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1 **The elastic modulus variation during the shotcrete curing jointly investigated by the**
2 **convergence-confinement and the hyperstatic reaction methods**

3 Pierpaolo Oreste¹, Giovanni Spagnoli², Cesar Alejandro Luna Ramos³

4 ¹ Department of Environmental, Land and Infrastructural Engineering, Politecnico di Torino, Corso
5 Duca Degli Abruzzi 24, 10129 Torino, Italy, ORCID: 0000-0001-8227-9807

6 ² BASF Construction Solutions GmbH, Dr.-Albert-Frank-Straße 32, 83308 Trostberg, Germany,

7 Phone: +49 8621 86-3702, <http://orcid.org/0000-0002-1866-4345>, E-mail:

8 giovanni.spagnoli@basf.com (corresponding author)

9 ³ Faculty of Engineering, Universidad Mariana, Calle 18 No. 34-104 Pasto, Colombia,

10 celuna@umariana.edu.co

11 **ABSTRACT**

12 Induced stresses in sprayed concrete (or shotcrete) are quite complex to evaluate and depend on
13 many factors such as the size and depth of the tunnel, the geomechanical characteristics of the
14 surrounding ground in which the tunnel is excavated, the type of shotcrete, the evolution of its
15 mechanical parameters over time and the excavation face advance rate. In particular, the
16 evolution of the mechanical properties of the shotcrete is crucial regarding the interaction with the
17 tunnel wall and the development of the bending moments and the normal forces which occur
18 along the circumference of the lining. In this research, a new calculation procedure based on the
19 combined use of two calculation methods the Convergence Confinement Method (CCM) and the
20 Hyperstatic Reaction Methods (HRM) is presented. Thanks to this procedure, it is possible to
21 progressively apply the load acting on the lining as the curing phase of the concrete progresses
22 and therefore with the evolution of its mechanical parameters. This procedure has been applied
23 to several examples of calculation, obtaining useful considerations regarding the mechanical
24 behavior of the shotcrete lining when some fundamental parameters of the calculation change. As
25 it is possible to achieve bending moments and forces in the lining with the progress of the load
26 steps. It is also possible to determine the trend of the lining safety factor over time and at the end

27 of the loading phase, allowing a proper design of the support, with particular attention to the type
28 of shotcrete and the thickness of the lining.

29 **Keyword:** Hyperstatic reaction method; Convergence confinement method; lining; shotcrete;
30 rock; curing

31 **NOTATION LIST**

32	A	Area of the lining section
33	E_{rm}	Elastic modulus of the rock mass
34	$E_{,mean}$	Mean value of the elastic modulus of shotcrete
35	$E_{,t}$	Elastic modulus of shotcrete at the time t
36	$E_{,0}$	Value of the asymptotic elastic modulus of the shotcrete, for $t = \infty$
37	$\{F\}$	Nodal forces applied to the numerical model
38	J_z	Moment of inertia of the lining section
39	K	Global stiffness matrix
40	k_i	Local stiffness matrix of the element i ;
41	K_n	Normal stiffness of the interaction spring in the node of the model
42	K_0	Lateral earth pressure
43	K_s	Shear stiffness of the interaction spring in the node of the model
44	l	Length of the one-dimensional element
45	M	Bending moment
46	N	Normal force
47	p	Internal tunnel pressure
48	p_{cr}	Critical pressure at the limit between the elastic and the plastic behavior
49	p_{fict}	Fictitious internal tunnel pressure
50	p_0	Lithostatic pressure
51	R	Tunnel radius
52	r	Generic radial coordinate
53	$\{S\}$	Vector of nodal displacements
54	T	Shear force
55	t_0	Final installation time of the support
56	u	Tunnel wall radial displacement
57	ν	Poisson's ratio
58	α	Time constants (t^{-1}) of the curing equation for the elastic modulus
59	α_i	Angle of inclination of the element i th with respect to the horizontal
60	ϕ	Rotation of the element in correspondence to the nodes

61	δ	Advance step
	δn	nodal normal displacement between the structure and the rock mass
	δs	shear displacement between the structure and the rock mass
62	$\sigma_{c,t}$	Unconfined compressive strength for the shotcrete at the time t .
63		

64 **INTRODUCTION**

65 Sprayed concrete or shotcrete (SC) is pumped under pressure through a pneumatic hose and
66 projected into place at high velocity (30 to 50 m/s), which is compacted and finally cures (DIN
67 18551, 1992; Thomas, 2009; Hemphill, 2013), see Fig. 1.

68 Because SC compared with ordinary concrete has a shorter setting time and high early age
69 mechanical properties (Wang et al., 2015), it is normally used for solving stability problems in
70 tunnels and other underground constructions such as mines, hydropower projects and slope
71 stabilization (e.g. Melby, 1994). SC can be employed for temporary and permanent supports.
72 However, regarding the design and construction of modern tunnels, SC single layer lining is
73 becoming the trend of future development (Franzen et al., 2001). With SC as permanent final
74 lining, long-term performance requirements, such as good bonding, high final density,
75 compressive strength and chemical resistance, have to improve (Melby, 1994).

76 SC mechanical properties are influenced by its components such as cement, microsilica,
77 aggregates, plasticizers, accelerators and fibers (Melby, 1994; Thomas 2009). Accelerators are
78 particularly important in their selection as the use of SC in underground constructions requires the
79 compliance with early age strength and the possibility of being employed in thick layers without
80 the risk of detachments and movements (Prudencio, 1998).

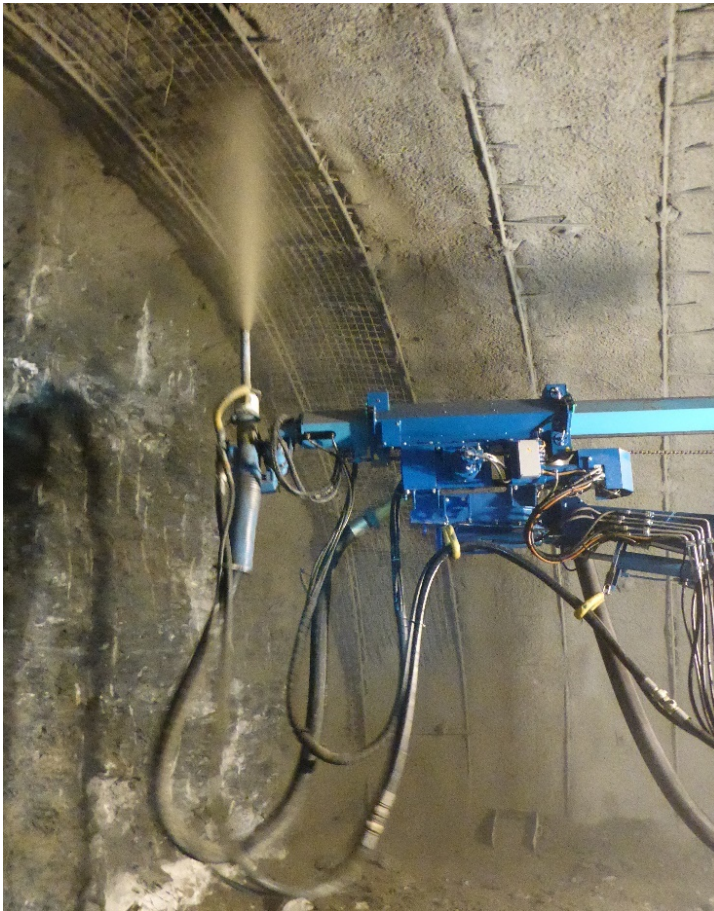
81 The early-age strength of SC is frequently more important than its ultimate strength. The advance
82 speed of tunnel operations is strongly influenced by the rate of development of early-age
83 strength, since it determines, both in soft ground and weak rock, when the excavation face can
84 proceed again. As a matter of fact, re-entry is mainly influenced by the tunnel drive progression to
85 ensure the safety of personnel to continue development (Mohajerani et al., 2015). Re-entry times
86 range from 2 to 4 hours, where the Unconfined Compressive Strength (UCS) of the SC reaches
87 1MPa (Clements, 2004; Concrete Institute of Australia, 2010), however, this value is not
88 standardized and it can be also lower, if safety is ensured (see Rispin et al., 2009). Iwaki et al.
89 (2001) empirically determined that an UCS of 0.5–1MPa should be an adequate strength for SC
90 to protect against rock-fall, although the safe re-entry times, based on strength measurements, is
91 still determined on project basis (Mohajerani et al., 2015).

92 Because coring should not take place until an UCS value of at least 5MPa (Clements, 2004), or
93 between 8–10MPa, as Jolin and Beaupré (2003) suggest, the assessment of strength
94 improvement is normally indirectly performed by means of the J-curves method for minimum
95 strength (DIN EN 14487-1, 2006) by using the needle penetration method up to 1MPa strength
96 (DIN EN 14488-2, 2006) and the stud driving method between 1 and 56 MPa strength (DIN EN
97 14488-2, 2006; ÖVBB, 2006). Conventional compressive strength tests on cored samples are
98 only performed from UCS from 5 to 100MPa according to the DIN EN 12504-1 (2009).

99 After the SC application, with the restart of the tunnel excavation, the lining load phase starts.
100 This loading phase occurs during the curing of the SC when the mechanical characteristics
101 (strength and stiffness) vary over time at a certain rate. Each load step, due to each excavation
102 face advance, produces different effects on the lining, due to the different stiffness and strength of
103 the SC. The final tensional state and, therefore, the final conditions of the lining are the ultimate
104 result of this complex loading mechanism due to the excavation face advance (while the SC
105 cures) and the corresponding variations in its mechanical characteristics (Oreste, 2003).

