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The mechanical characteristics of two-component grout used in segmental lining

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Abstract

In this work, the effective influence of the mechanical characteristics of the filling material on the safety factors of the support system is analyzed. Through an extensive parametric analysis, developed by adopting proven analytical methods, on 243 different cases of tunnels excavated using a TBM in a soil mass, at different depths and with different excavation radii, it was possible to identify the conditions in which the safety factors can be effectively low. In all these cases, therefore, it is necessary to intervene on the mechanical characteristics of the filling material, requiring elastic modules and strengths such as to guarantee higher values of the safety factors, avoiding risks on the possible failure of the concrete that makes up the segmental lining and of the same filling material that connects the support system to the tunnel wall.

Key words: two-component grout; filling material; segmental lining; Tunnel Boring Machine (TBM); convergence-confinement method; Einstein and Schwartz method; unconfined compressive strength.

23 **Abbreviations and nomenclature**

24 UCS Unconfined compressive strength

25 UCS_{sl} Unconfined compressive strength for concrete

26 UCS_{fm} Unconfined compressive strength for the filling material

27 c Cohesion of the ground

28 C^* Compressibility ratio of the support system

29 E Elastic modulus of the ground

30 E_{fm} Elastic modulus of the filling material

31 E_{sl} Elastic modulus of the segmental lining (concrete)

32 F^* Flexibility ratio of the support system

33 k_{sys} Stiffness of the support system

34 k_{sl} Radial stiffness of the segmental lining

35 K_0 Lateral earth pressure at rest in the ground

36 M_{max} Maximum moment that develops in the support system

37 N_{crown} Normal force at the center of the cap

38 $N_{sidewall}$ Normal force at the sidewall

39 p Pressure inside the tunnel acting on the walls

40 p_{eq} Final entity of the loads acting on the support system

41 p_0 Hydrostatic initial stress state (undisturbed)

42	R_{pl}	Plastic radius of the tunnel
43	u_{eq}	Final entity of the tunnel wall displacement
44	u_0	Displacement of the tunnel wall when the support system is installed
45	R	Tunnel radius
46	t_{fm}	Thickness of the filling material
47	t_{sl}	Thickness of the segmental lining
48	z	Tunnel depth
49	ν	Poisson ratio of the ground
50	ν_{fm}	Poisson's ratio of the filling material
51	ν_{sl}	Poisson's ratio of the concrete constituting the segmental lining
52	$\sigma_{\vartheta,max}$	Maximum circumferential stresses:
53	φ	Friction angle of the ground
54	φ_{sl}	Friction angle of the concrete
55	φ_{fm}	Friction angle of the filling material
56	Ψ	Dilatancy of the ground
57	ξ	Incremental coefficient that takes into account the transfer of stresses from one ring
58		to the adjacent one
59	η	Coefficient that takes into account the presence of longitudinal joints in segmental
60		lining
61		

62 **Introduction**

63 In mechanized tunnelling excavation, due to the difference between the excavated diameter
64 and the lining external diameter (Do et al., 2013; 2015; Zaheri et al., 2020), a gap is created
65 (e.g. Beghoul and Demagh, 2019; Oggeri et al., 2021;), which must be completely filled in
66 order to lock linings in the designed position and avoid segment movement due to its weight
67 and stresses applied by the surround ground and the shield (Sharghi et al., 2018), to prevent
68 water inflow inside the tunnel increasing the waterproofing, to minimize surface settlements
69 due to the over-excavation generated by the passage of the TBM (Maidl et al., 1995).

70 The usual mix-design for one m³ of the two-component grout varies widely and is influenced
71 by the project's specifications, the site's needs, and the availability of equipment. However,
72 it contains cement, bentonite, water, retarder and sodium silicate as an accelerator (e.g.
73 Peila et al., 2011; Di Giulio et al., 2020).

74 **As for the two-component grout**, it needs to cure quickly, be stable and to achieve
75 satisfactory short-term compressive strength (Todaro et al., 2022) - normally about 0.5 to
76 1MPa at 24 hours - in order to control settlements (Sharghi et al., 2018). Besides, its curing
77 environment is confined between the lining and the ground. For that reason, the void
78 grouting cannot be directly observed after the tunnel construction, and therefore it is not
79 simple to simulate its behaviour (Dai et al., 2010), but the quality check can be done only
80 through indirect methods (e.g. Kravitz et al., 2019). The mechanical values of the two-
81 component grout may vary from project to project due to different testing procedures and
82 equipment required to measure strength values (generally Vicat needle and penetrometer
83 for the early curing and compressive strength tests for ages older than 24 hours, see Fig. 1)
84 and a lack of standards regarding the compressive strength assessment (Todaro et al.,
85 2020) creates uncertainty.

86 Early strength testing are considered to be troublesome because there is no clear norm.
87 Additionally, tests for direct compressive strength can be conducted on cubes or cylinders,

88 therefore a correlation is required (BS, 1983). Variations in the grout's compressive strength
89 could cause operational and design problems because it is one of the fundamental metrics
90 that demonstrates how well the grout supports the load (Rahmati et al., 2022).



91

92 **Fig. 1 Vicat needles for early strength (A), penetrometers (B) and a cube for the**
93 **compressive strength test (C).**

94 While the majority of the literature concerning the two-component grout focuses on the
95 mechanical response of different mix-designs (e.g. Thewes and Budach, 2009; Pelizza et
96 al., 2011; Flores, 2015; Todaro et al., 2021), very little information is available about the
97 interaction with the linings (e.g. Ochmański et al., 2018; Oggeri et al., 2021; 2022; Oreste et
98 al., 2021), or in general about modelling its behaviour, e.g. Bezuijen and Talmon (2003), Oh
99 and Ziegler (2014), Dias and Bezuijen (2015), Shah et al. (2018), Ochmański et al. (2021).

100 The support system made up of the segmental lining and the surrounding filling material has
101 a complex operating mechanism not only due to the presence of joints inside the segmental
102 lining, but also to the evolution of the mechanical parameters of the filling material over time,
103 during the taking period. This evolution leads to varying the overall stiffness of the system
104 and, therefore, the response of the system to the loads transmitted by the soil/rock. In the
105 present study, for simplicity, the filling material has been hypothesized with a single value of
106 its elastic modulus, which must therefore represent the average value that is detected during
107 the stage of its aging.

108 In this work the effect of the mechanical characteristics of the two-component material on
109 the stress state induced in segmental lining, in the various situations during the excavation
110 of tunnels with a TBM machine is investigated in detail. More specifically, using reliable
111 analytical calculation methods, the stress developing in the segmental lining and in the filling
112 material will be analyzed as the elastic modulus of the latter changes, for different diameters
113 and depths of the tunnel and types of soil.

114 The results of the developed parametric analysis will be able to indicate the influence of the
115 mechanical characteristics of the filling material on the stress conditions of the segmental
116 lining, in order to determine its physical and mechanical properties required by two-
117 component grout in the tunnel design phase.

118 The analysis developed in this article using simplified calculation methods allows to estimate
119 the stress state in the segmental lining in order to then proceed to a preliminary sizing of the
120 support system. Further investigations and verifications are, however, required. In fact, a
121 subsequent detailed calculation phase is required with two-dimensional and three-
122 dimensional numerical modeling. This calculation tool requires the construction of the grid
123 of numerical elements and for this reason it is useful, or rather indispensable, to have a
124 preliminary geometric evaluation of the thicknesses of the segmental lining and of the filling
125 material. Finally, the results of the numerical calculation are able to definitively justify the
126 design choices and establish the dimensions of all the components of the support system.

127 **Simplified methods of tunnel segmental lining analysis**

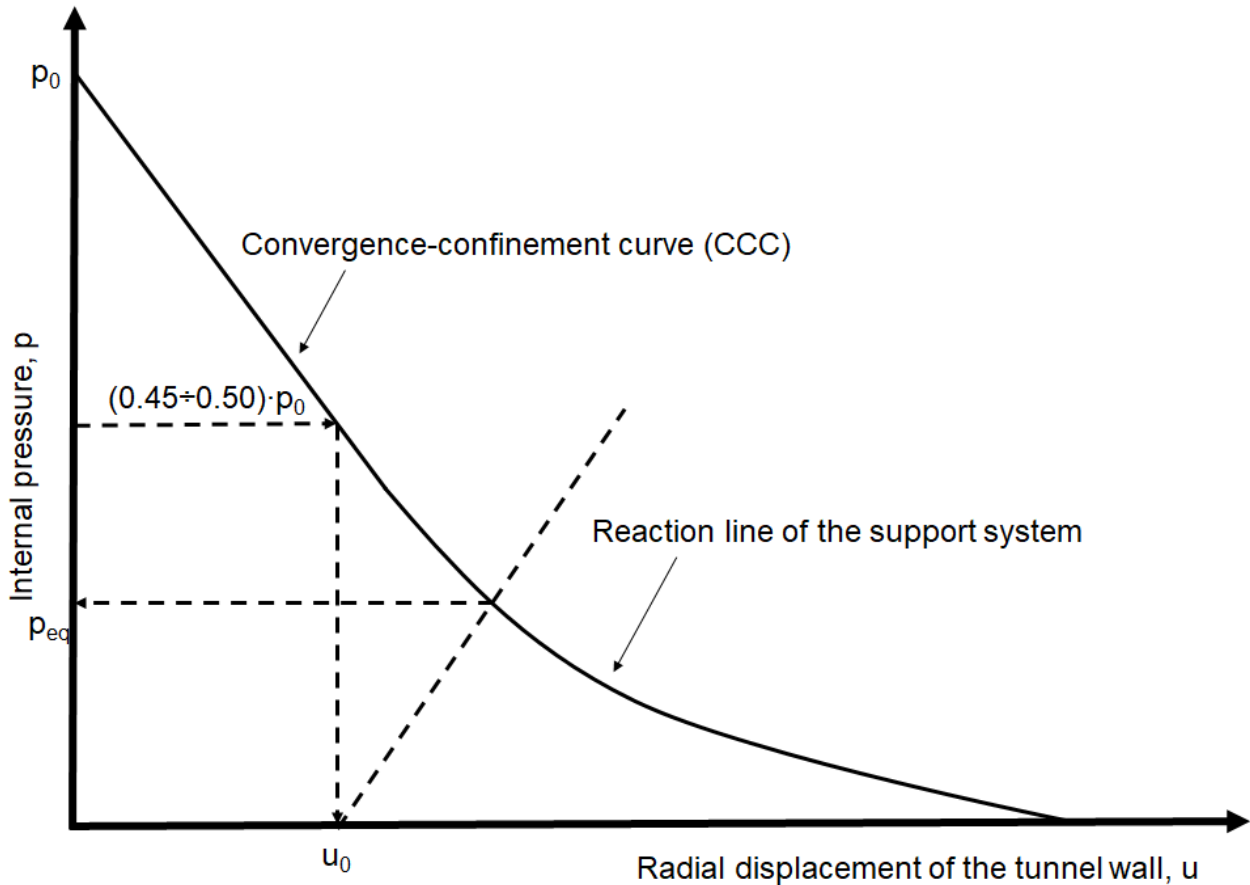
128 A calculation method widely used to analyze the behavior of tunnel supports is the
129 convergence-confinement method, abbreviated as CCM (Oreste, 2003; 2009; Panet and
130 Guenot, 1982; Amberg and Lombardi, 1974). Through this simple method, it is possible to
131 evaluate the final load p_{eq} transmitted by the soil/rock surrounding the tunnel to the adopted
132 supporting system. Two different curves on the internal pressure/radial displacement of the

133 tunnel wall graph are drawn: the convergence-confinement curve (CCC) and the reaction
134 line of the support system (Fig. 2).

