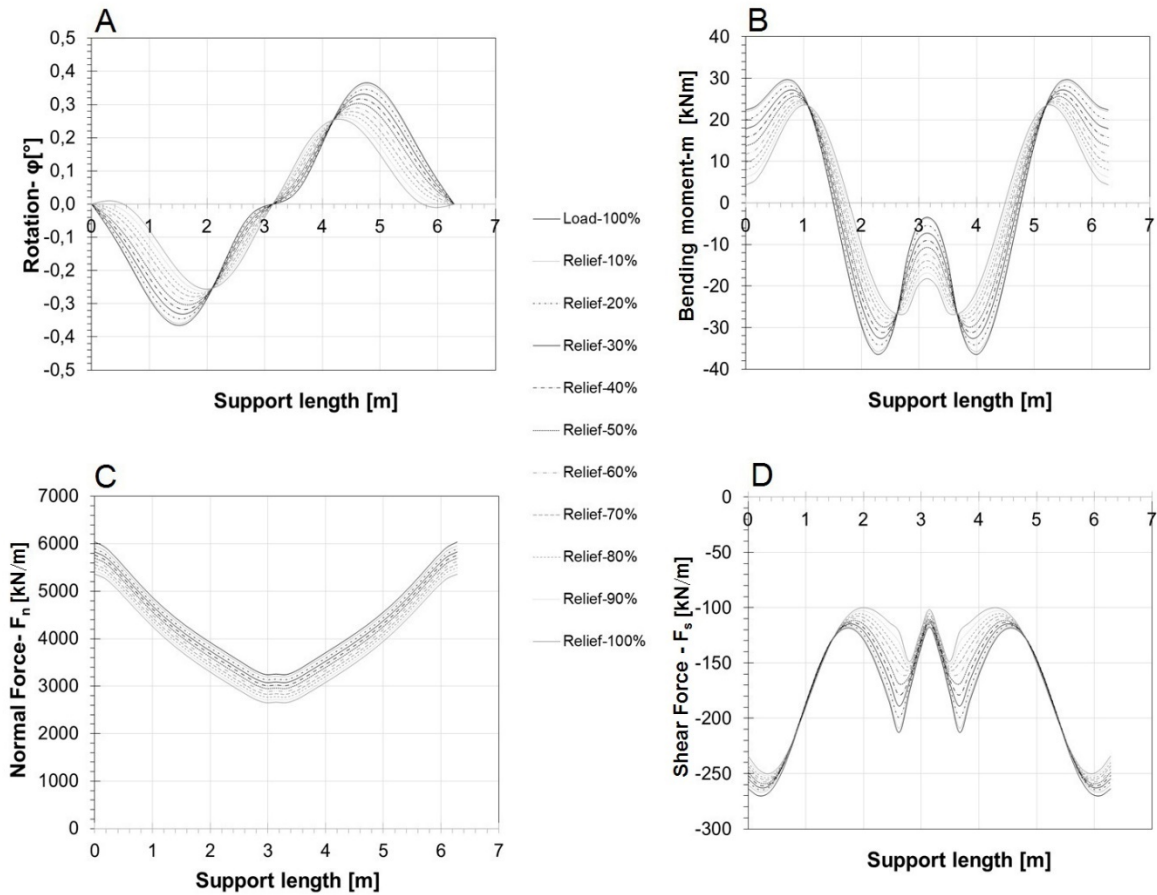
280 **Fig. 6 Case 2: Convergence-confinement curve of the tunnel and the initial and final**  
 281 **reaction line of the shotcrete lining.**

282 Changing the value of  $E_\infty$  will also change the value of  $E_2$ , which, as seen previously, de-  
 283 pends on  $E_1$  and  $E_\infty$ . Therefore,  $E_2 = E_1 = 8000 \text{ MPa}$ .

284 The trend of the rotation changes with respect to the previous case, but in this case also it  
 285 tends to attenuate over time due to the creep. Bending moments also diminish and decrease  
 286 more than normal forces. The resulting reductions, in terms of maximum in absolute value,  
 287 increase, and are as follows (Fig. 7):

- 288 • rotation: 30.13%;
- 289 • bending moments: 26.68%;
- 290 • normal forces: 11.20%;

291 • shear forces: 7.2%.



292

293 **Fig. 7 Case 2: Results of rotation (A), bending moments (B), normal (C) and shear**  
 294 **forces (D) for case 2 along the lining profile.**

295 As regards the variations of the elastic modulus corresponding to each step and the respec-  
 296 tive associated times, the results are reported in Tab. 3.