106 The Converge Confinement Method (CCM) and the Hyperstatic Reaction Method (HRM) have
107 been used in this paper to study in detail the behavior of the tunnel support under external loads
108 with increasing elastic modulus values of SC simulating the curing effect. CCM generally requires
109 a mean stiffness of the SC lining to obtain the support reaction line (Oreste, 2003). In this
110 research, the reaction line of the SC lining is considered as curve, in order to simulate the curing
111 effect of the SC during the loading phase of the support. CCM was useful to evaluate the
112 magnitude of the various loading steps developing over time during the excavation face advance.
113 In the HRM the interaction between ground and support is represented by Winkler type springs.
114 This method permits to determine the displacement of the lining and the developed bending
115 moments and forces in order to design it (Oreste, 2007; Do et al. 2014a; 2014b). In the specific
116 case, at the HRM model different loading steps, obtained with the CCM, have been applied,
117 considering in each of these steps the effective stiffness value reached by the SC and hence by
118 the support. Due to the results obtained with the combined analysis of the two calculation
119 methods, it was possible to obtain a detailed evaluation of the stress state of the support, which

120 can consider both the effect of the characteristics of the SC employed (with the evolving curve of
121 strength and stiffness with time) and the advance rate of the excavation face.



122

123 **Fig. 1 Spraying the tunnel roof with the shotcrete spraying machine (picture courtesy**
124 **Roland Mayr, BASF)**

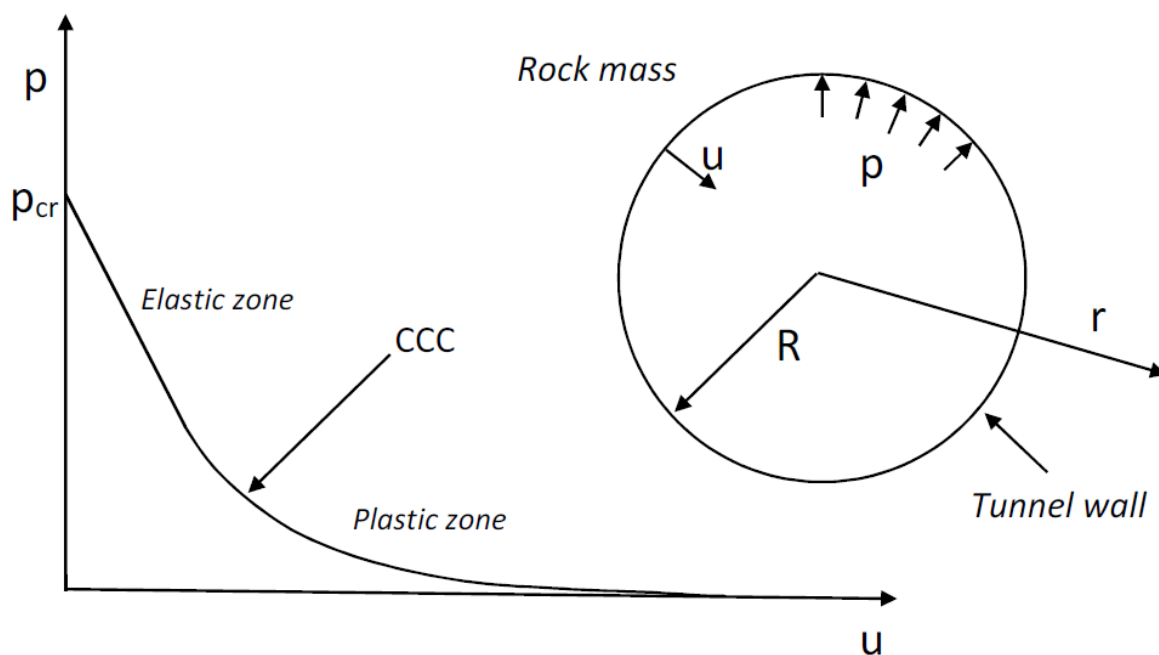
125 **NUMERICAL MODEL**

126 The numerical procedure developed to obtain a detailed analysis of the stress and strain state of
127 a SC lining tunnel **presented in this paper can be studied easily by a combined analysis of CCM**
128 **and HRM.** The necessary calculation parameters are as follows: mechanical parameters of the
129 rock, tunnel radius, lithostatic stress state at the corresponding depth, lining thickness, evolving
130 curve of the strength and stiffness of the SC over the time, the advance rate of the excavation
131 face and the frequency and duration of the excavation operation stand still, to allow the support
132 installation and other operations on the site.

133 The CCM is based on the analysis of the stress and strain state that develops in the rock around
134 a tunnel. The simplicity of the method is due to the important hypotheses on which it is based
135 (e.g. Oreste, 2009; 2014; Spagnoli et al., 2017):

- 136 • Circular and deep tunnels (boundary conditions of the problem to infinity);
- 137 • Lithostatic stresses of a hydrostatic type and constant in the surrounding medium of the
138 tunnel (the variation of the stresses with depth due to the weight of the rock is neglected);
- 139 • Continuous, homogeneous and isotropic rock mass;
- 140 • Bi-dimensional problem and plane stress field.

141 CCM consists of the definition of the convergence-confinement curve (CCC), that is the
142 relationship between the internal pressure and the radial displacement ($p - |u|$) on the boundary
143 of the tunnel represented by a circular void (Oreste, 2009), see Fig. 2.



144
145 **Fig. 2: Convergence-confinement method: Geometry of the problem and example of a**
146 **convergence-confinement curve. Key: p : Internal tunnel pressure, R : Tunnel radius, r :**
147 **Radial coordinate, u : Radial displacement of the tunnel wall, p_{cr} : Critical pressure**
148 **(modified by Oreste, 2009).**

149 Along with the CCC it is possible to draw on the same graph also the reaction line of the SC lining
150 (RLSL). This reaction line starts from a point on the abscissa (where pressure is zero) but the
151 displacement u^* is different from zero. The pressure p (the radial load on the lining,

152 corresponding also to the radial pressure applied by the lining on the tunnel wall) increases with
 153 increasing displacement u (the radial displacement of the tunnel wall). At the lining installation
 154 (initial point of the reaction line), the pressure applied at the extrados is zero, but a displacement
 155 of the tunnel wall, u^* , already occurred (Oreste, 2003). The reaction line is concave because the
 156 stiffness of the SC increases over the time, causing increased loads on the lining and reduced
 157 radial displacement of the tunnel wall (Oreste, 2003), see Fig. 3. The pressure difference at a
 158 certain displacement level u between the CCC and RLSL is called fictitious pressure (p_{fict}) and it
 159 is the static contribute of the excavation face on the investigated vertical section of the tunnel.
 160 The fictitious pressure can be evaluated as a function of the (positive) distance x between the
 161 investigated section and the excavation face, with the well-known equation of Panet and Guenot
 162 (1982):

$$p_{fict} = a \cdot p_0 \cdot \frac{b}{x + b} \quad (1)$$

163 Where: $a = 0.72$ and $b = 0.845 \cdot R$.

164 Starting from the initial point of the reaction line ($p = 0; u = u^*$) and knowing the initial elastic
 165 modulus of the SC after the re-entry, it is possible to obtain the initial slope of the reaction line, k
 166 (Oreste, 2009) based on the support geometry (tunnel radius and thickness), the elastic modulus
 167 and the Poisson ratio, ν , of the SC. Proceeding with a numerical approach, an initial segment of
 168 the RLSL for a small increase Δu of u is drawn. At the end of this first segment, p_{fict} can be
 169 evaluated as the difference between CCC and RLSL and from the fictitious pressure the distance
 170 x reached by the excavation face, using equation 1 (Fig. 3).

171 As excavation advance rate is known, and hence the relation linking x to the time, t , at each
 172 distance x reached by the excavation face with respect to the investigated section, a time value t
 173 corresponding subsequent to the SC lining installation can be given. At first load step Δp
 174 (evaluated as the difference from the final value and the initial value of p in the first segment of
 175 the RLSL) the reached time at the end of the first segment can be associated and therefore also
 176 the mean elastic modulus of the SC in the period corresponding to the initial linear part of RLSL.
 177 The method continues in the same way for successive small linear segments, until the
 178 intersection between the CCC and the RLSL is obtained. The intersection point between the two

179 curves represents the final stage of the loading process when the excavation face is advanced at
 180 a distance where static effects on the investigated vertical section of the tunnel are negligible
 181 (Fig. 3).

182 The procedure for the generic calculation step j is the following:

- 183 • Evaluation of the pressure p reached by the RLSL in the final point of the previous
 184 segment $p_{lin,j-1}$ and by difference between CCC and RLSL in such a point, evaluation of
 185 the fictitious pressure $p_{fict,j-1} = p_{j-1} - p_{lin,j-1}$, p_{j-1} is the pressure read on CCC in
 186 correspondence of the displacement u_{j-1} ;
- 187 • If the $p_{fict,j-1}$ is known, the corresponding distance x_{j-1} of the excavation face is
 188 calculated using equation 1;
- 189 • Knowing the face advance rate, the duration and frequency of still stands of the
 190 excavation phase, i.e. the relation $x = f(t)$, it is possible to determine the time t_{j-1}
 191 subsequent to the installation of the SC in the investigated section;
- 192 • If the evolving trend of the elastic modulus of the SC over the time is known, it is possible
 193 to determine the elastic modulus E_{j-1} and therefore the stiffness of the SC lining k_{j-1} in
 194 function of the time t_{j-1} ;
- 195 • The knowledge of the stiffness k_{j-1} allows to draw the new straight line of the RLSL for
 196 the step j for a predetermined amplitude of the radial displacement u equal to Δu ; at the
 197 end of such a segment we obtain: $p_{lin,j} = p_{lin,j-1} + k_{j-1} \cdot \Delta u$;
- 198 • The difference $p_{lin,j} - p_{lin,j-1}$ is the loading step $\Delta p_{lin,j}$ of the step j , linked to the mean
 199 elastic modulus of the SC, $E_{mean,j}$ in the step j where $E_{mean,j} = 0.5(E_{j-1} + E_j)$.

200 Therefore, in the detailed study of the stress state in the SC lining, the knowledge of the evolving
 201 trend of the SC, $E = f(t)$, is fundamental. Generally, the variation of the UCS over the time,
 202 $\sigma_c = f(t)$, is evaluated. Then, the relation between the elastic modulus and UCS is considered
 203 constant over time. This is given by the equation of Chang (1993):

$$\sigma_{c,t} = \left(\frac{E_{t}}{3.86} \right)^{1/0.6} \quad (2)$$

204 Where:

205 E_{t} is the SC elastic modulus at the time t ;

206 $\sigma_{c,t}$ is the UCS for the SC at the time t .