135 The convergence-confinement method is based on the following fundamental assumptions:

- 136 • Circular cavity at a great depth
- 137 • Homogeneous mechanical parameters of the ground;
- 138 • Hydrostatic type of the undisturbed initial stress p_0 : the vertical stress is equal to the
139 horizontal one.

140 To obtain a correct evaluation of the load transmitted to the support system, it is necessary
141 to locate the reaction line on the graph and, therefore, define the displacement u_0 of the
142 tunnel wall at the time of installation of the support system. Some calculation procedures
143 are available in the literature to estimate u_0 (e.g. Vlachopoulos and Diederichs, 2009;
144 Spagnoli et al., 2016). In the case of segmental lining installed on the tail of the TBM, i.e. at
145 a certain distance from the tunnel face, a value equal to the displacement corresponding to
146 an internal pressure of $\alpha \cdot p_0$ ($\alpha = 0.45-0.50$) on the CCC is generally adopted.



147

148 **Fig. 2. Convergence-confinement method: intersection of the convergence-**
 149 **confinement curve with the reaction line of the support system. Key: p : inner pressure**
 150 **applied to the tunnel wall; u : radial displacement of the tunnel wall; p_0 : in situ vertical**
 151 **stress; p_{eq} : final radial load on the support system; u_0 : radial displacement of the**
 152 **tunnel wall where the support system is installed.**

153 For the case of ideal elasto-plastic behavior of the ground (Oreste, 2009), the convergence-
 154 confinement curve can be obtained by evaluating the radial displacement u of the tunnel
 155 wall as a function of the internal pressure p , through the following equations:

156
 157 For $< [p_0 \cdot (1 - \sin(\varphi)) - c \cdot \cos(\varphi)]$:

$$\begin{aligned}
158 \quad u &= \frac{1+\nu}{E} \cdot \left\{ \left[\frac{R^{N_\Psi+1}}{R^{N_\Psi}} \cdot \sin(\varphi) + (1 - 2 \cdot \nu) \cdot \left(\frac{R_{pl}^{N_\Psi+1}}{R^{N_\Psi}} - R \right) \right] \cdot \left(p_0 + \frac{c}{\tan(\varphi)} \right) - \right. \\
159 \quad & \left. \frac{1+N_\Phi \cdot N_\Psi - \nu \cdot (N_\Psi+1) \cdot (N_\Phi+1)}{(N_\Phi+N_\Psi) \cdot R^{(N_\Phi-1)}} \cdot \left(\frac{R_{pl}^{(N_\Phi+N_\Psi)}}{R^{N_\Psi}} - R^{N_\Phi} \right) \cdot \left(p + \frac{c}{\tan(\varphi)} \right) \right\} \quad (1)
\end{aligned}$$

160 where R_{pl} is the plastic radius of the tunnel:

$$161 \quad R_{pl} = R \cdot \left[\frac{\left(p_0 + \frac{c}{\tan(\varphi)} \right) \cdot (1 - \sin(\varphi))}{p + \frac{c}{\tan(\varphi)}} \right]^{\frac{1}{(N_\Phi-1)}} \quad (2)$$

$$162 \quad N_\Phi = \frac{1 + \sin(\varphi)}{1 - \sin(\varphi)} \quad (3)$$

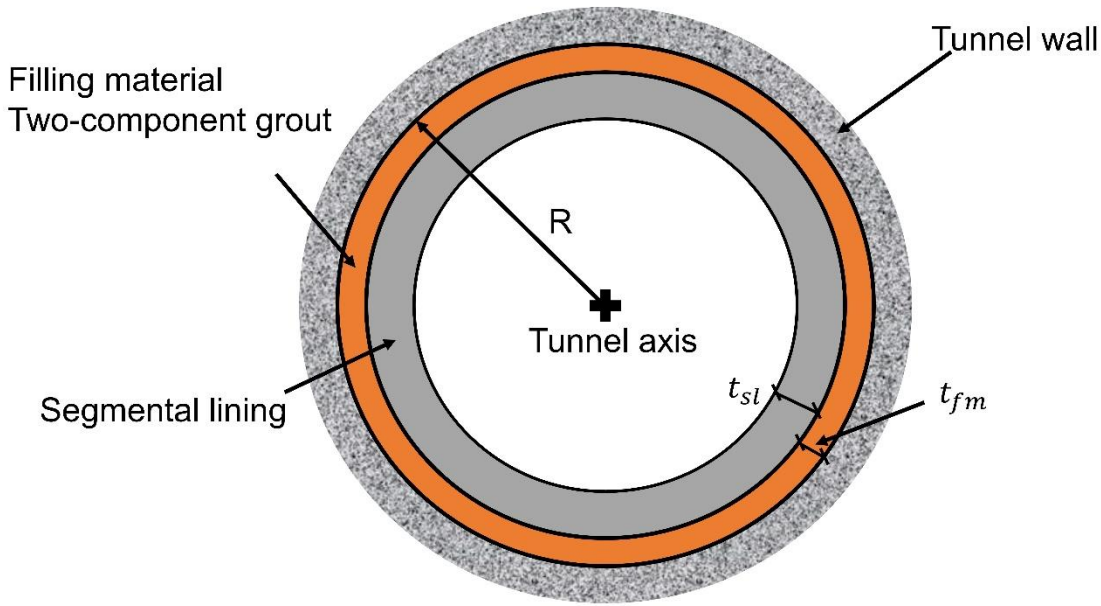
$$163 \quad N_\Psi = \frac{1 + \sin(\Psi)}{1 - \sin(\Psi)} \quad (4)$$

164 R is the tunnel radius, c , φ and Ψ are respectively the cohesion, friction angle and dilatancy
165 of the ground, E and ν are respectively the elastic modulus and the Poission ratio of the
166 ground.

167 For $p > [p_0 \cdot (1 - \sin(\varphi)) - c \cdot \cos(\varphi)]$:

$$168 \quad u = \frac{1+\nu}{E} \cdot (p_0 - p) \cdot R \quad (5)$$

169 As regards the reaction line of the support system, it is necessary to consider the presence
170 of segmental lining and filling material (two-component material) in the space between the
171 segmental lining and the surrounding ground (Fig. 3).



172

173 **Fig. 3. Cross section of the support system. Key: R : tunnel radius; t_{sl} : thickness of**
 174 **the segmental lining; t_{fm} : thickness of the filling material-not to scale (modified after**
 175 **Oggeri et al. 2021) .**

176 On the basis of what developed by Oreste (2003) it is possible to determine the stiffness of
 177 the k_{sys} support system (segmental lining and ring of filling material around it) on the basis
 178 of the following equation:

$$179 \quad k_{sys} = \frac{2 \cdot E_{fm} \cdot (1 - \nu_{fm}) \cdot R \cdot \left[\frac{E_{fm}}{(1 + \nu_{fm})} + (R - t_{fm}) \cdot k_{sl} \right]}{E_{fm} \cdot (1 - 2 \cdot \nu_{fm}) \cdot R^2 + (R - t_{fm})^2 \cdot \left[E_{fm} + (1 - 2 \cdot \nu_{fm}) \cdot (1 + \nu_{fm}) \cdot k_{sl} \cdot t_{fm} \cdot \left(1 + \frac{R}{(R - t_{fm})} \right) \right]} - \frac{E_{fm}}{(1 + \nu_{fm}) \cdot R} \quad (6)$$

180 where:

$$181 \quad k_{sl} = \frac{E_{sl}}{(1 + \nu_{sl})} \cdot \frac{(R - t_{fm})^2 - (R - t_{fm} - t_{sl})^2}{(1 - 2 \cdot \nu_{sl}) \cdot (R - t_{fm})^2 + (R - t_{fm} - t_{sl})^2} \cdot \frac{1}{(R - t_{fm})} \quad (7)$$

182 E_{fm} and ν_{fm} are respectively the elastic modulus and the Poisson's ratio of the filling
183 material; E_{sl} and ν_{sl} are respectively the elastic modulus and the Poisson's ratio of the
184 segmental lining; t_{fm} and t_{sl} are respectively the thickness of the filling material and
185 segmental lining; k_{sl} is the radial stiffness of the segmental lining.

186 The stiffness of the support system allows to draw the reaction line of Fig. 2, since it
187 represents the slope of the line on the graph:

$$188 \quad p = k_{sys} \cdot (u - u_0) \quad (8)$$

189 In equation 6 it is necessary to introduce the elastic modulus E_{fm} of the two-component
190 material, which shows a variation over time (Oggeri et al., 2021; 2022; Oreste et al., 2021).
191 For this reason, it is necessary to enter an average value representative of the elastic
192 modulus during the period of loading of the support system, taking into account the following
193 parameters that affect this evaluation:

- 194 • the downtime of the TBM after the injection of the two-component material;
- 195 • the average advancement speed of the TBM after the installation of the segmental lining
196 and the injection of the two-component material.