Step	E shotcrete [MPa]	t [year]
1	7638.99	0.66
2	7227.13	1.67
3	7068.87	2.18
4	6913.90	2.76
5	6762.14	3.45

6	6613.52	4.29
7	6467.98	5.37
8	6325.45	6.84
9	6185.87	9.17
10	6049.17	14.83

297 **Tab. 3 – Case 2: variation of the elastic modulus of the SC over time during the creep**  
298 **process, according to the adopted mechanical scheme; time associated to each step,**  
299 **after the construction phase (initial condition).**

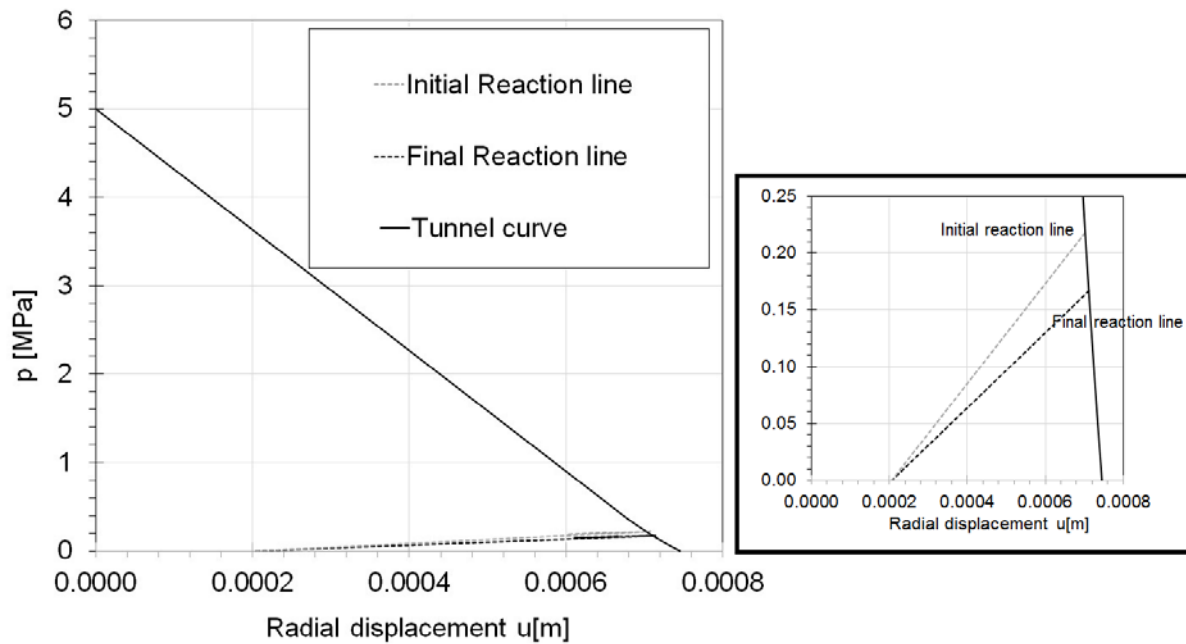
300 **Case 3**

301 In case 3 the same parameters adopted in case 1 are used, but a different type of rock mass  
302 with better mechanical characteristics is assumed, i.e. with RMR = 60. The geomechanical  
303 parameters of the rock mass are illustrated in Tab. 4.

<b>Rock parameter</b>	<b>Unity of measure</b>	<b>Value</b>
Elastic modulus ( $E_{rm}$ )	[MPa]	17780
Coefficient of Poisson ( $\nu$ )	[-]	0.30
Peak cohesion ( $c_p$ )	[MPa]	2
Residual cohesion ( $c_r$ )	[MPa]	2
Peak friction angle ( $\varphi_p$ )	[°]	37
Residual friction angle ( $\varphi_r$ )	[°]	37
Dilatancy ( $\psi$ )	[°]	16