207 A method to represent the variation of the elastic modulus over the time is given by Pottler
208 (1990):

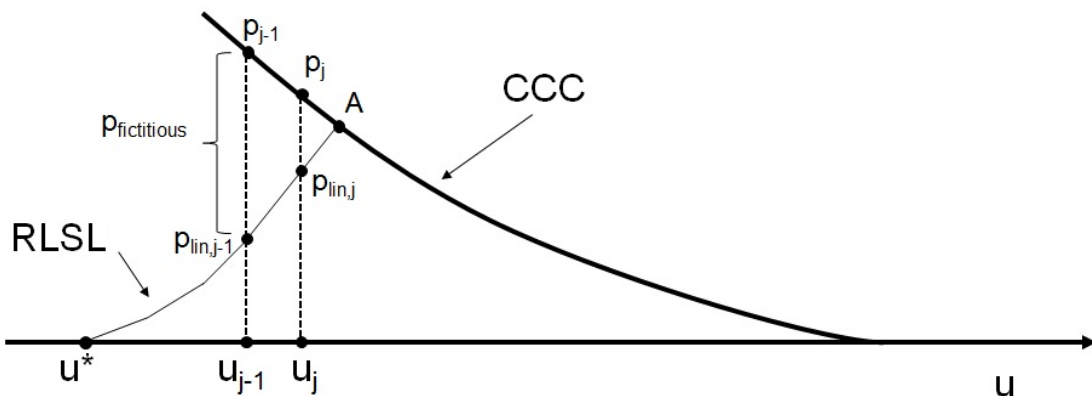
$$E_t = E_0 \cdot (1 - e^{-\alpha t}) \quad (3)$$

209 Where:

- 210 • E_t is the SC elastic modulus at the time t ;
- 211 • E_0 is the value of the asymptotic elastic modulus of the SC, for $t = \infty$;
- 212 • α is a time constant (t^{-1}).

213 From the practical point of view, UCS of SC is measured over the time subsequent to the lining
214 installation and from these values, a series of elastic modulus values for different times is
215 obtained.

216 Then the negative exponential curve, which best approximates these obtained points, i.e. the
217 pairs of values of the elastic modulus and the associated time, is obtained. This curve will have a
218 particular value of the asymptotic elastic modulus, E_0 , and of the coefficient α in equation 3.



219
220 **Fig. 3 Convergence-confinement curve and reaction curve of the shotcrete lining with**
221 **numerical integration of the reaction curve of the shotcrete lining and a calculation step. A**
222 **is the interaction between reaction line and CCC to identify the final load process. Not to**
223 **scale.**

224 The analysis with HRM permits to evaluate in detail the behavior of SC (Oreste, 2007). In more
225 detail, it is possible to analyze the interaction between the SC lining and the surrounding rock
226 mass, during the loading phase of the support. This loading phase can take place gradually,
227 depending on the different load steps identified in the CCM analysis as outlined above. At each

228 load step, the stiffness value of SC lining is updated. HRM allows to obtain the exact course of
 229 the bending moment (M), the normal force (N) and the shear force (T) along the whole SC lining
 230 at each load step and at the end of the loading stage of the lining (in the final state when the
 231 excavation face is far from the investigated section). The knowledge of the values of M , N , and T
 232 allows to evaluate at each point of the lining the normal and the shear stresses that are
 233 developed, and thus also the safety factor against the SC failure. It is therefore possible to
 234 determine the minimum safety factor present along the SC lining, for each load step and at the
 235 end of the loading phase of the support. Very interesting is the determination of the safety factor
 236 over time: in this way, it is possible to check whether the SC lining has transient conditions in
 237 which the safety factor drops to lower values than the obtained final value. HRM is based on the
 238 finite element method (FEM) and consists in dividing the SC lining of the tunnel into one-
 239 dimensional elements. These elements have axial and flexural stiffness and are therefore able to
 240 develop axial displacements, lateral displacements and rotations at their ends. The one-
 241 dimensional elements are interconnected in succession through nodes. At each node, Winkler
 242 springs are applied in both perpendicular and tangential direction to the lining. These springs
 243 allow to simulate the interaction between the lining and the rock wall.

244 From the local stiffness matrix of each element it is possible to come to the definition of the
 245 overall stiffness matrix of the lining. In this paper only half of the lining was considered, for
 246 symmetry reasons with respect to the vertical axis passing through the center of the tunnel. The
 247 elements considered are 36, therefore the total number of nodes is 37. The global stiffness matrix
 248 K is given by the following expression:

$$K = \begin{bmatrix} k_{1,a} & k_{1,b} & 0 & 0 & 0 & \cdots & 0 \\ k_{1,c} & k_{1,d} + k_{2,a} & k_{2,b} & 0 & 0 & \cdots & 0 \\ 0 & k_{2,c} & k_{2,d} + k_{3,a} & k_{3,b} & 0 & \cdots & 0 \\ 0 & 0 & k_{3,c} & k_{3,d} + k_{4,a} & \ddots & \cdots & 0 \\ 0 & 0 & 0 & \ddots & \ddots & \ddots & 0 \\ \vdots & \vdots & \vdots & \vdots & \ddots & \ddots & k_{i,b} \\ 0 & 0 & 0 & 0 & 0 & k_{i,c} & k_{i,d} \end{bmatrix} \quad (4)$$

249 where the terms $k_{i,a}$, $k_{i,b}$, $k_{i,c}$, $k_{i,d}$ represent the 3x3 sub-matrices of the local k_i stiffness matrix
 250 of the i th one-dimensional element of the SC lining:

$$k_i = \begin{bmatrix} \frac{EA}{I}c^2 + \frac{12EJ}{I^3}zs^2 & \frac{EA}{I}c^2 - \frac{12EJ}{I^3}zs^2 & -\frac{6EJ}{I^2}zs & -\frac{EA}{I}c^2 - \frac{12EJ}{I^3}zs^2 & -\frac{EA}{I}c^2 + \frac{12EJ}{I^3}zs^2 & -\frac{6EJ}{I^2}zs \\ \frac{EA}{I}cs - \frac{12EJ}{I^3}zc^2 & \frac{EA}{I}s^2 + \frac{12EJ}{I^3}zc^2 & \frac{6EJ}{I^2}zc & -\frac{EA}{I}cs + \frac{12EJ}{I^3}zc^2 & -\frac{EA}{I}s^2 - \frac{12EJ}{I^3}zc^2 & \frac{6EJ}{I^2}zc \\ -\frac{6EJ}{I^2}zs & \frac{6EJ}{I^2}zc & \frac{4EJ}{I}z & \frac{6EJ}{I^2}zs & -\frac{6EJ}{I^2}zc & \frac{2EJ}{I}z \\ -\frac{EA}{I}c^2 - \frac{12EJ}{I^3}zs^2 & -\frac{EA}{I}cs + \frac{12EJ}{I^3}zc^2 & \frac{6EJ}{I^2}zs & \frac{EA}{I}c^2 + \frac{12EJ}{I^3}zs^2 & \frac{EA}{I}cs - \frac{12EJ}{I^3}zc^2 & \frac{6EJ}{I^2}zs \\ -\frac{EA}{I}cs + \frac{12EJ}{I^3}zc^2 & -\frac{EA}{I}s^2 - \frac{12EJ}{I^3}zc^2 & -\frac{6EJ}{I^2}zc & \frac{EA}{I}cs - \frac{12EJ}{I^3}zc^2 & \frac{EA}{I}s^2 + \frac{12EJ}{I^3}zc^2 & -\frac{6EJ}{I^2}zc \\ -\frac{6EJ}{I^2}zs & \frac{6EJ}{I^2}zc & \frac{2EJ}{I}z & \frac{6EJ}{I^2}zs & -\frac{6EJ}{I^2}zc & \frac{4EJ}{I}z \end{bmatrix} \quad (5)$$

$c = \cos \alpha_i \quad s = \sin \alpha_i$

251 where α_i is the angle of inclination of the element i th with respect to the horizontal; E is the
252 elastic modulus of SC lining, A the area of the lining section, J the moment of inertia of the lining
253 section, l is the length of the one-dimensional element.

254 $[k_{i,a}], [k_{i,b}], [k_{i,c}], [k_{i,d}]$ are thus positioned within the local stiffness matrix k_i :

$$[k]_i = \begin{bmatrix} k_{i,a} & k_{i,b} \\ k_{i,c} & k_{i,d} \end{bmatrix} \quad (6)$$

255 The elements of a diagonal band of the global stiffness matrix (equation 4) are then modified to
256 add the values of the normal and tangential stiffness of the springs simulating the interaction of
257 the SC lining with the rock wall (Oreste, 2007).

258 Once the global stiffness matrix K is defined, and knowing the vector of the nodal forces $\{F\}$
259 applied to the numerical model (i.e. the external loads applied to the lining), it is possible to
260 determine the vector of nodal displacements $\{S\}$ from the following relation:

$$[K] \cdot \{S\} = \{F\} \quad (7)$$

261 From the vector of the nodal displacements, it is possible to obtain the radial displacements of the
262 lining, which give indications of its global deformation and also of the interactions with the rock
263 wall. From the nodal displacements, it is also possible to obtain the normal force N , the shear
264 force T and the bending moment M . From these stress characteristics, it is possible to define in
265 detail the existing stress state in the lining and, therefore, also the factor of safety that the lining
266 reaches for each load step and over time.

267 For each load step of the lining, the global stiffness matrix as function of the elastic modulus of
268 SC reached for the specific load step is evaluated. The load step is used in order to determine the

269 nodal forces for each step. The vector of the nodal displacements obtained for each load step will
 270 update the total displacements achieved; the values of M , N , T and the normal tangential stresses
 271 obtained for each load step update the corresponding overall values achieved. The final situation
 272 is represented by the total displacements and total stresses, as the sum of the values obtained
 273 for each step of loading.

274 **NUMERICAL RESULTS AND DISCUSSION**

275 The calculation procedure proposed in this article has been applied to some examples, in order to
 276 verify which can be the effect on the stress state in the SC lining, by varying the characteristics of
 277 the SC (in particular the curing rate and final elastic modulus) and the advance rate of the
 278 excavation face.

279 Different geometries of the tunnel were considered, along with various rock mass types. In
 280 general, six main examples are presented, each of which has four cases. The cases considered
 281 include the following assumptions, in accordance with the underlying hypotheses of the
 282 calculation methods which were used in the procedure presented.