197 In the case of a linear elastic behavior of the ground, the convergence-confinement curve
198 becomes a line (eq. 5) and p_{eq} can be obtained from the following simple expression:

$$199 \quad p_{eq} = \frac{\alpha \cdot p_0}{\frac{E}{(1+\nu) \cdot R \cdot k_{sys}} + 1} \quad (9)$$

200 k_{sys} it is a very important parameter because it is able to describe the response, in
201 deformation terms, of the support system to the loads applied by the surrounding soil/rock.

202 For the detailed analysis of support systems, the method of Einstein and Schwartz (1979)
 203 can also be used. Through this method it is possible to evaluate the bending moments and
 204 the normal forces that develop along the profile of a support system of a circular and deep
 205 cavity. The main hypothesis assumed by the authors consists in considering the support
 206 system continuously connected to the surrounding ground. An elastic behavior is foreseen
 207 both for the ground and for the material constituting the support system. The following
 208 equations are able to provide the maximum moment M_{max} that develops in the support
 209 system, together with the normal force at the center of the crown N_{crown} and on the sidewalls
 210 $N_{sidewall}$ (Einstein and Schwartz, 1979; Guan et al., 2015):

$$211 \quad M_{max} = (1 + \xi) \cdot \frac{p_{eq} \cdot (R - t_{fm})^2 \cdot (1 - K_0)}{(1 + K_0) \cdot (1 - a_0^*) + (1 - K_0) \cdot (3 - 6 \cdot a_2^*)} \cdot (1 - 2 \cdot a_2^*) \quad (10)$$

$$212 \quad N_{crown} = \frac{p_{eq} \cdot R \cdot (1 + K_0)}{(1 + K_0) \cdot (1 - a_0^*) + (1 - K_0) \cdot (3 - 6 \cdot a_2^*)} \cdot (2 \cdot a_2^* - a_0^*) \quad (11)$$

$$213 \quad N_{sidewall} = \frac{p_{eq} \cdot R \cdot (1 + K_0)}{(1 + K_0) \cdot (1 - a_0^*) + (1 - K_0) \cdot (3 - 6 \cdot a_2^*)} \cdot (2 - a_0^* - 2 \cdot a_2^*) \quad (12)$$

214 where:

$$215 \quad a_0^* = \frac{C^* \cdot F^* \cdot (1 - \nu)}{C^* + F^* + C^* \cdot F^* \cdot (1 - \nu)} \quad (13)$$

$$216 \quad a_2^* = \frac{(F^* + 6) \cdot (1 - \nu)}{2 \cdot F^* \cdot (1 - \nu) + 6 \cdot (5 - 6 \cdot \nu)} \quad (14)$$

$$217 \quad C^* = \frac{E \cdot R \cdot (1 - \nu_{sl}^2)}{\left(E_{fm} + E_{sl} \cdot \frac{t_{sl}}{t_{sl} + t_{fm}} \right) \cdot (t_{fm} + t_{sl}) \cdot (1 - \nu^2)} \quad (15)$$

$$218 \quad F^* = \eta \cdot \frac{12 \cdot E \cdot (R - t_{fm})^3 \cdot (1 - \nu_{sl}^2)}{E_{sl} \cdot t_{sl}^3 \cdot (1 - \nu^2)} \quad (16)$$

219 K_0 is the lateral earth pressure at rest in the ground (in the initial undisturbed conditions);

220 E and ν are respectively the elastic modulus and the Poisson ratio of the ground;

221 C^* and F^* are compressibility ratio and flexibility ratio of the support system, respectively. In
222 evaluating C^* it was assumed that the average elastic modulus representative of the support
223 system is the average of the values of the segmental lining and the filling material, weighted
224 on the respective thicknesses. As regard F^* , only the contribution from segmental lining is
225 assumed, neglecting the presence of the filling material.

226 ξ is an incremental coefficient that takes into account the transfer of stresses from one ring
227 to the adjacent one, in correspondence with the longitudinal joints of the segmental lining; a
228 value of 0.45 can be used (Guan et al., 2015). η is a coefficient that takes into account the
229 presence of longitudinal joints in segmental lining, reducing its bending stiffness with respect
230 to a continuous lining; it varies between 0.4 and 0.7, with an intermediate value of 0.55
231 (Guan et al., 2015).

232 The simplified analysis of the stress state in the segmental lining (sl) and in the filling material
233 (fm) leads to the following maximum circumferential stresses $\sigma_{\vartheta,max}$:

$$234 \sigma_{\vartheta,max,sl} = \frac{6 \cdot M_{max}}{t_{sl}^2} + \frac{\max(N_{crown}; N_{sidewall})}{t_{sl}} \cdot \frac{E_{sl} \cdot t_{sl}}{E_{sl} \cdot t_{sl} + E_{fm} \cdot t_{fm}} \quad (17)$$

$$235 \sigma_{\vartheta,max,fm} = \frac{\max(N_{crown}; N_{sidewall})}{t_{fm}} \cdot \frac{E_{fm} \cdot t_{fm}}{E_{sl} \cdot t_{sl} + E_{fm} \cdot t_{fm}} \quad (18)$$

236 In the definition of the stress state, it is assumed that the bending moment is completely
237 absorbed by the segmental lining alone, since the bending stiffness of the filling material is
238 negligible. The normal force N is distributed, on the other hand, in a proportional way to the
239 normal stiffness, between the segmental lining and the filling material.

240 In addition to the circumferential stresses obtained by eq. 17 and 18, it is also necessary to
241 consider the presence of radial stresses, which are in both cases equal to p_{eq} .

242 Once the stress state induced in the two materials is known, it is possible to determine the
243 safety factors in relation to the risk of a possible failure, adopting the Mohr-Coulomb strength
244 criterion:

$$245 \quad F_{s,sl} = \frac{UCS_{sl} + \frac{1+\sin(\varphi_{sl})}{1-\sin(\varphi_{sl})} p_{eq}}{\sigma_{\vartheta,max,sl}} \quad (19)$$

$$246 \quad F_{s,fm} = \frac{UCS_{fm} + \frac{1+\sin(\varphi_{fm})}{1-\sin(\varphi_{fm})} p_{eq}}{\sigma_{\vartheta,max,fm}} \quad \text{if } \sigma_{\vartheta,max,fm} \geq p_{eq} \quad (20a)$$

$$247 \quad F_{s,fm} = \frac{UCS_{fm} + \frac{1+\sin(\varphi_{fm})}{1-\sin(\varphi_{fm})} \sigma_{\vartheta,max,fm}}{p_{eq}} \quad \text{if } \sigma_{\vartheta,max,fm} < p_{eq} \quad (20b)$$

248 Where UCS and φ are respectively the uniaxial compression strength and the friction angle
249 of the material (concrete for segmental lining or filling material).

250 The evaluation of the safety factors with regard to the possible failure of the two materials
251 constituting the support system is able to drive the design phase and define the mechanical
252 and geometric characteristics. More specifically, it will be necessary to evaluate:

- 253 • the thickness of the segmental lining and the filling material;
- 254 • the required average elastic modulus of the two-component material that constitutes the
255 filling material, during the loading phase of the support system.

256 **Results and discussion**

257 To evaluate the stress state induced in the segmental lining and in the filling material in the
258 various cases that may be encountered during the construction of a tunnel using a TBM in
259 a soil mass, a parametric analysis was developed consisting of 243 cases, varying:

- 260 • Tunnel radius R : 2, 3.5 and 5 m;
- 261 • Tunnel depth z : 25, 100, 175 m;
- 262 • Elastic modulus of the filling material E_{fm} : 50, 500 and 1000 MPa;
- 263 • Type of ground: soft ($E=100$ MPa), medium ($E =500$ MPa) and stiff ($E =1000$ MPa);
- 264 • Lateral earth pressure at rest in the ground K_0 : 0.5, 1.0 and 1.50;

265 The values adopted in the analysis represent the extremes and the central value of the
266 variability ranges of the single parameters, which are typically encountered in the excavation
267 of tunnels with TBM machines. They have been identified through an extensive analysis of
268 real cases of tunnels for which the TBM has been adopted as a means of excavation.

269 By elastic modulus E_{fm} of the filling material, it is meant the average elastic modulus of the
270 two-component during the loading phase of the support system, that is, in the first phases
271 following its installation in which the Tunnel Boring Machine (TBM) moves forward.

272 A recurring value of the thickness of the segmental lining (t_{sl}) of 30 cm is adopted in the
273 calculations. The thickness of the filling material was assumed to be 15 cm (t_{fm}). For the
274 elastic modulus of the concrete a value equal to 35 GPa (E_{sl}) was considered. The Poisson
275 ratios used in the calculation were 0.30 (ν), 0.15 (ν_{sl}), 0.09 (ν_{fm}), respectively for the ground,
276 concrete and filling material. The value of the η coefficient in equation 15 was cautiously
277 assumed to be 0.4, i.e. equal to the minimum value of its detected variability interval. The
278 UCS strength for the concrete was assumed to be 40 MPa (UCS_{sl}), while for the filling
279 material a value of 1 MPa (UCS_{fm}) was cautiously adopted, the minimum value among those

280 detected in the laboratory tests available in the literature. The friction angles of the concrete
281 (φ_{sl}) and of the filling material (φ_{fm}) have been set equal to 40° and 30°, respectively.

282 The results of the calculation in terms of maximum circumferential stress in the segmental
283 lining ($\sigma_{\vartheta,max,sl}$ of eq. 17) together with the safety factors FS_{sl} and FS_{fm} (eq. 19 and 20), are
284 shown in the following figures. They allow detecting the effects of the influencing
285 parameters, in particular of the two-component filling material, on the induced stress-state
286 of the tunnel segmental lining and of the same filling material.

287 Figures 4 to 6 show the maximum circumferential stresses in segmental lining ($\sigma_{\vartheta,max,sl}$) as
288 the coefficient K_0 varies for the case of tunnel radius $R = 3.5$ m, respectively for a depth of
289 25 m (Fig. 4), 100 m (Fig. 5) and 175 m (Fig. 6). It can be seen how the maximum stresses
290 in concrete always increase as K_0 distances from the unit, reaching significantly larger
291 values for $K_0 = 0.5$ or $K_0 = 1.5$. Furthermore, the elastic modulus of the ground E has a
292 significant importance on the maximum stress in the concrete of segmental lining: as the
293 elastic modulus decreases, the stress increases significantly, especially when the elastic
294 modulus is less than 500 MPa. As regards the elastic modulus of the two-component
295 material E_{fm} , its effect on the maximum stress in the concrete is noted, especially when the
296 elastic modulus of the ground E is high and only for $E_{fm} < 500$ MPa. In fact, in all the analyzed
297 cases, there is no difference in the maximum stress as the E_{fm} varies between 500 and
298 1000 MPa. The depth of the tunnel obviously has effects on the stress state of the segmental
299 lining: as the depth increases, the maximum stress in the segmental lining increases, almost
300 proportional to the depth. The trend of the shown diagrams, however, remains the same at
301 different depths, varying only the value of the stress.