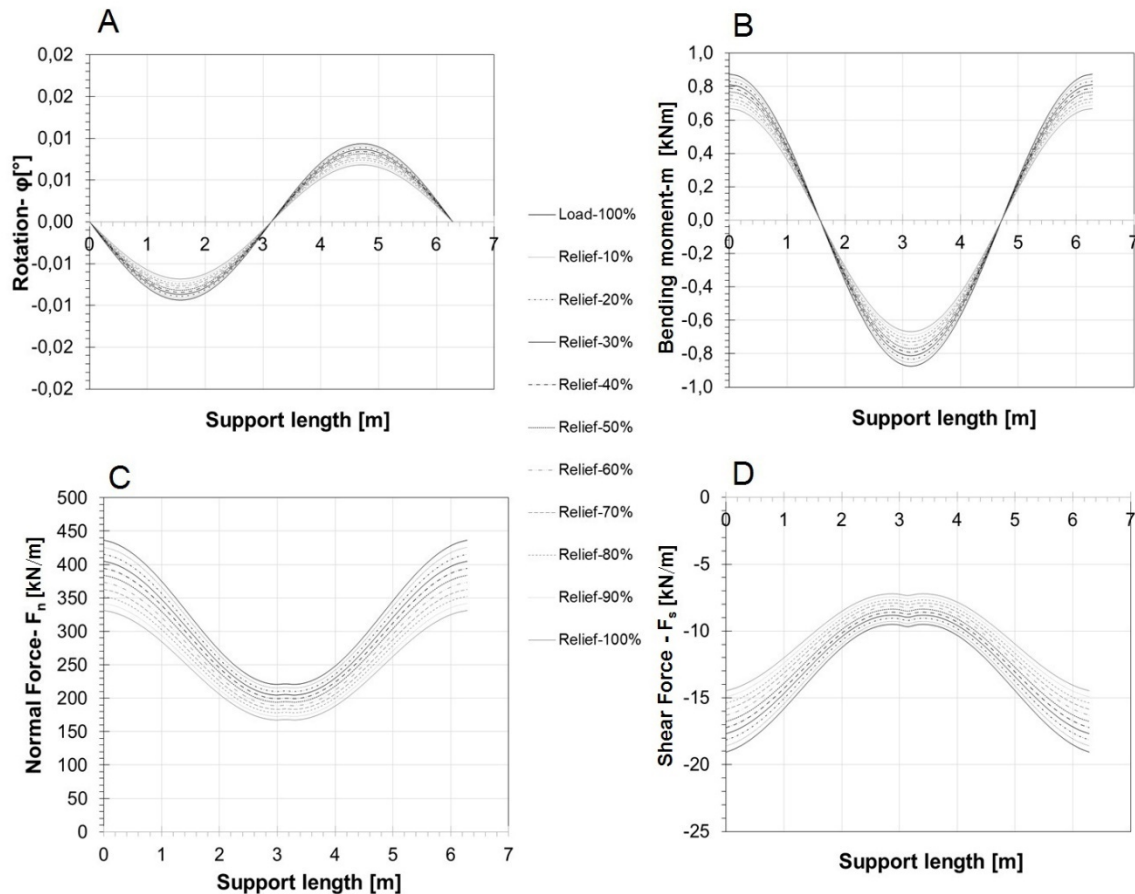
304 **Tab. 4 Geomechanical parameters arbitrary assumed for the rock with RMR=60.**

305 A new convergence-confinement curve will be obtained, which will show considerably re-  
306 duced displacements of the tunnel wall for the best rock mass quality (Fig. 8).



308 **Fig. 8 Case 3: Convergence-confinement curve of the tunnel and the initial and final**  
309 **reaction line of the shotcrete lining (with enlargement on the right side).**

310 The variations in the stress-strain state of the lining, from the initial condition to the final con-  
311 dition, are shown in Fig. 9.



312

313 **Fig. 9 Case 3: Results of rotation (A), bending moments (B), normal (C) and shear**  
 314 **forces (D) for case 3 along the lining profile.**

315 The rotation changes course; however, it tends to decrease over time due to creep. Bending  
 316 moments also diminish and there is a greater attenuation of normal forces and shear forces  
 317 for this case. The resulting percentage reductions, in terms of maximum in absolute value,  
 318 are the following:

- 319 • rotation: 27.66%;
- 320 • bending moments: 23.34%;
- 321 • normal forces: 24.08%;
- 322 • shear forces: 24.08%.

323 As regards the variations of the elastic modulus corresponding to each step and the respec-  
 324 tive associated times, the results are reported in Tab. 5.