- 283 • a bi-dimensional stress state considering circular and deep tunnels;
- 284 • a continuous, homogeneous and isotropic rock mass.

285 The first example (example 1) refers to a tunnel of 2m radius excavated in a rock of poor quality.
 286 The geomechanical parameters are shown in Tab. 1. The lithostatic stress p_0 is 7MPa and the
 287 fictitious internal pressure p_{fict} at the face is $0.72 \cdot p_0$, where the SC lining is installed. SC lining
 288 has a thickness of 20cm. The horizontal stress in the lithostatic environment is $\frac{1}{2}$ of the vertical
 289 one ($K_0 = 0.5$).

Rock Mass Parameters	
Elastic modulus [MPa]	3160
Poisson's ratio	0.30
Peak cohesion [MPa]	0.15
Residual cohesion [MPa]	0.12
Peak angle of friction [°]	20
Residual angle of friction [°]	16
Dilatancy [°]	16

290 **Table 1. Geomechanical parameters for the rock mass for example 1**

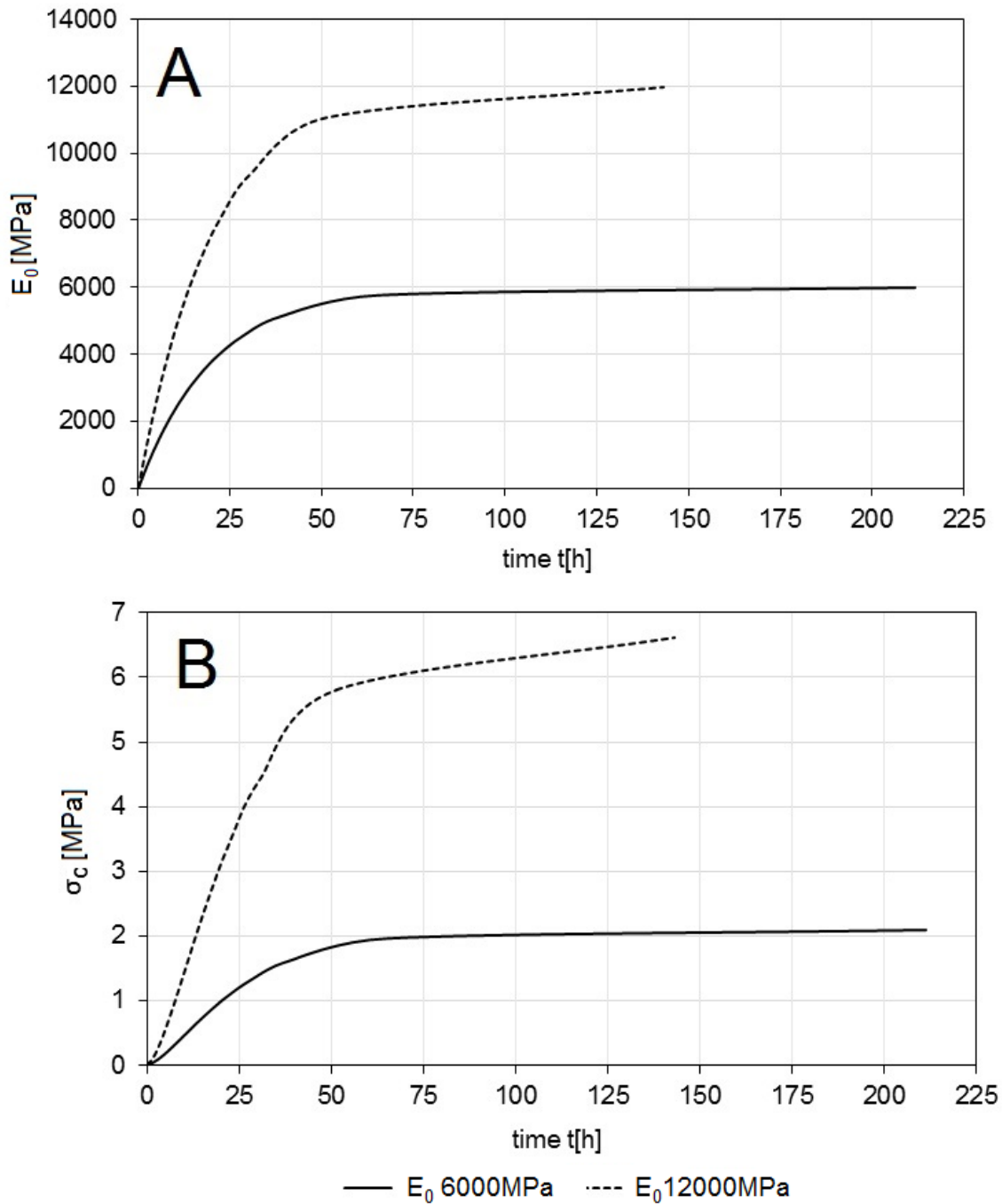
291 Since the calculation procedure uses HRM, the values of the stiffness of the interaction springs of
292 the support with the ground are obtained by the following expressions:

$$293 \quad K_n = 2 \cdot \frac{E_{rm}}{R} \cdot b \quad (8)$$

$$294 \quad K_s = \frac{K_n}{2} \quad (9)$$

295 Where: $b = 2 \cdot R \cdot \cos(2,5^\circ) \cdot \sin(2,5^\circ)$, R and E_{rm} is the elastic modulus of the rock mass.

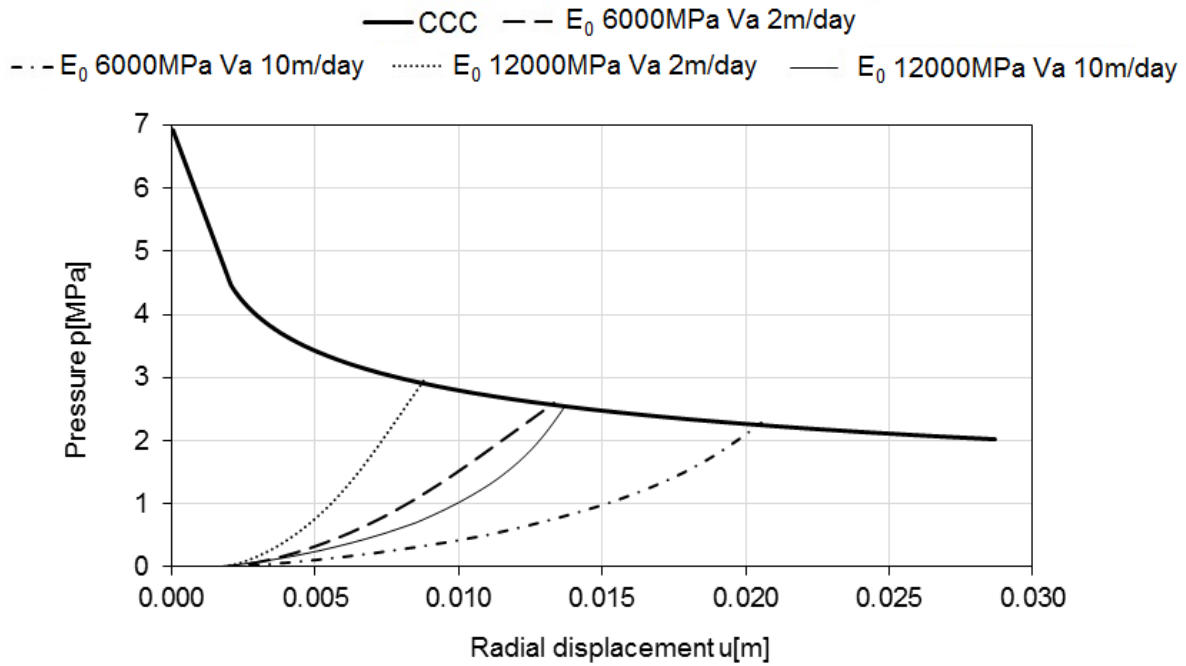
296 Two different types of SC were assumed with a final and asymptotic value of the elastic modulus
297 ($E_{,0}$) of 6000 and 12000MPa, both with a Poisson's ratio, ν , 0.15. The time constant α has a value
298 of 0.05 h^{-1} in both cases (eq. 3). The diagrams relating the modulus of elasticity and UCS varying
299 with time are shown in Fig. 4.



300
 301 **Fig. 4 Progressive increase of the asymptotic elastic modulus (A) and UCS (B) of the**
 302 **shotcrete with time for the two considered typologies in the example 1.**

303 The other parameter to be varied is the daily mean rate of tunnel advance (assumed as 2 m/day
 304 and 10m/day), with support installation time t_0 and the advance step δ equal to 1h and 1.2m,
 305 respectively.

306 The reaction lines of the SC linings are shown in Fig. 5 for the four analyzed cases.



307

308 **Fig. 5 Reaction curves of the SC lining as a function of the face advance rate (Va) and the**
 309 **mechanical characteristics of the shotcrete for the example 1.**