302 For smaller tunnel radii ($R = 2$ m) the same considerations seen for $R = 3.5$ m apply, with
303 the only exception that the growth of the maximum stress is not particularly marked for
304 elastic modules of the ground E below 500 MPa. On the contrary, for $R = 5$ m, the significant

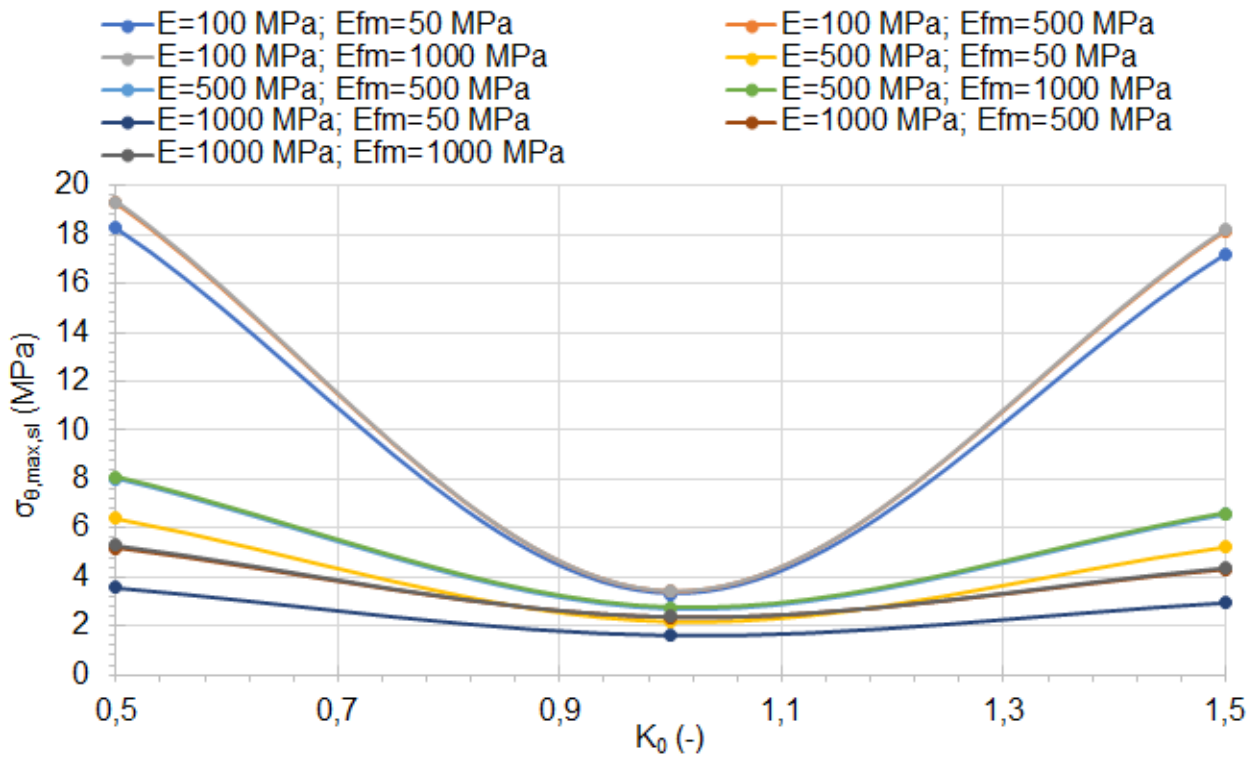
305 increase in the maximum stress for $E < 500$ MPa detected in the case of 3.5 m radius is even
306 more pronounced.

307 Obviously, there is a reduction in the stress state in the segmental lining as the tunnel radius
308 decreases and the opposite for larger radii.

309 Of particular interest is the analysis of the safety factors of segmental lining with regard to
310 concrete failure. The following figures (Fig. 7-15) show the $FS_{s,l}$ as K_0 , E and E_{fm} vary, for
311 the three values of R and the three of z considered in the analysis.

312 The lowest safety factors $FS_{s,l}$ are obtained for K_0 far from the unit, for E_{fm} greater than 500
313 MPa and for lower elastic modules of the ground E . When E is low, the effect of E_{fm} on the
314 safety factors of the segmental lining vanishes. Furthermore, for $E_{fm} > 500$ MPa the influence
315 of the elastic modulus of the two-component material on the safety factor of the segmental
316 lining is never detected. Obviously the $FS_{s,l}$ tend to decrease with the increasing depth and
317 tunnel radius.

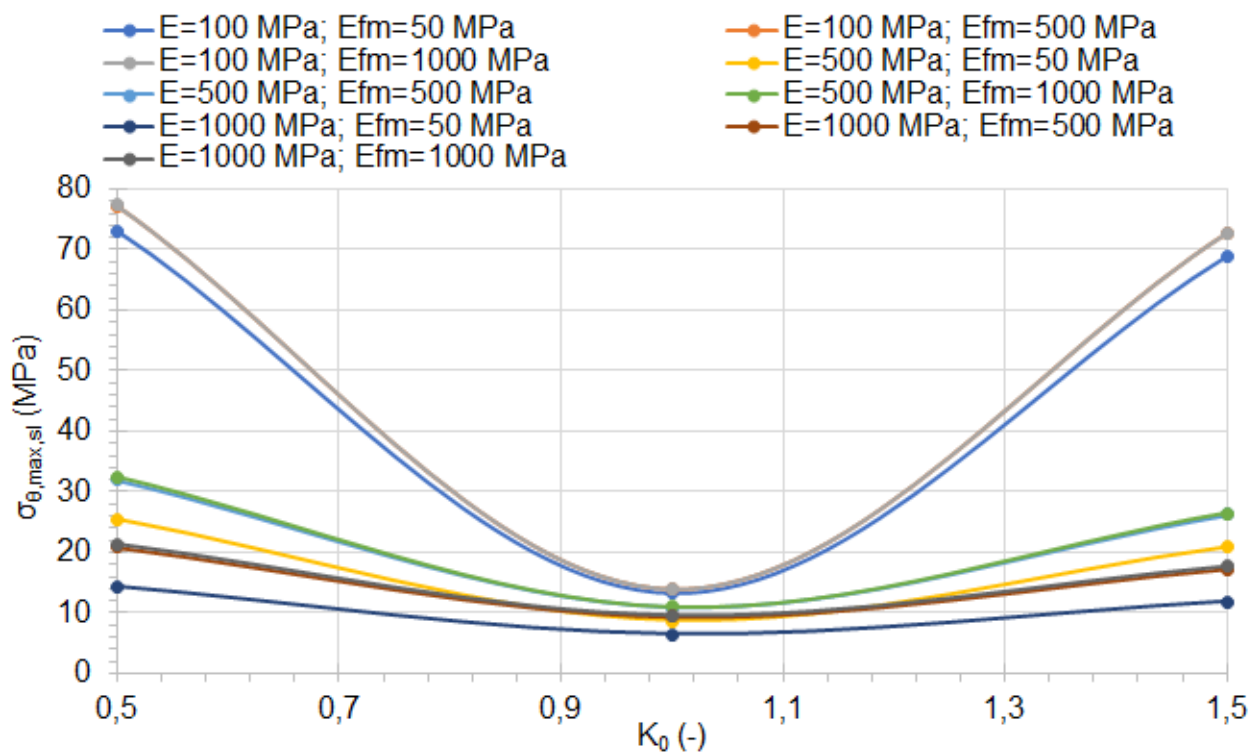
318 The graphs shown can be very useful in the design phase, in order to decide the
319 characteristics of the two-component material to fill the gap between the segmental lining
320 and the tunnel wall and the thicknesses of the segmental lining and the filling material. Only
321 through an evaluation of the safety factors, in fact, it is possible to decide the fundamental
322 parameters of the support system design in order to guarantee a certain distance from risk
323 situations in relation to the possible failure of the concrete.



324

325 **Fig. 4. Maximum circumferential stress ($\sigma_{\theta,max,sl}$) in the concrete of the segmental**
 326 **lining, as the coefficient K_0 varies for different values of the elastic modulus of the**
 327 **ground (E) and of the elastic modulus of the filling material (E_{fm}). Case of a tunnel**
 328 **with radius $R = 3.5$ m and depth $z = 25$ m.**

