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1 **Two-dimensional numerical analysis on the rock-bolt interaction considering shear**
2 **and normal relative displacements**

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8 **Abstract**

9 Fully grouted passive bolts are widely used in underground or surface rock excavations and
10 in particular in stabilizing potentially unstable blocks of rock due to sliding on natural
11 discontinuities. Their operating mechanism is complex, but it is possible to consider two
12 stabilizing forces that each bolt applies to the block of rock. These forces depend on the
13 mechanical parameters governing the bolt-rock interaction, which are difficult to evaluate. In
14 this work, specific numerical analyzes of great detail have been developed, able of
15 evaluating the bolt-rock interaction (in shear and perpendicular to the interface that
16 separates them) for numerous cases that were obtained by varying the main geometric
17 parameters of the bolt, the mechanical properties of the binder material and rock. Thanks to
18 this complex study, it was possible to describe the variability of the interaction parameters
19 and to define, through graphs, the trend of the stabilization forces as the main geometric
20 and mechanical parameters that can be encountered in practice change. The graphs
21 obtained are a useful tool for the correct design of fully geouted passive bolts and the
22 stabilization of potentially unstable rock blocks on the walls of underground cavities or on
23 the faces of surface excavations.

24 **Key words:** passive bolt, cement grout, rock block stabilization, rock reinforcement, bolt-
25 rock interaction; stabilizing forces

26

27 **Nomenclature**

| | | |
|----|----------------|---|
| 28 | E_{binder} | Elastic modulus of the material constituting the annular binder |
| 29 | E_{rock} | Elastic modulus of rock |
| 30 | $(EA)_{bolt}$ | axial bolt stiffness |
| 31 | $(EJ)_{bolt}$ | flexural bolt stiffness |
| 32 | k | stiffness of the normal interaction springs |
| 33 | L_a | length of the bolt section that crosses the potentially unstable block |
| 34 | L_p | length of the bolt section in the stable rock (anchoring length) |
| 35 | $N_{0,max}$ | axial stabilizing force that the bolt applies to the rock block |
| 36 | N_{slip} | force for a unit bolt length which causes the bolt-rock interface to fail |
| 37 | N_{test} | applied axial force at the bolt head during a slip test |
| 38 | N_{yield} | force causing the steel bar failure under a tensile stress |
| 39 | t_{binder} : | thickness of the binder annulus |
| 40 | $T_{0,max}$ | transversal stabilizing forces that the bolt applies to the rock block |
| 41 | | (perpendicular to the bolt axis, directed upward, in the plane of the bolt axis |
| 42 | | and the block displacement vector) |
| 43 | T_{test} | transversal force applied to the bolt head during an in situ test |
| 44 | v | relative axial displacement between the bolt and the surrounding rock |
| 45 | y | transversal displacement of the bolt (against the surrounding rock) as it |
| 46 | | undergoes deformation due to the movement of the block |

| | | |
|----|--------------------|--|
| 47 | α | parameter characterising the rock-bolt interaction in the axial direction |
| 48 | | between the bolt and the surrounding rock $\alpha = \sqrt{\frac{\beta_c \cdot P_{hole}}{EA}}$ |
| 49 | β | parameter characterizing the rock-bolt interaction in the transversal direction |
| 50 | | between the bolt and the surrounding rock $\beta = \sqrt[4]{\frac{k \cdot \Phi_{hole}}{4 \cdot EJ}}$ |
| 51 | β_c | stiffness of the shear interaction springs at the bolt-rock interface |
| 52 | δ | displacement vector of the rock block (parallel to the slip surface) |
| 53 | $\delta_{ax,test}$ | measured axial displacement of the bolt head |
| 54 | $\delta_{tr,test}$ | measured transversal displacement of the bolt head |
| 55 | Φ_{bar} | diameter of the steel bar |
| 56 | Φ_{hole} | diameter of the hole (of the bolt) |
| 57 | σ | normal stress (perpendicular) to the outer surface of the bolt |
| 58 | τ | shear stress that exists at the rock-bolt interface |
| 59 | ϑ | angle which forms the displacement vector of the block δ with the direction of |
| 60 | | the bolt axis |
| 61 | | |

62 **Introduction**

63 Passive bolts have long been employed in geotechnical engineering to stabilize soils and
64 rocks. A passive bolt is made up of a bar that is placed into a borehole that is dug into the
65 soil or rock mass nearby and fastened to it with a cementitious or resin-based injection.
66 According to Windsor and Thompson (1993), 1) the rock or soil, 2) the reinforcing bar, 3)
67 the internal fixture to the borehole wall, and 4) the exterior fixture to the excavation surface
68 are the four main parts of a rock bolt reinforcement system. For example, by eliminating joint
69 movements and pushing the rock mass to maintain itself, the rock bolting system in particular
70 may increase the competency of disturbed rock masses (Kaiser et al., 1992).