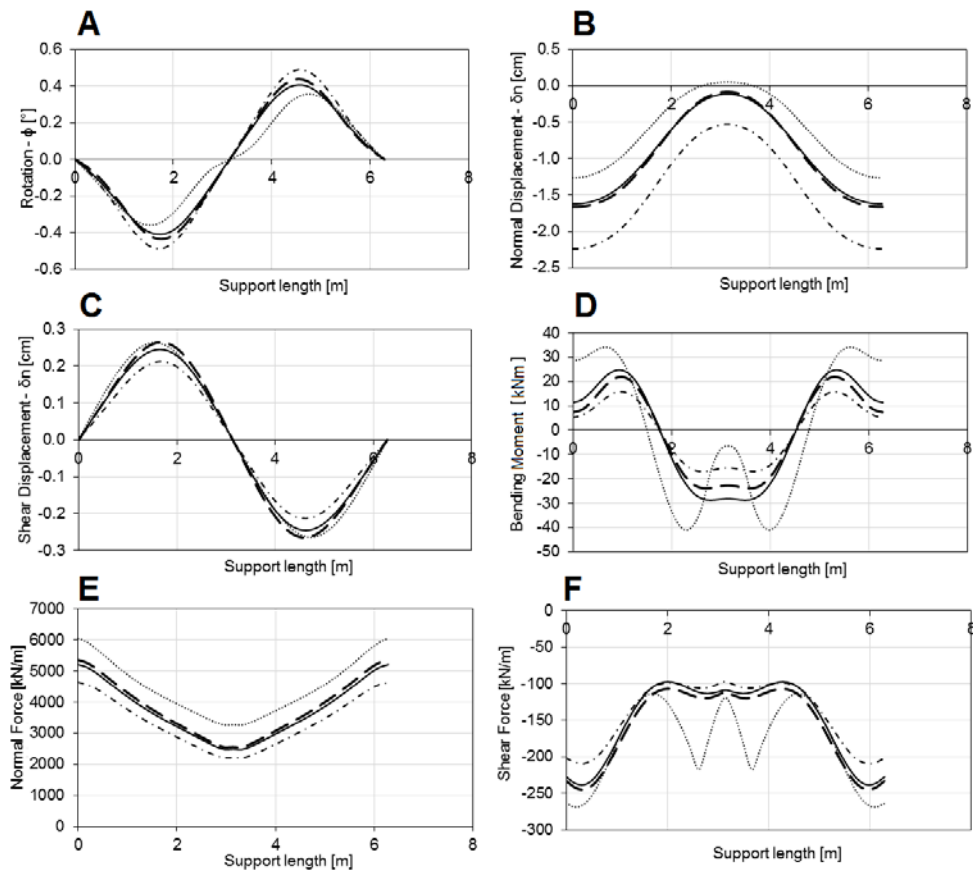
310 It is possible to see in Fig. 5 the change of the equilibrium point (intersection between the CCC
 311 and the SCRL) for each of the cases. In addition, it can be observed that the reaction line is not
 312 straight but curved. This is because the calculation model considers the curing time of the SC, i.e.
 313 the progressive increase of the modulus of elasticity and UCS from the installation of the support
 314 to the point at which the maximum asymptotic strength and stiffness of the SC has been
 315 obtained.

316 The influence of the SC type and advance rate (Va) appears to be very important in the final
 317 evaluation of the equilibrium point and, hence, of the final loading on the SC lining and the final
 318 displacement of the tunnel wall.

319 The final load on the lining, as well as the final displacement of the tunnel wall, may vary
 320 significantly depending on the type of SC used and the tunnel face advancing speed. The highest
 321 final stress values are found for the most rigid type of SC and the lowest advance rate.

322 Also the stress and displacement characteristics of the lining can vary significantly. In the
 323 following the values referring to the final condition (at the equilibrium point) for example 1 are
 324 shown (Fig. 6).

— E_0 6000MPa V_a 2m/day ··· E_0 6000MPa V_a 10m/day - - - E_0 12000MPa V_a 2m/day - - - E_0 12000MPa V_a 10m/day



325

326 **Fig. 6 Variation of the rotation (A), normal displacement (B), shear displacement (C),**
 327 **bending moment (D), normal force (E) and shear force (F) for the two considered type of**
 328 **SC and two assumed advance rates (V_a) of the tunnel face, with reference to the final**
 329 **equilibrium point (example 1).**

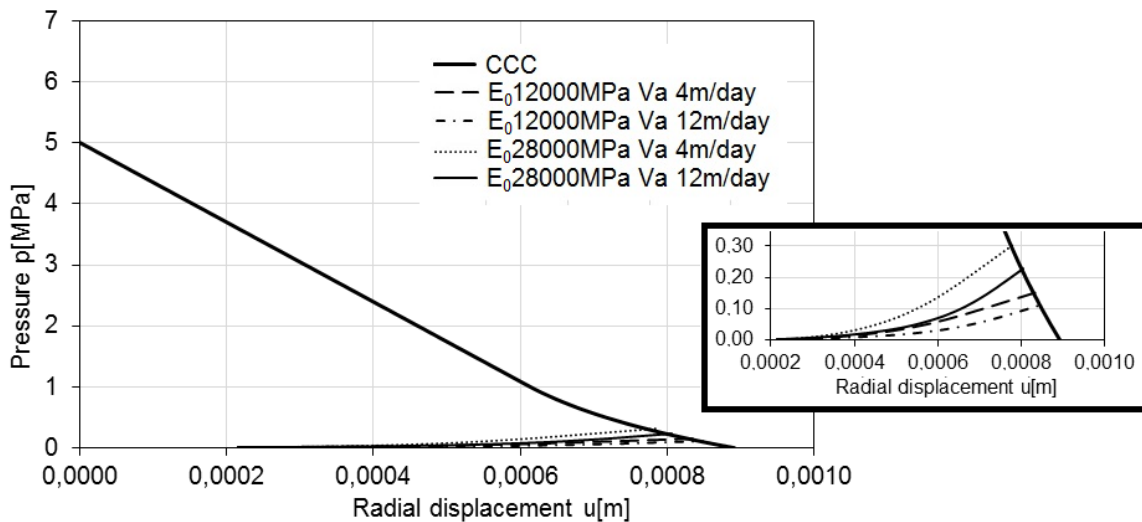
330 Of particular interest is the trend of normal displacements, bending moments, normal and shear
 331 forces along the lining (*i.e. length of the beam elements considered for the calculation*). Lower
 332 stiffness during the concrete setting period and faster advance speed provide larger normal
 333 displacements. Conversely, higher stiffness and lower advance rate produce lower normal
 334 displacements. The highest peak moments are detected in the lining when using high stiffness
 335 SC and low advance speed. The opposite is for lower stiffness and higher advance speed. Same
 336 considerations can be made for normal and shear forces.

337 In the example 2 a tunnel with a radius R of 2.5m, excavated in a rock with poor mechanical
 338 properties (RMR=40, see Tab. 2), is considered. The lithostatic pressure p_0 is 5MPa. Also in this
 339 example, the lining thickness is 20cm and K_0 is 0.5.

Rock Mass Parameters	
Elastic modulus [MPa]	21170
Poisson's ratio	0.30
Peak cohesion [MPa]	1.5
Residual cohesion [MPa]	1.5
Peak angle of friction [°]	33
Residual angle of friction [°]	33
Dilatancy [°]	16

340 **Table 2. Geomechanical parameters for the rock mass in the example 2**

341 Four different cases were analyzed in which higher final elastic modulus values of the support
342 (E_0) were taken as 12000 and 28000MPa. The α time constant has a value of 0.05 h^{-1} and the
343 Poisson's ratio ν of 0.15. The tunnel advance daily rates were arbitrary assumed to be 4 m/day
344 and 12 m/day, with support installation time t_0 and the advance step δ of 1 h and 1.2 m
345 respectively. The different reaction lines of the SC lining in conjunction with the CCCs are
346 presented in Fig. 7, where it is possible to identify the equilibrium point corresponding to each
347 analyzed case.

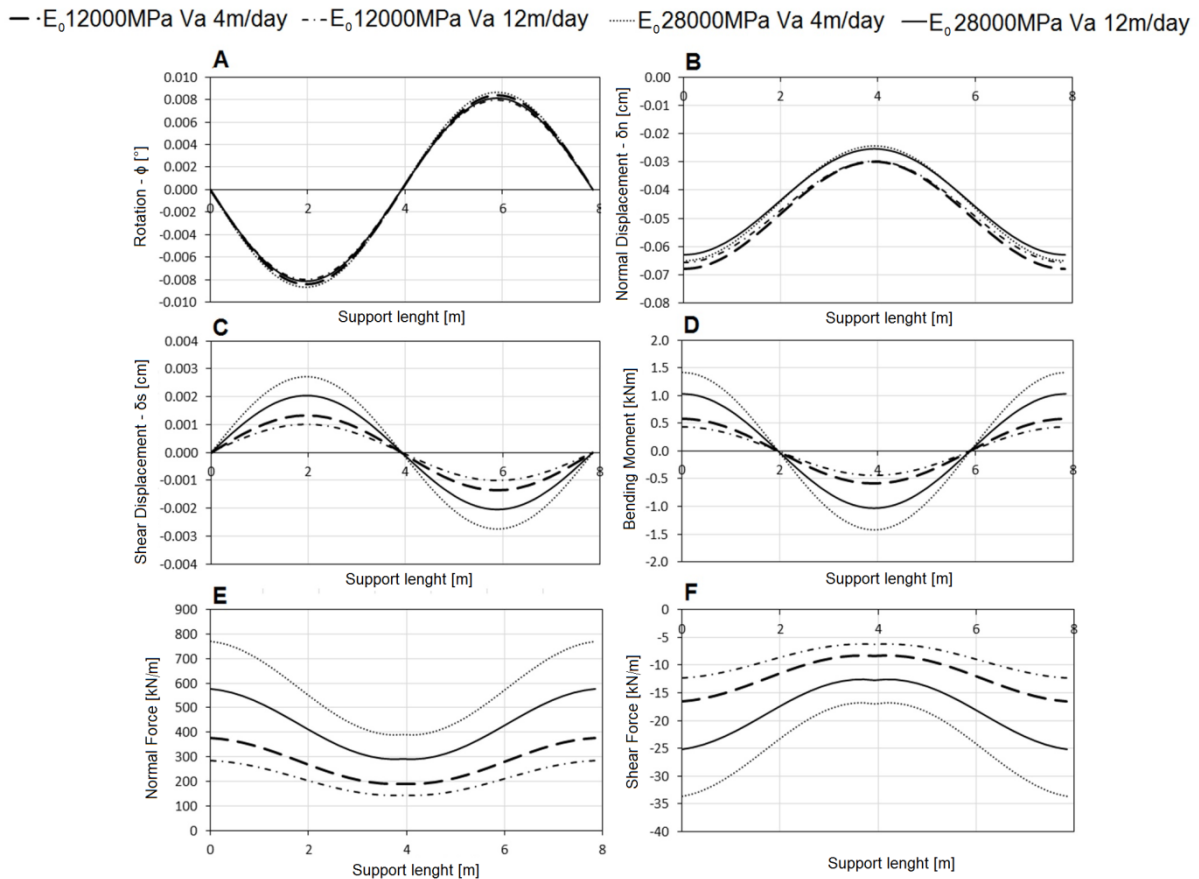


348

349 **Fig. 7 Reaction curve of the shotcrete lining (with enlargement on the right side) as a**
350 **function of the face advance rate (Va) and the shotcrete type considered in the example 2.**

351 In this second example, lower final pressures are observed on the lining, but the differences
352 between the 4 cases considered are in very high percentages. Higher final pressures have a
353 higher final elastic modulus and a lower advance rate.