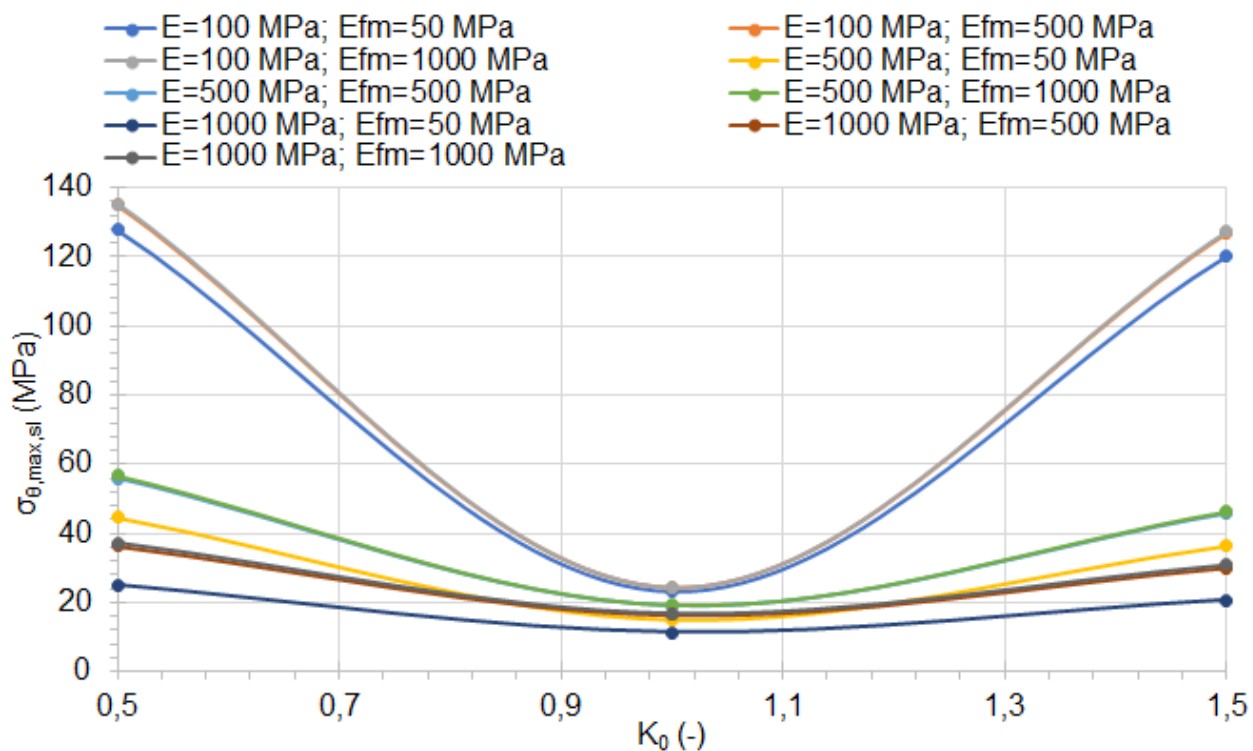
329



330

331 **Fig. 5. Maximum circumferential stress ($\sigma_{\vartheta,max,sl}$) in the concrete of the segmental**
 332 **lining, as the coefficient K_0 varies for different values of the elastic modulus of the**
 333 **ground (E) and of the elastic modulus of the filling material (E_{fm}). Case of a tunnel**
 334 **with radius $R = 3.5$ m and depth $z = 100$ m.**

335

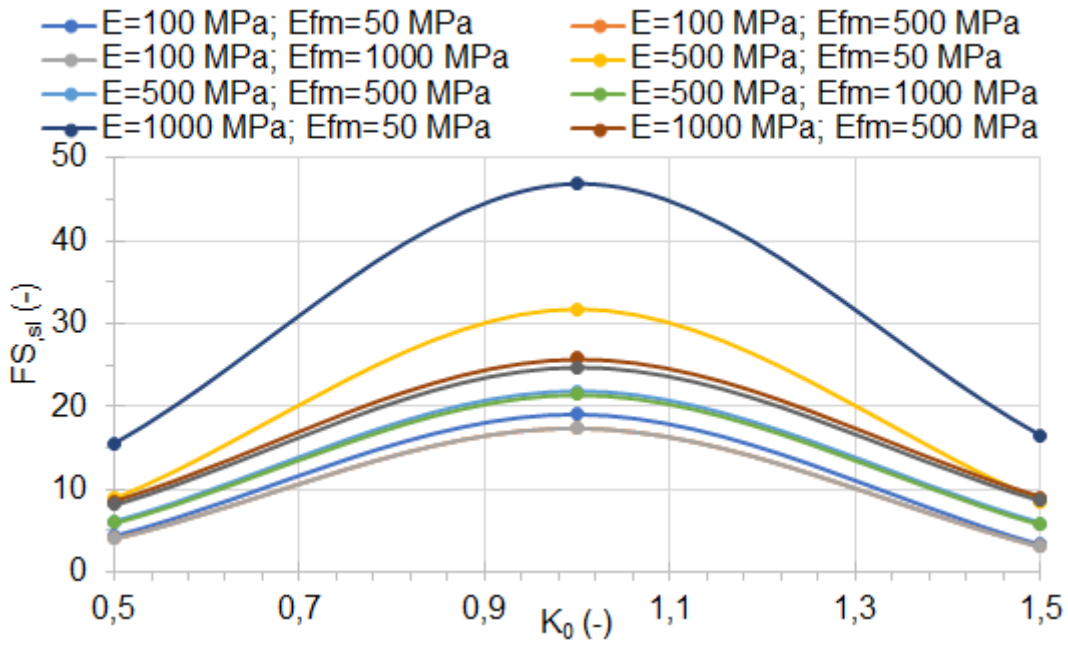


336

337 **Fig. 6. Maximum circumferential stress ($\sigma_{\vartheta,max,sl}$) in the concrete of the segmental**
 338 **lining, as the coefficient K_0 varies for different values of the elastic modulus of the**
 339 **ground (E) and of the elastic modulus of the filling material (E_{fm}). Case of a tunnel**
 340 **with radius $R = 3.5$ m and depth $z = 175$ m.**

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342



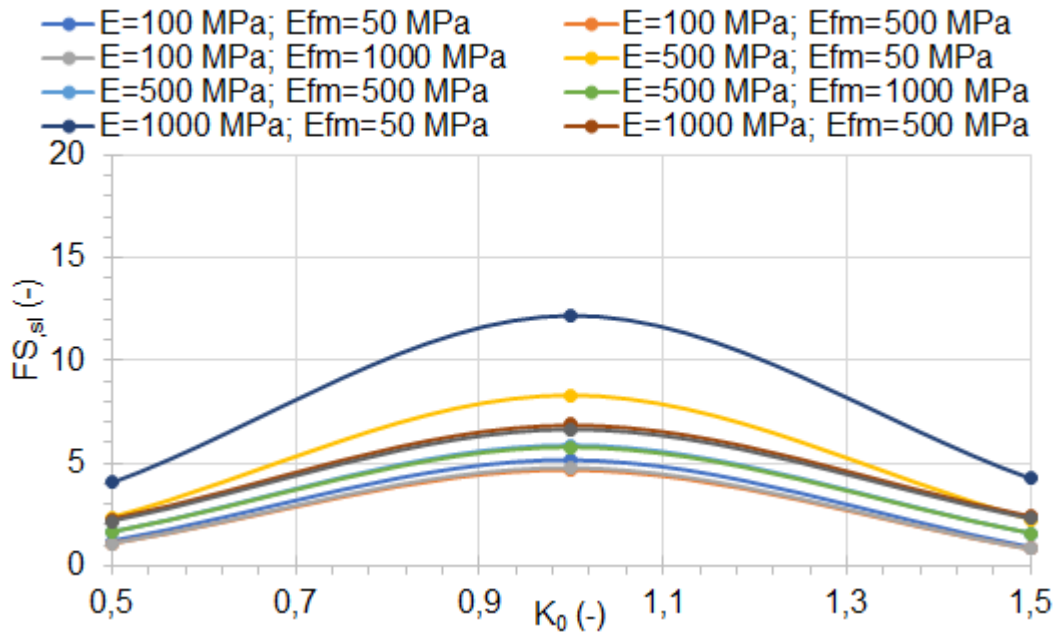
343

344 **Fig. 7. Safety factors in segmental lining (FS_{sl}) as the coefficient K_0 varies for**
 345 **different values of the elastic modulus of the ground (E) and of the elastic modulus**
 346 **of the filling material (E_{fm}). Case of a tunnel with radius $R = 2$ m and depth $z = 25$ m.**

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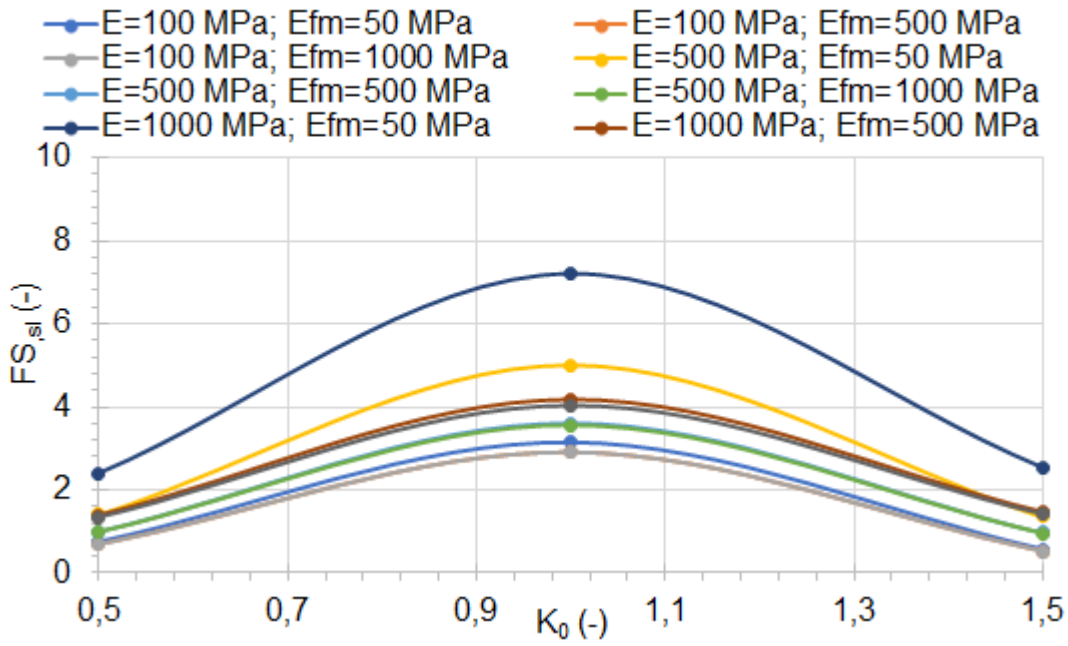
351 **Fig. 8. Safety factors in segmental lining (FS_{sl}) as the coefficient K_0 varies for**
 352 **different values of the elastic modulus of the ground (E) and of the elastic modulus**
 353 **of the filling material (E_{fm}). Case of a tunnel with radius $R = 2$ m and depth $z = 100$ m.**