Step	E shotcrete [MPa]	t [year]
1	7474.58	0.32
2	6785.17	0.85
3	6362.81	1.29
4	5965.19	1.81
5	5590.82	2.44
6	5238.32	3.24
7	4906.40	4.31
8	4593.85	5.85
9	4299.54	8.53
10	6049.17	19.46

325 **Tab. 5 - Case 3: variation of the elastic modulus of the SC over time during the creep**  
326 **process, according to the adopted mechanical scheme; time associated to each step,**  
327 **after the construction phase (initial condition).**

328 Fig. 10 shows the trends in the variation of the elastic modulus of concrete over time for the 3  
329 proposed cases as well as for other two cases:

- 330 • case 4 has a different viscosity while for  $E_{\infty}$  it is assumed again that it is equal to  
331 75%  $E_1$ . Viscosity for case 4 is:

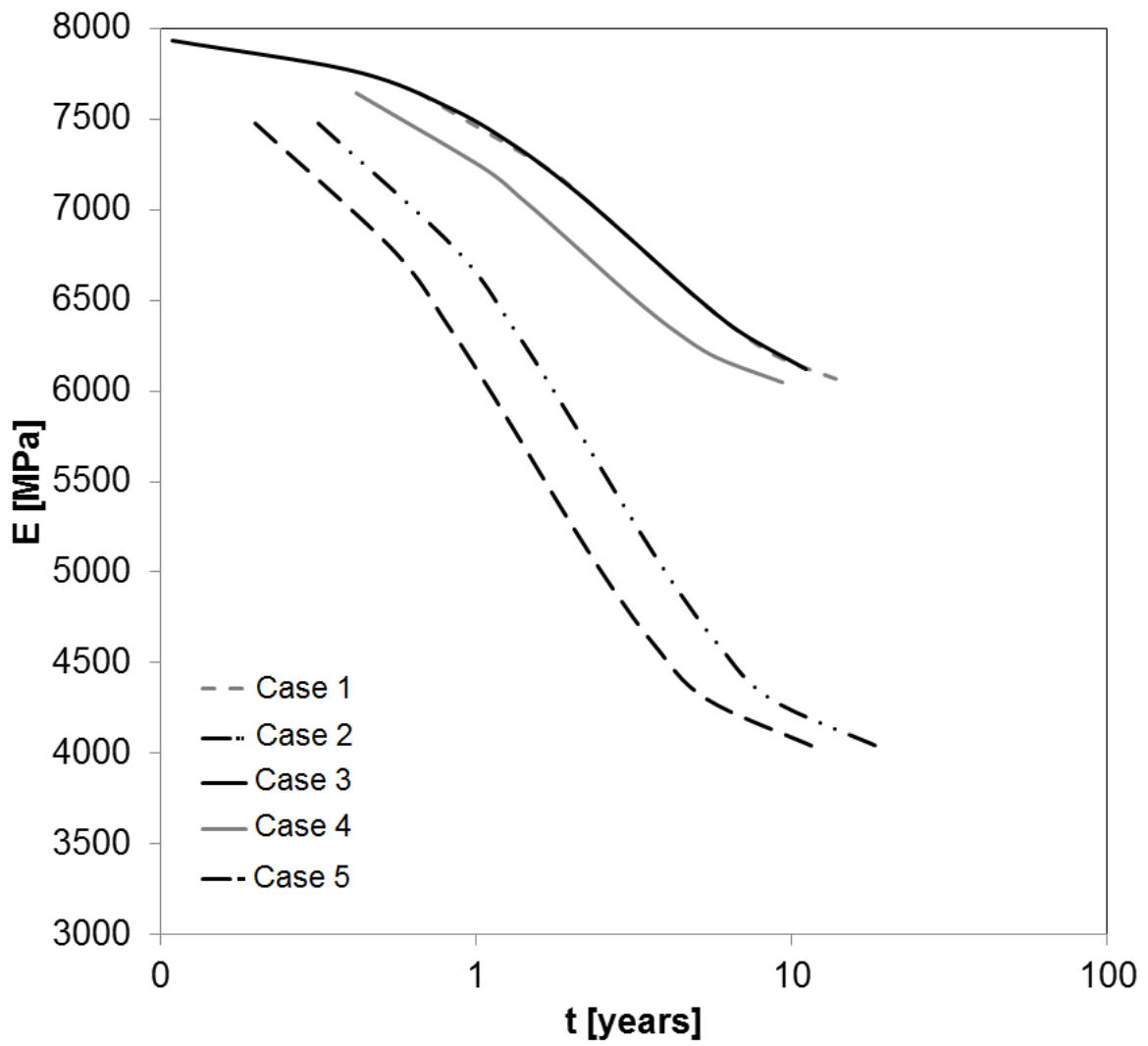
$$332 \quad \eta = \frac{-3 \cdot E_2}{\ln\left(\frac{1}{3}\right)} \quad (16)$$

333 The characteristic curve and the graphs related to the variations of rotation, normal  
334 and shear nodal displacements, bending moments, normal and shear forces are the  
335 same as in case 1. The only difference with respect to case 1 is regarding the times  
336 associated with each step and, therefore, in the development rate of secondary de-  
337 formations during the creep phase.