354 The results in terms of displacements and stress characteristics along the lining circumference for
 355 the four cases presented in this example, when the final condition is reached, are shown in Fig. 8.



356
 357 **Fig. 8 Variation of the rotation (A), normal displacement (B), shear displacement (C),**
 358 **bending moment (D), normal force (E) and shear force (F) for the two considered types of**
 359 **SC and two assumed velocities of advance (V_a) of the tunnel face, with reference to the**
 360 **final equilibrium point (example 2).**

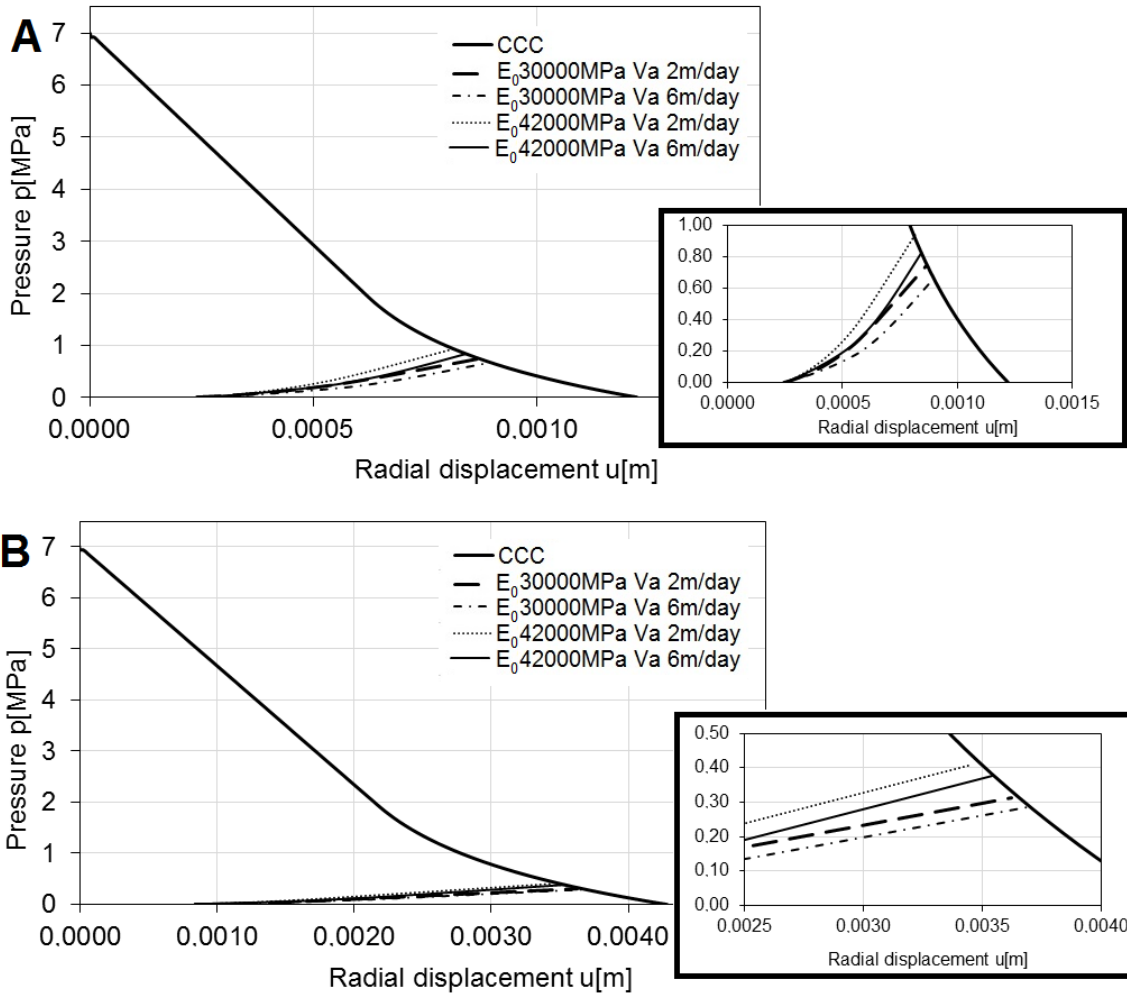
361 Examples 3 and 4 refer to two tunnels built on rock with the same characteristics, differing from
 362 one another only in size. Examples three and four were analyzed in four different cases, in which
 363 the elastic modulus values of SC were obtained by the UCS values given in Melbye (1994). The
 364 first proposed SC installation was implemented in the tunnel of Blisadona (Austria) where a final
 365 value of elastic modulus of 30000MPa was calculated based on equation 2. The second is a SC
 366 installed in a tunnel located at Quarry Bay Station (Hong Kong) where a final value of elastic
 367 modulus of 42000MPa was calculated. The time constant α (equation 3) and the Poisson's ratio ν
 368 of the SC were assumed to be 0.05 h^{-1} and 0.15 respectively. The mechanical properties of the
 369 rock mass arbitrary assumed for these examples are shown in Tab. 3. For the example 3 a radius
 370 of 2m has been assumed, while for the example 4 a larger dimension with a radius of 7m has

371 been hypothesized. The in situ hydrostatic stress p_0 was assumed as 7MPa, with a SC lining
 372 thickness of 20cm and K_0 value of 0.5. The daily advance rates were arbitrary assumed for both
 373 examples 2m/day and 6m/day, with installation time of the support t_0 equal to 6h and the
 374 advance step δ of 3.5m.

Rock Mass Parameters	
Elastic modulus [MPa]	21170
Poisson's ratio	0.30
Peak cohesion [MPa]	1.5
Residual cohesion [MPa]	1.5
Peak angle of friction [°]	33
Residual angle of friction [°]	33
Dilatancy [°]	16

375 **Table 3. Geomechanical parameters for the rock mass for example 3 and 4**

376 In Fig. 9 the reaction lines of the SC lining for the four considered cases are shown. It is worth
 377 noticing as for the example of the smallest tunnel (example 3), considering all the other
 378 parameters being equal in the calculation, the differences in terms of final load on the lining and
 379 final tunnel wall displacement are more pronounced. In the case of a large tunnel (example 4),
 380 the differences between the 4 cases examined are smaller.
 381 However, even in these two calculation examples it is noted that the major final pressures are
 382 observed for the lining with a higher stiffness and with lower face advance rate.

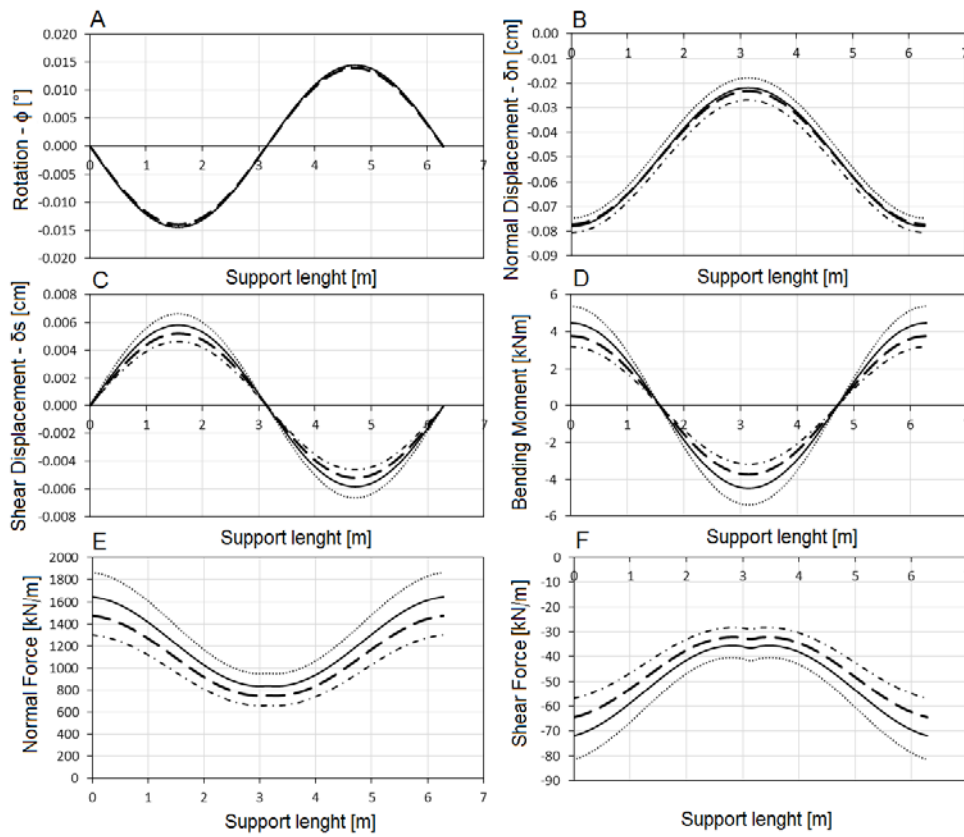


383

384 **Fig. 9 CCCs and reaction curve of the shotcrete lining (with enlargement on the right side)**
 385 **as a function of the velocity of advance (Va) and the final elastic modulus of the shotcrete,**
 386 **for example 3 (A) and example 4 (B).**

387 Displacements and stress characteristics along the lining are shown in Figs. 10 and 11.

— E_0 30000MPa V_a 2m/day - - - E_0 30000MPa V_a 6m/day E_0 42000MPa V_a 2m/day — E_0 42000MPa V_a 6m/day