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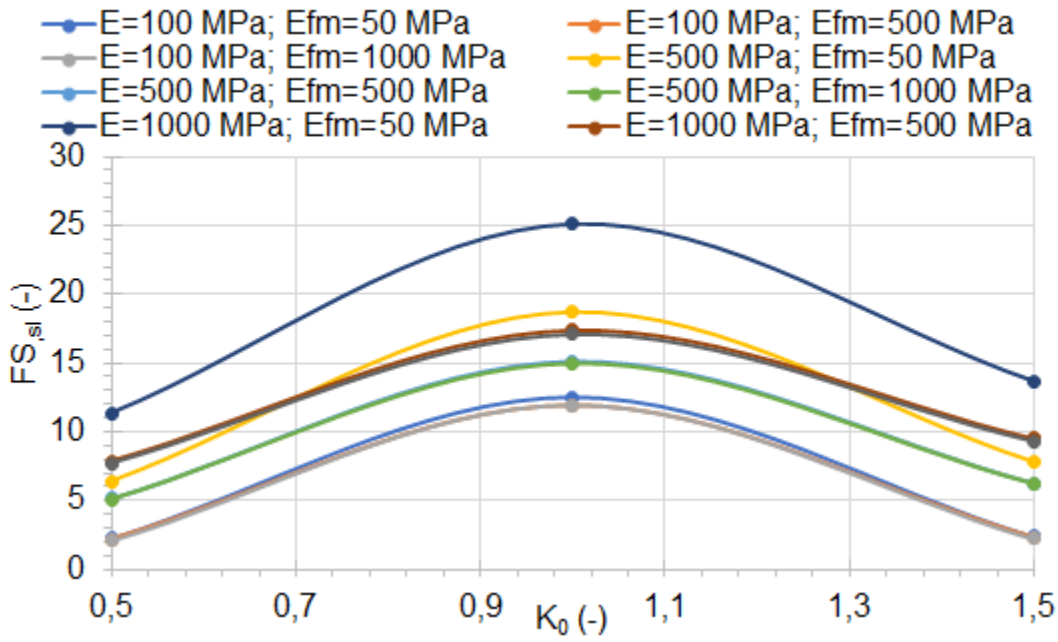
358

359 **Fig. 9. Safety factors in segmental lining (FS_{sl}) as the coefficient K_0 varies for**
 360 **different values of the elastic modulus of the ground (E) and of the elastic modulus**
 361 **of the filling material (E_{fm}). Case of a tunnel with radius $R = 2$ m and depth $z = 175$ m.**

362

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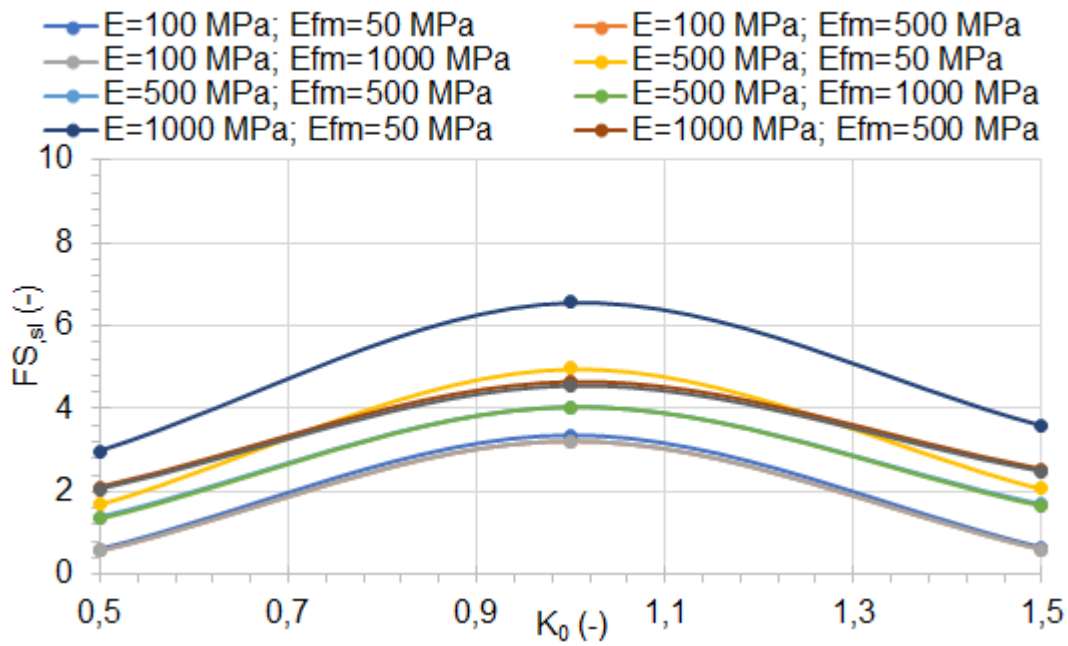
365

366 **Fig. 10. Safety factors in segmental lining (FS_{sl}) as the coefficient K_0 varies for**
 367 **different values of the elastic modulus of the ground (E) and of the elastic modulus**
 368 **of the filling material (E_{fm}). Case of a tunnel with radius $R = 3.5$ m and depth $z = 25$ m.**

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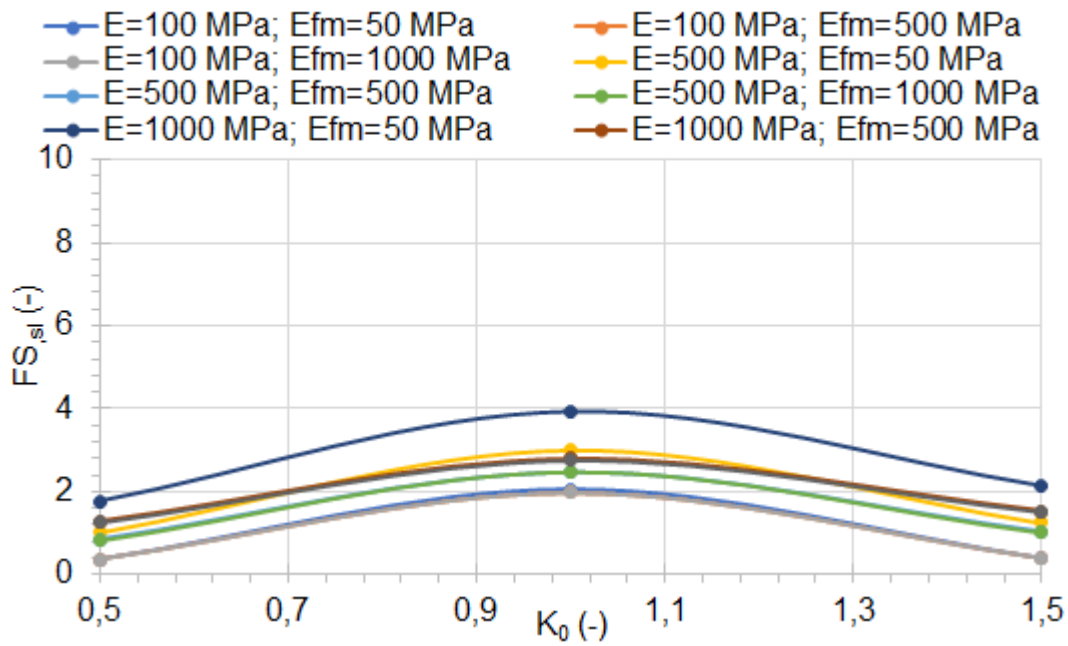
372

373 **Fig. 11. Safety factors in segmental lining (FS_{sl}) as the coefficient K_0 varies for**
 374 **different values of the elastic modulus of the ground (E) and of the elastic modulus**
 375 **of the filling material (E_{fm}). Case of a tunnel with radius $R = 3.5$ m and depth $z = 100$**
 376 **m.**

377

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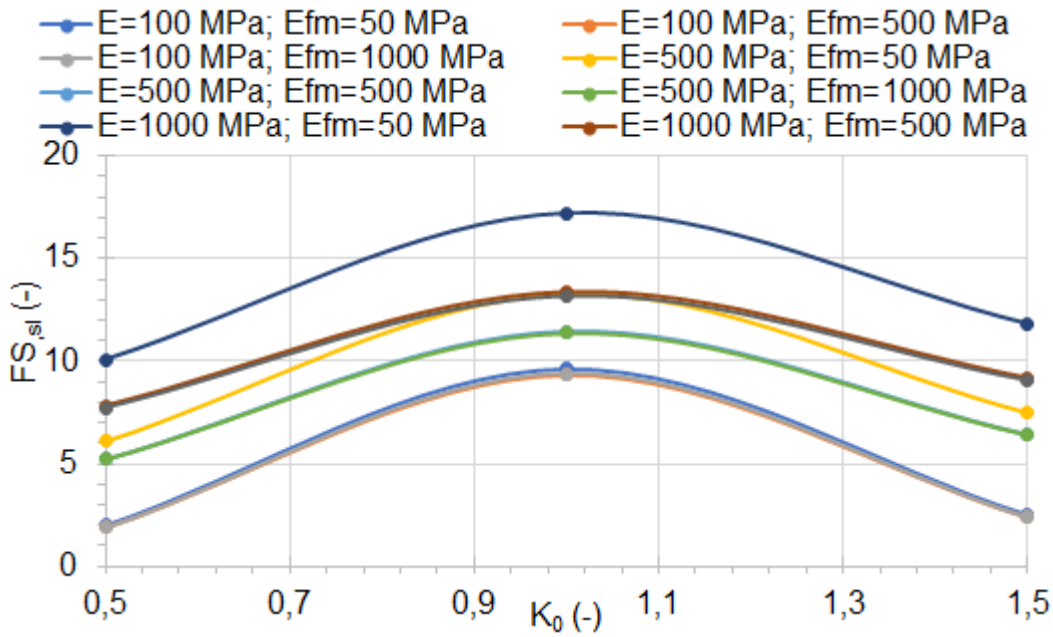
380

381 **Fig. 12. Safety factors in segmental lining (FS_{sl}) as the coefficient K_0 varies for**
 382 **different values of the elastic modulus of the ground (E) and of the elastic modulus**
 383 **of the filling material (E_{fm}). Case of a tunnel with radius $R = 3.5$ m and depth $z = 175$**
 384 **m.**