338 • case 5 has an elastic modulus  $E_{\infty} = 50\% \cdot E_1$  and a viscosity based on the assump-  
339 tion that the secondary deformation is equal to one third of the total secondary defor-  
340 mation after three years; in this case the two changes made in cases 2 and 4 are  
341 combined. The results obtained will coincide with case 2 as regards the convergence-  
342 confinement curve and the graphs related to rotation variations, bending moments,  
343 normal and shear forces, while the times associated to each step and with the mod-  
344 ule decreasing will change again (not shown).

345 The curves of the cases 1, 2, 4 and 5 are linked by the same  $E_{\infty}$  but have different viscosi-  
346 ties and the pattern changes.

347 The curves characterized by the lower viscosity (case 2 and 5) and therefore by a faster  
348 creep show a trend of the elastic modulus which decreases more rapidly and each step is  
349 reached in a shorter time. The lines are obtained considering for each case 10 steps to simu-  
350 late the creep process.



351

352 **Fig. 10 Variation over the time of the elastic modulus  $E$  of the SC for the proposed**  
 353 **cases.**

354 Tab. 6 summarizes the results obtained in the numerical examples in terms of rotation, bend-  
 355 ing moment, normal and shear forces, in the initial and final conditions.

Rotation [°]	Max		Min	
	Initial value	Final value	Initial value	Final value
Case 1	0.365	0.320	-0.365	-0.320
Case 2	0.365	0.255	-0.365	-0.255

Case 3	0.0094	0.0068	-0.0094	-0.0068
Case 4	0.365	0.320	-0.365	-0.320
Case 5	0.365	0.255	-0.365	-0.255
<b>Internal bending moments [kN·m]</b>	<b>Initial value</b>	<b>Final value</b>	<b>Initial value</b>	<b>Final value</b>
Case 1	29.68	26.49	-36.43	-31.03
Case 2	29.68	23.55	-36.43	-26.71
Case 3	0.874	0.67	-0.874	-0.67
Case 4	29.68	26.49	-36.43	-31.03
Case 5	29.68	23.55	-36.43	-26.71
<b>Internal normal forces [kN/m]</b>	<b>Initial value</b>	<b>Final value</b>	<b>Initial value</b>	<b>Final value</b>
Case 1	6037.40	5805.82	3243.93	3034.33
Case 2	6037.40	5360.80	3243.93	2651.96
Case 3	436.46	331.35	220.64	167.51
Case 4	6037.40	5805.82	3243.93	3034.33
Case 5	6037.40	5360.80	3243.93	2651.96
<b>Internal shear forces [kN/m]</b>	<b>Initial value</b>	<b>Final value</b>	<b>Initial value</b>	<b>Final value</b>
Case 1	-117.67	-112.80	-269.88	-262.10
Case 2	-117.67	-100.60	-269.88	-250.21
Case 3	-9.51	-7.22	-19.06	-14.47
Case 4	-117.67	-112.80	-269.88	-262.10

Case 5	-117.67	-100.60	-269.88	-250.21
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356 **Tab. 6 Variation of the maximum and minimum values for rotation, bending moments,**  
357 **normal and shear forces in the initial and final conditions.**

358 From the analysis of the results obtained, it is possible to see how the creep phenomenon on  
359 the SC used as a tunnel support produces a reduction of the bending moments, normal and  
360 shear forces over time. This phenomenon is generally more evident on bending moments,  
361 compared to normal and shear forces. When secondary deformations are important, i.e.  
362 when the creep is very evident, a more pronounced reduction of the normal and shear forces  
363 is also noted. In rock masses of good geomechanical qualities, the reduction of normal and  
364 shear forces are in percentage comparable with the reduction observed for bending mo-  
365 ments.

366 These considerations turn out to be useful in the design phase of the support structure. In  
367 fact, when it is necessary to ensure the achievement of long-term lining safety factors, it is  
368 possible to take into account the creep phenomenon of the SC. This phenomenon, producing  
369 a decrease in the stress state of tunnel linings, makes it possible to increase the safety factor  
370 over time, until the final asymptotic value relative to the final situation is reached.