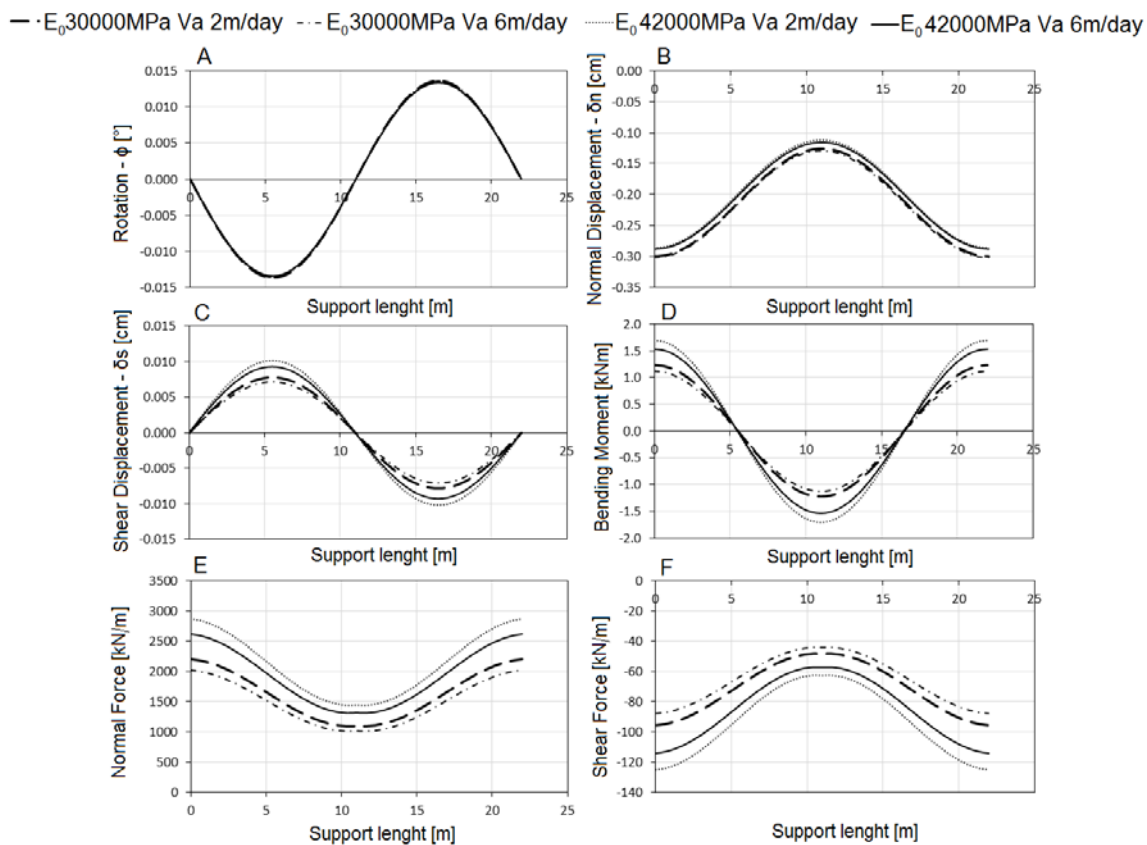


388

389 **Fig. 10** Variation of the rotation (A), normal displacement (B), shear displacement (C),
 390 bending moment (D), normal force (E) and shear force (F) for two considered types of SC
 391 and two assumed velocities of advance (V_a) of the tunnel face, with reference to the final
 392 equilibrium point (example 3).

393 ϕ

394 δ



395
 396 **Fig. 11 Variation of the rotation (A), normal displacement (B), shear displacement (C),**
 397 **bending moment (D), normal force (E) and shear force (F) for the two considered types of**
 398 **SC and two assumed velocities of advance (Va) of the tunnel face, with reference to the**
 399 **final equilibrium point (example 4).**

400 Even for these two examples, higher stress characteristics are observed for SC with higher
 401 stiffness during the concrete setting time and lower face advance rates. Major changes in terms
 402 of percentage occur among the four cases analyzed for the smaller tunnel, compared to the
 403 larger tunnel example.

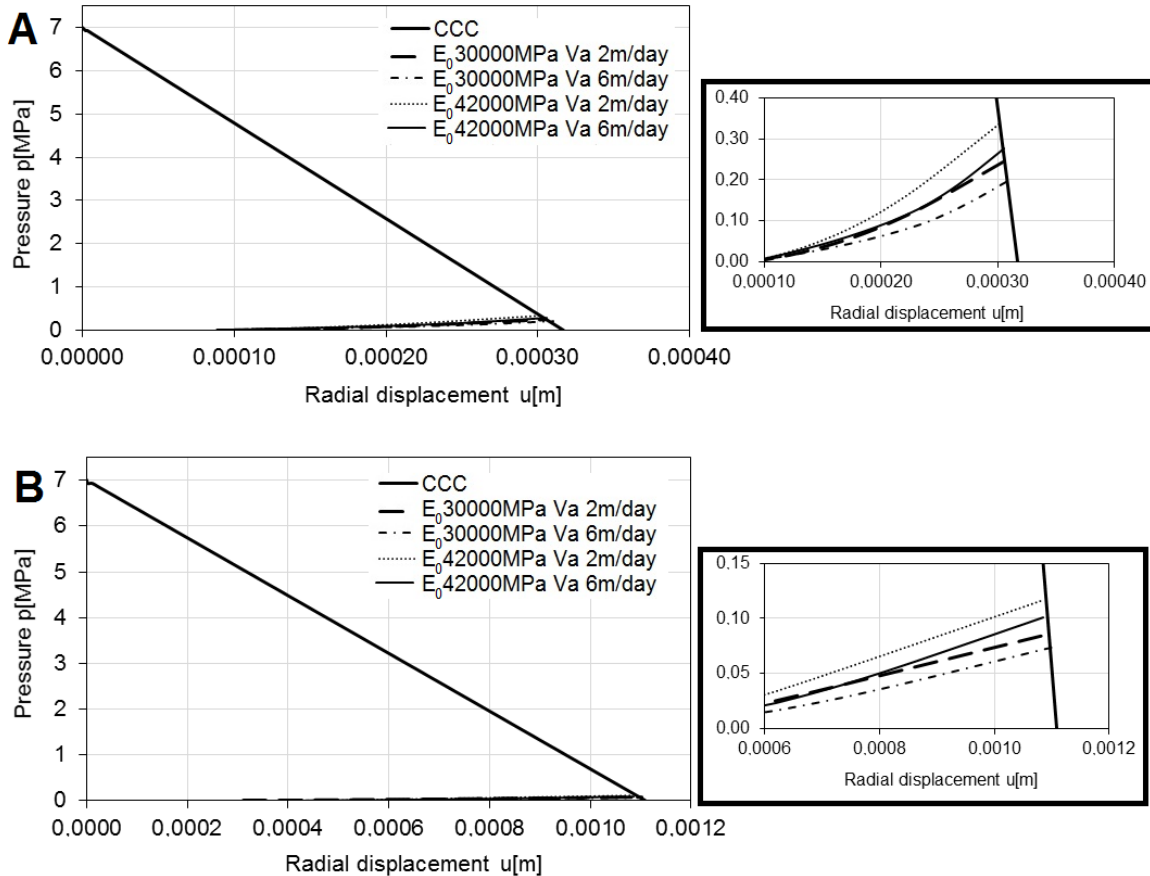
404 Examples 5 and 6 refer to two tunnels of radius 2m and 7m, respectively, excavated in a rock
 405 mass with the same characteristics. The rock in these two examples, unlike the previous two, is a
 406 rock mass of good mechanical properties corresponding to **RMR = 80**. The geomechanical
 407 parameters are listed in Tab. 4.

408 The lithostatic pressure p_0 is assumed to be 7MPa, the SC lining has a thickness of 20cm and K_0
 409 is equal to 0.5 for both examples. The daily advance rates and the SC types implemented in the
 410 support of these two examples are assumed to be the same types as in examples 3 and 4. The
 411 reaction lines of the SC lining in conjunction with the CCCs are shown in Fig. 12.

Rock Mass Parameters	
Elastic modulus [MPa]	57500
Poisson's ratio	0.30
Peak cohesion [MPa]	3.75
Residual cohesion [MPa]	3.75
Peak angle of friction [°]	42
Residual angle of friction [°]	42
Dilatancy [°]	16

412
413

Table 4. Geomechanical parameters of the rock mass in the example 5 and 6.

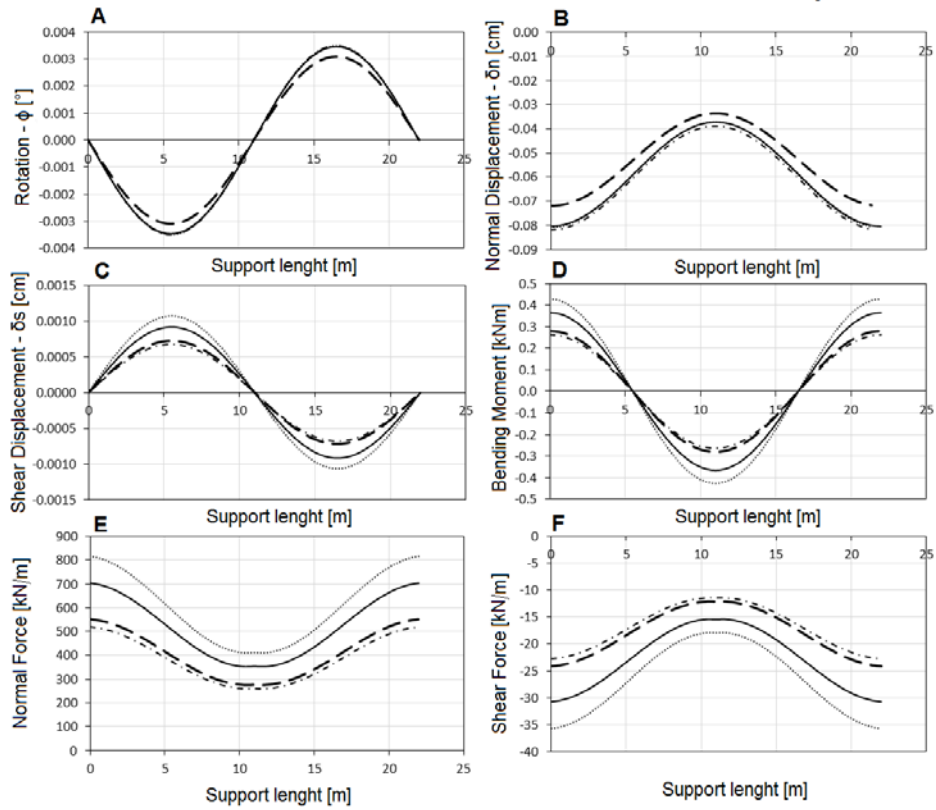


414

415 **Fig. 12 CCCs of the tunnel and reaction lines of the shotcrete lining (with enlargement on**
416 **the right side) as a function of the face velocity of advance (V_a) and the shotcrete types for**
417 **the example 5 (A) and 6 (B).**

418 The stress characteristics (M , N and F) to determine the stress state in the lining and the more
419 important displacements of the SC lining are shown in the Figs. 13 and 14.