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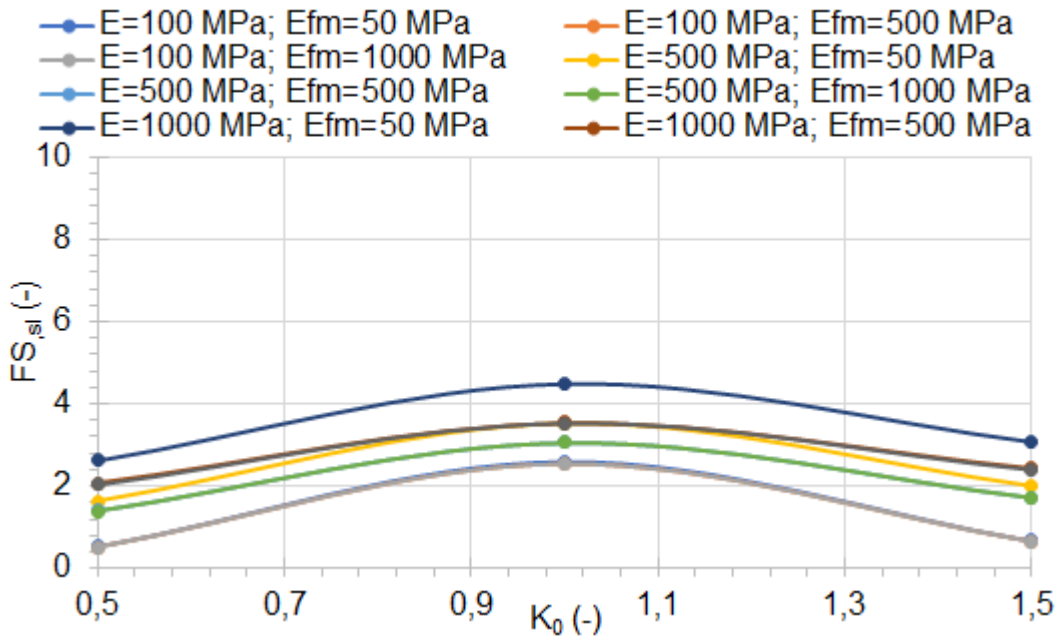
388

389 **Fig. 13. Safety factors in segmental lining (FS_{sl}) as the coefficient K_0 varies for**
 390 **different values of the elastic modulus of the ground (E) and of the elastic modulus**
 391 **of the filling material (E_{fm}). Case of a tunnel with radius $R = 5$ m and depth $z = 25$ m.**

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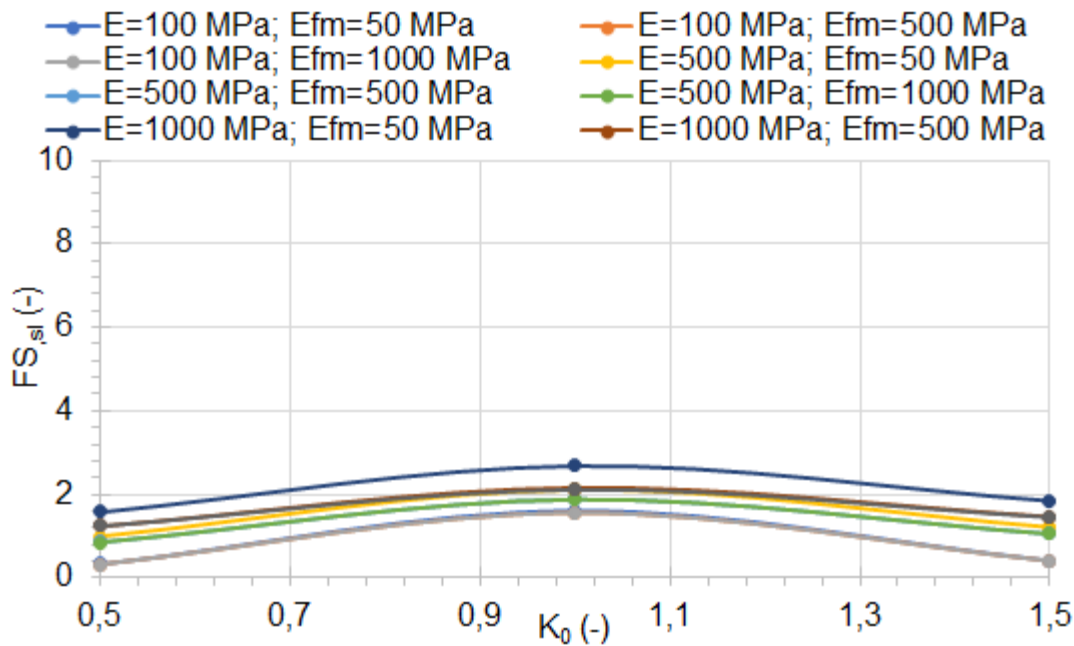
396 **Fig. 14. Safety factors in segmental lining (FS_{sl}) as the coefficient K_0 varies for**
 397 **different values of the elastic modulus of the ground (E) and of the elastic modulus**
 398 **of the filling material (E_{fm}). Case of a tunnel with radius $R = 5$ m and depth $z = 100$ m.**

399

400

401

402



403

404 **Fig. 15. Safety factors in segmental lining (FS_{sl}) as the coefficient K_0 varies for**
 405 **different values of the elastic modulus of the ground (E) and of the elastic modulus**
 406 **of the filling material (E_{fm}). Case of a tunnel with radius $R = 5$ m and depth $z = 175$ m.**

407

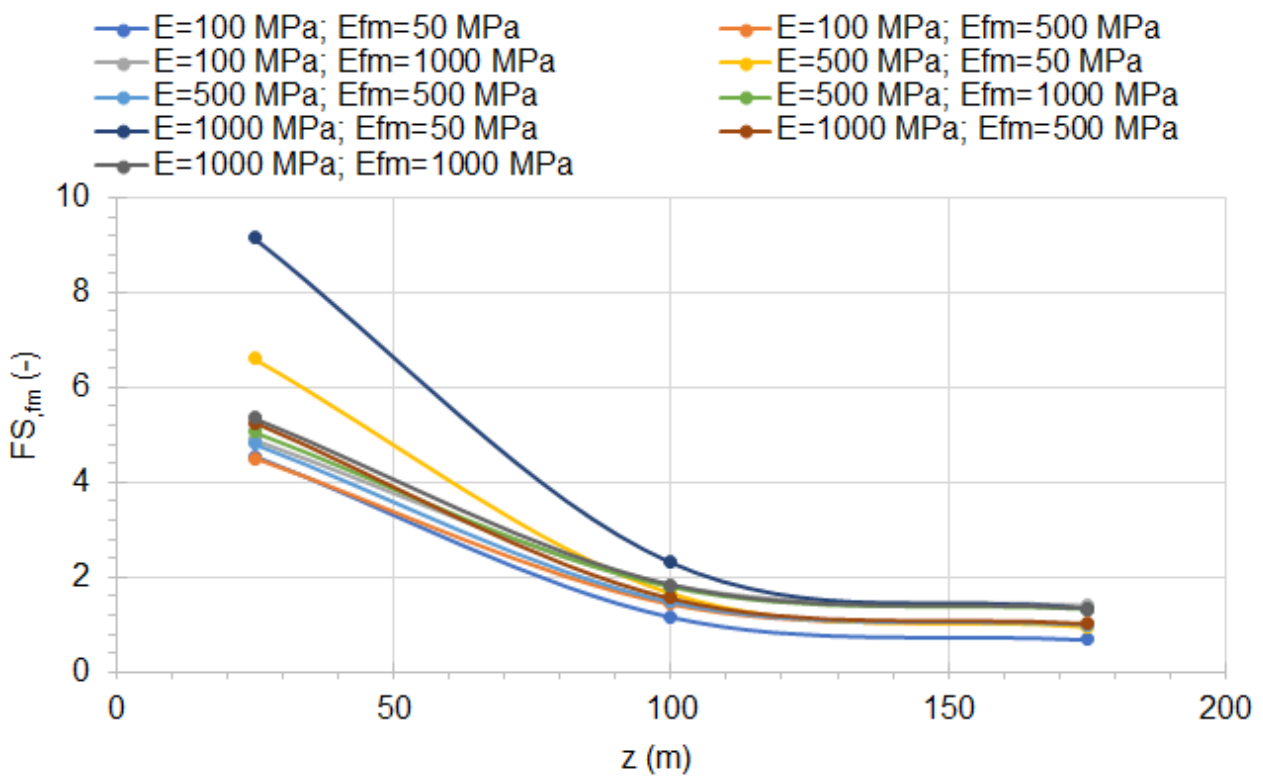
408 As for the safety factors of the filling material with regard to failure due to the stress state
 409 induced inside it, it can be noted that the coefficient K_0 has no importance: in fact, since the
 410 filling material has a negligible bending stiffness, the moments that develop inside it are
 411 practically nil; the existing circumferential stresses are due solely to the normal force N .

412 Figures 16-18 show the FS_{fm} as the depth z varies, for the different values of E and E_{fm}
 413 considered in the analysis, for the cases of $R = 2$ m (Fig. 16), $R = 3.5$ (Fig. 17) and $R = 5$ m
 414 (Fig. 18).

415 These safety factors were calculated by adopting a precautionary UCS_{fm} strength equal to
 416 1 MPa. It is clear that by intervening to increase the UCS_{fm} , an increase in the safety factor
 417 and a reduction in the risk of failure of the filling material around the segmental lining can be
 418 obtained.

419 From the analysis of Fig. 16 it can be seen how the $FS_{,fm}$ tends to decrease considerably up
 420 to 100-120 m in depth and then stabilize at minimum values. The depth of the tunnel,
 421 therefore, plays a fundamental role with regards to the possible risk of failure of the filling
 422 material, with all the possible consequences on the infiltration of groundwater into the tunnel
 423 and on the consequent possible chemical-physical aggression on the concrete of the
 424 segmental lining. The lowest values of the safety factor are obtained in correspondence of
 425 a ground with a low elastic modulus E and of a low stiffness of the filling material E_{fm} .
 426 The size of the tunnel has a marginal influence as can be seen with the comparison with
 427 Fig.17-18.