### 371 **Conclusions**

372 The combined analysis HRM-CCM allowed to analyze the behavior of the SC linings in the  
373 tunnel, obtaining information on the moments, normal and shear forces. The secondary de-  
374 formation effects over time due to creep were taken into account in this paper, using the  
375 Voigt-Kelvin model. A new procedure has been developed, which is able to analyze the  
376 stress and strain state of a SC lining during the creep phase, considering the reduction of the  
377 loads applied to the support and the increase in the deformation of the SC over time. The  
378 analysis carried out showed that in the studied rock masses the creep has beneficial effects  
379 on the SC lining with a reduction of the stress state; in particular, in the case of the rock  
380 mass with good geomechanical quality the reduction in percentage of the normal and shear

381 forces is substantial and comparable to the bending moment reduction. This is not the case  
382 for the rock mass with lower geomechanical quality, for which the shear and normal forces in  
383 the lining show a negligible reduction due to the creep phenomenon, while the bending mo-  
384 ment still remains to an high level.

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459

460 **FIGURE CAPTION**

461 **Fig. 1 Simplified load-deformation diagram at the end of the excavation and loading**  
462 **phase of the SC lining. Keys: OA represents the deformation occurring before the lin-**  
463 **ing is installed. AA' represents the loads in an incompressible support; OB represents**  
464 **the deformation of the walls of the tunnel; AB represents the deformation of the lining;**  
465 **BB' represents the load in the support (modified after Deere et al., 1970).**

466 **Fig. 2 Evaluation of the initial and final load on the lining through the convergence-**  
467 **confinement method. Key:  $p$  internal pressure of the tunnel;  $u$  radial displacement of**  
468 **the tunnel wall;  $k_{in}$  and  $k_{fin}$  initial and final stiffness of the SC lining;  $p_{in}$  and  $p_{fin}$  initial**  
469 **and final load on the SC lining; CCC convergence-confinement curve.**

470 **Fig. 3 Voigt-Kelvin creep model ( $\sigma$  is the applied load,  $E$  is the elastic modulus and  $\eta$  is**  
471 **the viscosity coefficient,  $\varepsilon$  is the deformation.**

472 **Fig. 4 Case 1: Convergence-confinement curve of the tunnel and the initial and final**  
473 **reaction line of the shotcrete lining.**

474 **Fig. 5 Case 1: Results of rotation (A), bending moments (B), normal (C) and shear**  
475 **forces (D) for case 1 along the lining profile.**

476 **Fig. 6 Case 2: Convergence-confinement curve of the tunnel and the initial and final**  
477 **reaction line of the shotcrete lining.**

478 **Fig. 7 Case 2: Results of rotation (A), bending moments (B), normal (C) and shear**  
479 **forces (D) for case 2 along the lining profile.**

480 **Fig. 8 Case 3: Convergence-confinement curve of the tunnel and the initial and final**  
481 **reaction line of the shotcrete lining (with enlargement on the right side).**

482 **Fig. 9 Case 3: Results of rotation (A), bending moments (B), normal (C) and shear**  
483 **forces (D) for case 3 along the lining profile.**

484 **Fig. 10 Variation over the time of the elastic modulus  $E$  of the SC for the proposed**  
485 **cases.**

486

487 **TABLE CAPTION**

488 **Tab. 1 Geomechanical parameters arbitrary assumed for the rock with RMR=30.**

489 **Tab. 2 – Case 1: variation of the elastic modulus of the SC over time during the creep**  
490 **process, according to the adopted mechanical scheme; time associated to each step,**  
491 **after the construction phase (initial condition).**

492 **Tab. 3 – Case 2: variation of the elastic modulus of the SC over time during the creep**  
493 **process, according to the adopted mechanical scheme; time associated to each step,**  
494 **after the construction phase (initial condition).**

495 **Tab. 4 Geomechanical parameters arbitrary assumed for the rock with RMR=60.**

496 **Tab. 5 - Case 3: variation of the elastic modulus of the SC over time during the creep**  
497 **process, according to the adopted mechanical scheme; time associated to each step,**  
498 **after the construction phase (initial condition).**

499 **Tab. 6 Variation of the maximum and minimum values for rotation, bending moments,**  
500 **normal and shear forces in the initial and final conditions.**