— E_0 30000MPa V_a 2m/day - - - E_0 30000MPa V_a 6m/day E_0 42000MPa V_a 2m/day — E_0 42000MPa V_a 6m/day

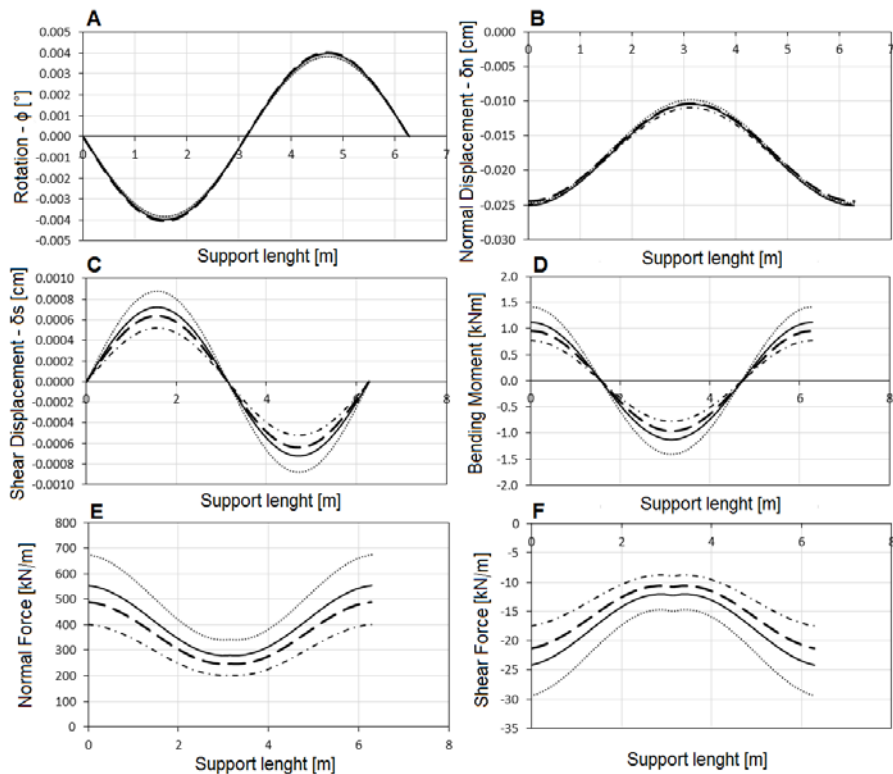


420

421 **Fig. 13 Variation of the rotation (A), normal displacement (B), shear displacement (C),**
 422 **bending moment (D), normal force (E) and shear force (F) for the two considered types of**
 423 **SC and two assumed velocities of advance (V_a) of the tunnel face, with reference to the**
 424 **final equilibrium point (example 5).**

425

— E_0 30000MPa V_a 2m/day - - - E_0 30000MPa V_a 6m/day E_0 42000MPa V_a 2m/day — E_0 42000MPa V_a 6m/day



426

427 **Fig. 14** Variation of the rotation (A), normal displacement (B), shear displacement (C),
 428 **bending moment (D), normal force (E) and shear force (F) for the two considered types of**
 429 **SC and two assumed velocities of advance (V_a) of the tunnel face, with reference to the**
 430 **final equilibrium point (example 6).**

431 In high-quality rock masses, such as those for example 5 and 6, the final load on the lining is of
 432 low magnitude. In fact, the intersection between the CCC and the RLSL is for low pressure
 433 values. In the example 6 ($R = 7m$) there are no noticeable differences in the RLSL performance
 434 for the four examined cases, but there are some differences in example 5 ($R = 2m$).

435 On the other hand, the differences between the bending moments and the forces that develop
 436 inside the lining are more pronounced. The same considerations done previously are also here
 437 valid. In percentage terms, the variations found in the four examined cases are higher for
 438 example 5 ($R = 2m$) than for example 6 ($R = 7m$). In addition, for $R = 7m$ and final elastic
 439 modulus of SC of 30GPa (lower stiffness between the two types of concrete used), the advance
 440 rate appears to have a minor influence on the trend of bending moments, normal and shear
 441 forces developed in the lining.

442 **CONCLUSIONS**

443 The sprayed concrete (shotcrete) linings represent one of the most popular tunnel supporting
444 works. Its operating mechanism is quite complex due to the installation method, the particular
445 load application phase and the SC curing with the consequent modification of the mechanical
446 properties of the SC over time. Precisely because of the complexity of the operation of this
447 support work, it is difficult to analyze the behavior and to evaluate its static conditions. The three-
448 dimensional numerical analysis, able to consider all the complex aspects of the operating
449 mechanism, requires very long calculation times.

450 In this article, after highlighting the fundamental characteristics of the SC, a new calculation
451 procedure based on the combined use of two widely used calculation methods for tunnel linings
452 was introduced: the Convergence-Confinement Method (CCM) and the Hyperstatic Reaction
453 Method (HRM).

454 The former, thanks to the evaluation of the sprayed concrete reaction line (RLSL) and the
455 intersection of the Convergence Containment Curve (CCC), allows obtaining the final load on the
456 support and the evolution of the load with the progress of the curing phase of the SC. The latter,
457 based on the results obtained with the former, allows determining the mechanical behavior of the
458 lining and the interaction with the tunnel wall with the progress of the applied load and the
459 development of mechanical parameters of the SC over time.

460 The interesting result is the trend of bending moments, normal and shear forces, and
461 displacement along the lining circumference during the transient loading phase and in the final
462 load condition.

463 From the stress characteristics, it is possible to assess the stress state in the SC and the safety
464 factors of the lining against compression or traction failure in the SC. Note that the safety factors
465 allow to correctly design the lining, defining in particular the average of the tunnel lining thickness.

466 The calculation procedure was then applied to examples, differentiated by the tunnel geometry
467 and the geomechanical quality of the surrounding rock mass. For each example, four different
468 cases were considered, taking into account two different types of SC and two different advance
469 rates of the tunnel excavation face. From the results, it was possible to develop useful
470 considerations on the parameters that mostly influence the mechanical behavior of the lining.

471 Thanks to the fact that the model is able to appropriately consider the evolution of the mechanical
472 properties of SC over time and the advance rate of the excavation face, it is a useful tool for
473 selecting two key parameters in a tunnel design, as the type of SC and the thickness of the lining.

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539

540 **FIGURE CAPTION**

541 **Fig. 1 Spraying the tunnel roof with the shotcrete spraying machine (picture courtesy**
542 **Roland Mayr, BASF)**

543 **Fig. 2: Convergence-confinement method: Geometry of the problem and example of a**
544 **convergence-confinement curve. Key: p : Internal tunnel pressure, R : Tunnel radius, r :**
545 **Radial coordinate, u : Radial displacement of the tunnel wall, p_{cr} : Critical pressure**
546 **(modified by Oreste, 2009).**

547 **Fig. 3 Convergence-confinement curve and reaction curve of the shotcrete lining with**
548 **numerical integration of the reaction curve of the shotcrete lining and a calculation step. **A****
549 **is the interaction between reaction line and CCC to identify the final load process. Not to**
550 **scale.**

551 **Fig. 4 Progressive increase of the asymptotic elastic modulus (A) and UCS (B) of the**
552 **shotcrete with time for the two considered typologies in the example 1.**

553 **Fig. 5 Reaction curves of the SC lining as a function of the face advance rate (V_a) and the**
554 **mechanical characteristics of the shotcrete for the example 1.**

555 **Fig. 6 Variation of the rotation (A), normal displacement (B), shear displacement (C),**
556 **bending moment (D), normal force (E) and shear force (F) for the two considered type of**
557 **SC and two assumed advance rates (V_a) of the tunnel face, with reference to the final**
558 **equilibrium point (example 1).**

559 **Fig. 7 Reaction curve of the shotcrete lining (with enlargement on the right side) as a**
560 **function of the face advance rate (V_a) and the shotcrete type considered in the example 2.**

561 **Fig. 8 Variation of the rotation (A), normal displacement (B), shear displacement (C),**
562 **bending moment (D), normal force (E) and shear force (F) for the two considered types of**
563 **SC and two assumed velocities of advance (V_a) of the tunnel face, with reference to the**
564 **final equilibrium point (example 2).**

565 **Fig. 9 CCCs and reaction curve of the shotcrete lining (with enlargement on the right side)**
566 **as a function of the **velocity of advance** (V_a) and the final elastic modulus of the shotcrete,**
567 **for example 3 (A) and example 4 (B).**

568 **Fig. 10** Variation of the rotation (A), normal displacement (B), shear displacement (C),
569 bending moment (D), normal force (E) and shear force (F) for two considered types of SC
570 and two assumed velocities of advance (V_a) of the tunnel face, with reference to the final
571 equilibrium point (example 3).

572 **Fig. 11** Variation of the rotation (A), normal displacement (B), shear displacement (C),
573 bending moment (D), normal force (E) and shear force (F) for the two considered types of
574 SC and two assumed velocities of advance (V_a) of the tunnel face, with reference to the
575 final equilibrium point (example 4).

576 **Fig. 12** CCCs of the tunnel and reaction lines of the shotcrete lining (with enlargement on
577 the right side) as a function of the face velocity of advance (V_a) and the shotcrete types for
578 the example 5 (A) and 6 (B).

579 **Fig. 13** Variation of the rotation (A), normal displacement (B), shear displacement (C),
580 bending moment (D), normal force (E) and shear force (F) for the two considered types of
581 SC and two assumed velocities of advance (V_a) of the tunnel face, with reference to the
582 final equilibrium point (example 5).

583 **Fig. 14** Variation of the rotation (A), normal displacement (B), shear displacement (C),
584 bending moment (D), normal force (E) and shear force (F) for the two considered types of
585 SC and two assumed velocities of advance (V_a) of the tunnel face, with reference to the
586 final equilibrium point (example 6).