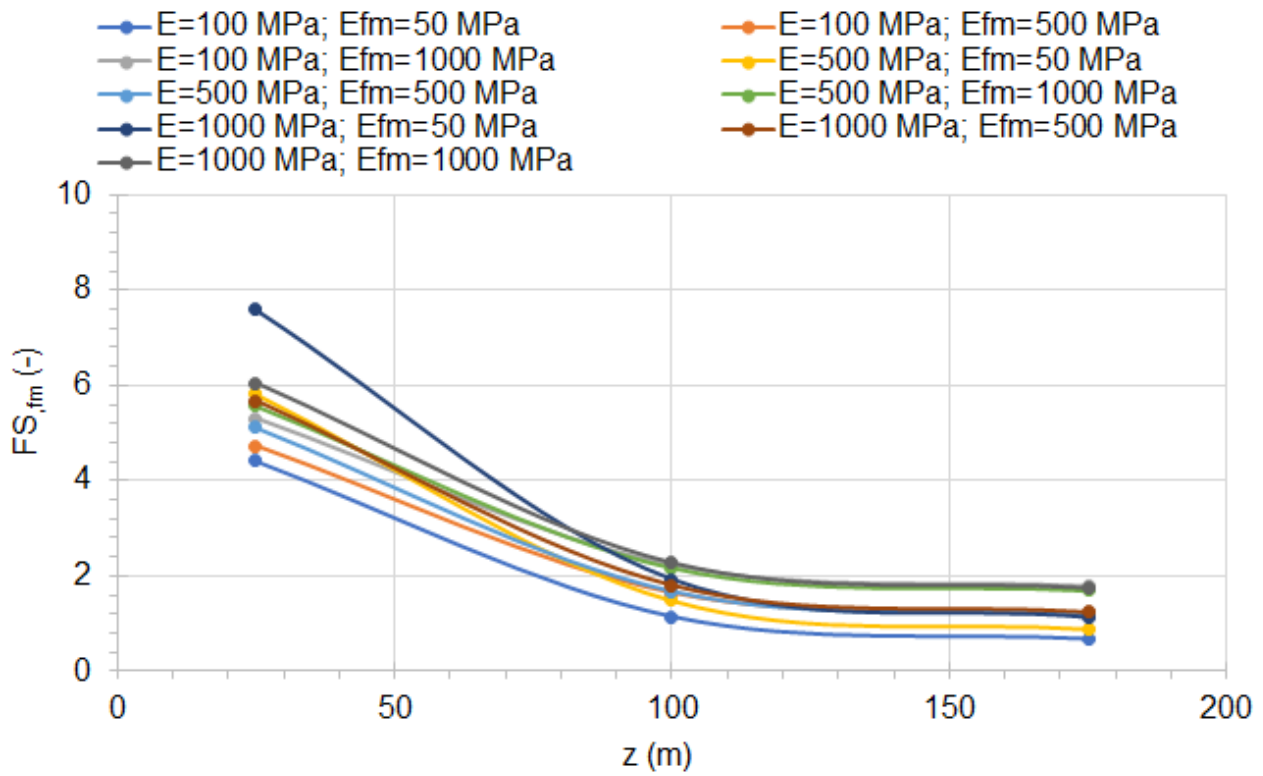
428



429

430 **Fig. 16. Safety factors in the filling material ($FS_{,fm}$) as the depth z of the tunnel varies,**
 431 **for different values of the elastic modulus of the ground (E) and of the elastic modulus**
 432 **of the filling material (E_{fm}). Case of a tunnel with radius $R = 2$ m.**

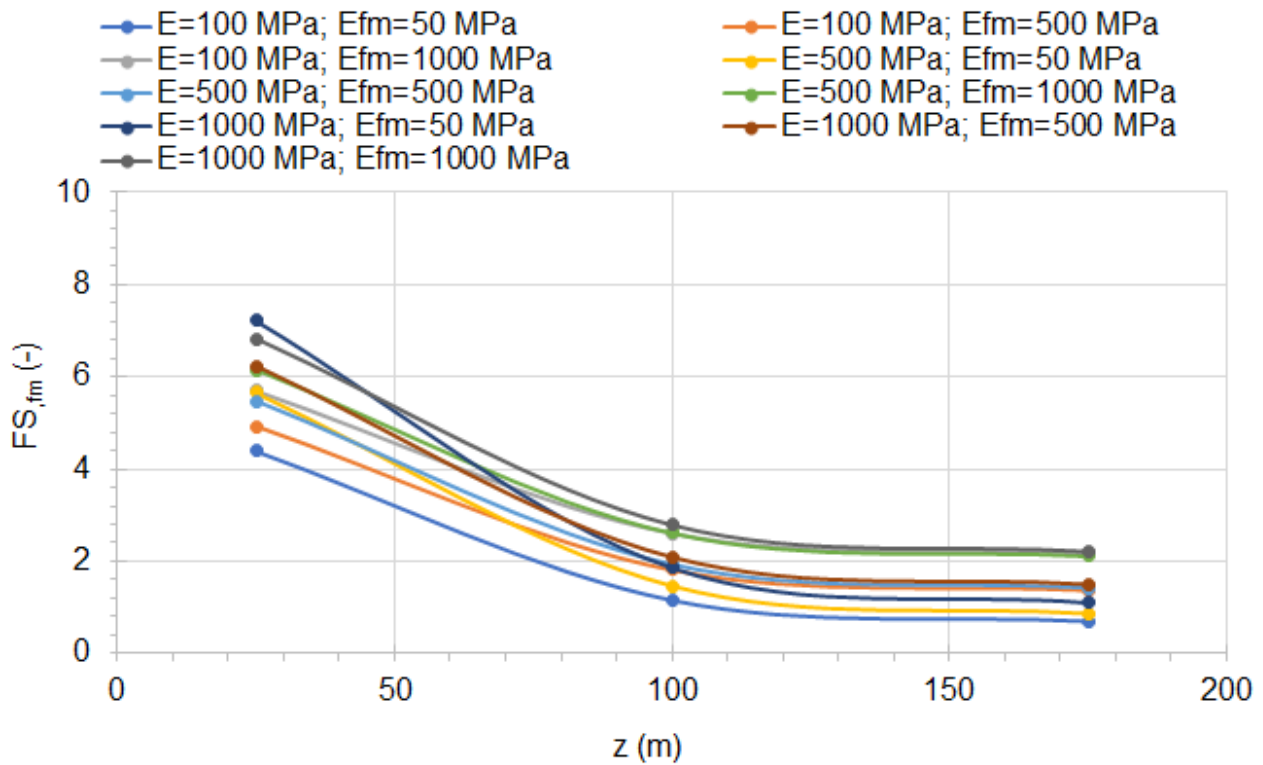
433



434

435 **Fig. 17. Safety factors in the filling material ($F_{s,f,m}$) as the depth z of the tunnel varies,**
 436 **for different values of the elastic modulus of the ground (E) and of the elastic modulus**
 437 **of the filling material ($E_{f,m}$). Case of a tunnel with radius $R = 3.5$ m.**

438



439

440 **Fig. 18. Safety factors in the filling material (FS_{fm}) as the depth z of the tunnel varies,**
 441 **for different values of the elastic modulus of the ground (E) and of the elastic modulus**
 442 **of the filling material (E_{fm}). Case of a tunnel with radius $R = 5$ m.**

443

444 **Conclusions**

445 As the two-component material cures over time, the mechanical characteristics tend to vary
 446 over time, until they stabilize after some time. In the study of the behavior of the support
 447 system, it is of interest to evaluate the average elastic modulus, during the loading phase of
 448 the support system. Several laboratory studies for the evaluation of the mechanical
 449 characteristics of the two-component material have been developed and the results are
 450 available in the scientific literature. In particular, a certain variability of the values is noted,
 451 as a function not only of the different types of materials used, but also of the sample
 452 preparation. Therefore, there is an uncertainty about the actual mechanical characteristics

453 of the filling material on site, during the construction of the tunnel and the installation of the
454 support system.

455 In this work, an extensive parametric analysis was developed (243 cases) able of
456 representing all possible cases of tunnels excavated using TBM machines in soils (from soft
457 to stiff), of different diameters and depths. The study was carried out using two different
458 analytical methods known in the literature: the convergence-confinement method (CCM)
459 and the Einstein and Schwartz method. From them it is possible to determine the stress
460 state induced in the concrete constituting the segmental lining.

461 From the results obtained, it is possible to detect how:

- 462 1. The K_0 coefficient (lateral earth pressure at rest in the ground) has a particular
463 influence on the value of the maximum stresses reached in the concrete of the
464 segmental lining: the further K_0 moves away from the unity, the greater the maximum
465 stress in the concrete;
- 466 2. The stiffness of the ground (elastic modulus E) produces effects on the maximum
467 stress in the concrete: the stress tends to increase as the elastic modulus decreases,
468 in particular for $E < 500$ MPa and for medium and high tunnel radii R ($R \geq 3.5$ m);
- 469 3. The stiffness of the filling material (elastic modulus E_{fm}) produces effects on the
470 maximum stress in the concrete especially when the elastic modulus E of the soil is
471 high; however, no influence of the filling material on the segmental lining is noted
472 when its elastic modulus E_{fm} is less than 500 MPa.
- 473 4. In general, the maximum stresses in concrete obviously tend to increase as the radius
474 of the tunnel and its depth increase.

475 Then considering a failure criterion for the concrete, it was possible to determine the safety
476 factor with regard to the possible failure of the segmental lining ($FS_{,sl}$). The obtained results
477 were plotted according to all the analyzed parameters, constituting a useful design tool for
478 sizing the support system in the presence of the filling material around the segmental lining.

479 In particular, the lowest safety factors are found for K_0 distant from the unity, for E_{fm} greater
480 than 500 MPa and for lower elastic modules of the ground. There is no influence on FS_{sl}
481 when $E_{fm} \geq 500$ MPa. In general, the safety factors tend to decrease as the depth of the
482 tunnel and its radius increase.

483 In the support system design phase, it must also be verified that the filling material does not
484 fail in the gap between the external profile of the segmental lining and the tunnel wall. For
485 this reason it is useful to analyze the trend of the safety factor of the filling material (FS_{fm})
486 as the parameters considered in the study vary. The graphs show that the lowest values are
487 obtained for high depths, soft soils and relatively low elastic modulus of the filling material.
488 In the design phase, therefore, it is possible to identify, also thanks to the procedure
489 developed in this paper, what the mechanical characteristics of the filling material must be
490 in order to guarantee adequate safety factors for the segmental lining and the filling material
491 itself. In particular, it is useful to intervene on the stiffness characteristic of the material (E_{fm})
492 given its influence both on the maximum stress in the concrete and in the filling material
493 itself. Furthermore, through a careful definition of the dosages, it is possible to reach a
494 uniaxial compressive strength (UCS) of the filling material, such as to avoid its failure with all
495 the consequences on the effective seal of the support system from the hydraulic point of
496 view and on its durability.

497 **Conflict of interests**

498 Authors declare they have no conflict of interest.

499 The authors declare that no funds, grants, or other support were received during the
500 preparation of this manuscript.

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