71 Tensile, compressive, shear, and bending stresses can be supported by fully grouted rock
72 bolts, which have the ground's gap between the rod and the ground totally filled with a
73 binding material. A debonding process that begins if the axial stress on the bar exceeds a
74 certain value and spreads throughout the interface is thought to be the most likely place for
75 fully grouted bolt failure, according to experience from around the world (e.g. Stillborg, 1994;
76 Li and Stillborg, 1999; Moosavi et al., 2005). For instance, due to an increase in axial, shear,
77 and bending moments in the bolt rod, a fully grouted bolt intersected by a joint may affect
78 the shearing of a joint and increase bolt resistance (Ranjbarnia et al., 2016; Oreste & Dias,
79 2012). According to Lang (1961), rock bolts can be used to "lock together" blocks in highly
80 fractured rock masses to form a "reinforced arch" around an underground aperture that can
81 stabilize the hollow. Rock bolting significantly affects the rigidity of a jointed rock mass in
82 addition to strengthening or stabilizing it (Chappell, 1989). Because they are simple to install,
83 versatile, and relatively inexpensive compared to other options, rock bolts are frequently
84 used to support jointed surrounding rock and reinforce the rock mass (Indraratna and Kaiser,
85 1990).

86 While for active bolts the tensile load transfers from the element as an active compressive
87 load, increasing therefore the resulting stress confinement in the rock, for passive bolts the
88 initial load on passive reinforcing parts is zero, and when the potentially unstable rock block
89 is moved, transmit stabilizing forces and the mobilized stabilizing load rises until the block
90 is fully stabilized (Carranza-Torres, 2009). It is crucial to consider the physical and
91 mechanical properties of the binder, either cementitious or resin-based during the design
92 phase of the bolt, because it interacts with the surrounding rock.

93 Cementitious and resin materials are typically used to secure the bolt within the hole, and
94 this type of set up is known as Continuous Mechanically Coupled (CMC) elements. For
95 cementitious binders, a common water to cement (w/c) ratio is between 0.35 and 0.5, and
96 the grout should be easily pumpable without being overly fluid (Kilic et al., 2002; Bawden,
97 2011). As for resin-based binders, a plastic cartridge containing two components (i.e. a resin
98 and catalyst in separate compartments) is inserted in the drilled hole ahead of the bolt
99 element (Bawden, 2011). Epoxy resins, silicate resins, polyester resins, and polyurethane
100 resins are examples of common forms of resin. The catalyst and resin are mixed via an
101 exothermic reaction as the cartridge is spun into the hole. Depending on the mix
102 requirements, the resin sets in 20 seconds to 3 minutes, forming a solid anchor. Aldrian et
103 al. (2019) claim however that very little grout can enter the surrounding cracks because the
104 cartridge capacity is fixed and the inserted steel is creating only the "pressure" necessary to
105 completely fill the annular gap.

106 Numerous laboratory and field studies have been conducted to examine the behavior of the
107 rock-bolt grouted system. Pull-out tests (tension loading) or shear tests (shear loading) can
108 be used to test the load capacity of bolt in the field or the lab. Standards like DIN-21521
109 (1990) or ISRM recommendations for rock bolt testing should be followed while conducting
110 rock bolt tests. There are three primary failure scenarios in the event of a grouted anchor in

111 the bedrock or concrete: failure of the rod, rock failure and failure at the interface rock/grout
112 or steel grout. The failure mode is frequently a rock failure for cases with minor embedment
113 depths where the embedment depth is between three and five times the diameter of the bolt
114 (Ljungberg 2016).

115 According to Gambarova (1981) and Li and Stillborg (1999), adhesion, mechanical interlock,
116 and friction made up the majority of the interfacial bond strength under the pullout test. Kilic
117 et al. (2002) concluded that the mechanical properties of the grouting materials, which can
118 be altered by the water to cement ratio, mixing time, additives, and curing time, are mostly
119 what determine the bolt capacity. The bolt bearing capacity improves with increasing bolt
120 diameter and length, which is limited to the ultimate tensile strength of the bolt materials.
121 Craig and Murnane (2013) tested polyurethane-based resin binders with bolts with the scope
122 of accelerating ground support activities. Li et al. (2016) observed that the unconfined
123 compressive strength (UCS) of the grout and bond strength are linearly related. As long as
124 the bolt shank's yield strain is not excessively high, the bond strength of the rock bolt—that
125 is, the average shear stress at the bolt-grout interface when the bolt begins to slide along
126 the interface—seems to rise with embedment length instead of remaining parameters.

127 Chen et al. (2017) observed that the bonding capacity from pull-out tests in the unconfined
128 situation grew linearly with sample diameter up to 356 mm before remaining constant after
129 that. The bonding capacity, however, increased linearly with sample diameter up to 300 mm
130 in confined conditions. After that, it seemed like bonding capability peaked. Additionally, the
131 bonding capacity was always greater in the restricted setting than it was in the unconfined
132 one. Similar results were obtained by Moosavi et al. (2002).

133 Li et al. (2017) observed that the pullout strength of a rock bolt is somewhat influenced by
134 their temperatures. Temperature improves the pullout strength for temperatures between
135 20°C and 35°C. Temperature causes a decrease in pullout strength at temperatures

136 between 50°C and 70°C. Salcher and Bertuzzi (2018) performed in situ pull-out test in an
137 Australian sandstone, with a cementitious and resin binder. Cement-grouted bolts
138 consistently performed in a stiff manner. It was demonstrated that rock bolts cement-grouted
139 in large diameter shale holes produced the least stiff results as well as the stiffest outcomes.
140 Shale resin bolts had more constant behavior. In shale, one may use cement-grouted bolts
141 in holes of a large diameter if a great rigidity is desired. The pull test findings showed no
142 correlation between bolt performance and resin annulus width. Bajwa et al (2017),
143 comparing grout and resin binders, observed that in small borehole the cementitious grouted
144 bolts achieved higher peak pull-out load in comparison with resin-grouted bolts, whereas for
145 larger boreholes the contrary was true. Aziz et al. (2018) evaluated the shear performance
146 of various pretensioned fully grouted cable bolts using a novel experimental single shear
147 testing technique. 19 single shear tests were performed to examine the effects of the bolt
148 type, surface profile type, pretension load, structure, bonding and debonding, and failure
149 modes. Comparing plain strand cable bolts to rough surface strand cables, it was discovered
150 that plain strand cable bolts debonded more easily for the same length of the cable
151 encapsulated in the host material. Spagnoli et al. (2021) presented promising data about
152 the mechanical properties of polyurea silicate with a true thixotropic behavior and pull-out
153 test results on anchors (rebars and hollow). About the half of tests ended up with the failure
154 of the bar rather than through an interface failure bolt/resin.

155 In this paper, the mechanical behavior of fully grouted passive bolts for the stabilization of
156 potentially unstable rock blocks on underground cavity walls or surface rock faces is
157 analyzed in detail. Some simplified equations (Oreste and Spagnoli, 2020) allow to
158 determine the stabilization forces of the bolt, on the basis of different geometric and
159 mechanical parameters. Two of these are of great importance because they are able to
160 describe the bolt-rock interaction in the axial and transverse directions. Unfortunately, these
161 interaction parameters are difficult to evaluate, even by resorting to specific in situ tests. A

162 detailed analysis through numerical modeling has made it possible to obtain these
163 parameters with a certain precision. Several cases have been considered, varying the
164 characteristics of the bolt and the rock, in a typical field of variability that can be encountered
165 in practice. The developed study allows to define the interaction parameters for different
166 types of bolt and rock and thus arrive at a quick evaluation of the stabilizing forces of the
167 bolt, a fundamental step for the design phase.

168

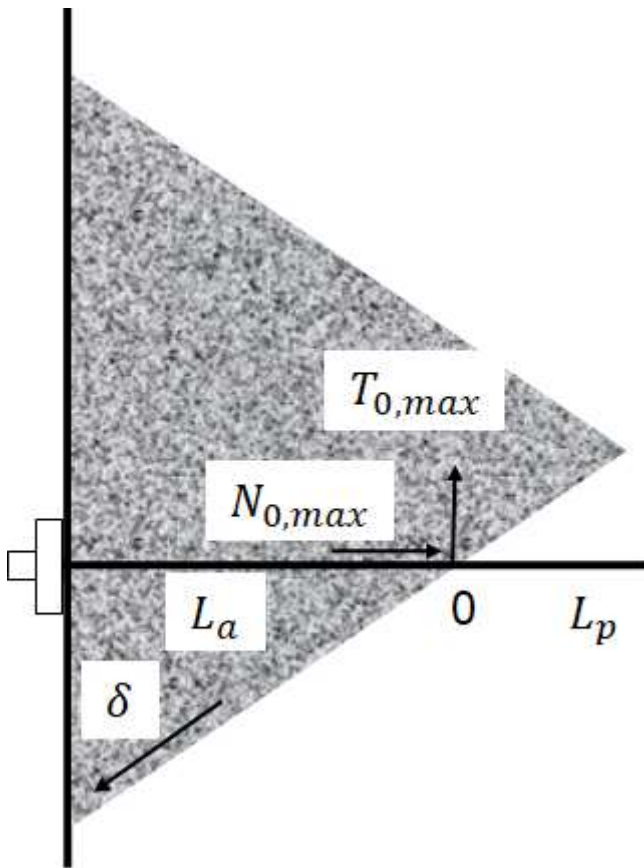
169 **Simplified equations and required parameters to analyse the stabilizing contribution** 170 **of a passive bolt to a rock block**

171 The analysis of the interaction between the fully grouted passive bolt and the surrounding
172 rock, was carried out by Oreste and Cravero (2008), Oreste (2009a; 2009b), Ranjbarnia et
173 al. (2014), Oreste and Spagnoli (2020). It is possible to identify the stabilizing forces that the
174 single bolt applies to a potentially unstable block of rock, which tends to move (even with
175 very small displacement values) along a sliding surface (Fig. 1). This analysis is based on
176 the assumption that the reaction of the rock to the displacements of the bolt can be
177 represented with independent springs (Winkler springs), capable of manifesting reaction
178 forces as a function of the relative displacements of each point of the bolt with respect to the
179 surrounding rock. The following hypotheses were considered:

- 180 • The bolt (steel bar and binder annulus) is represented by a one-dimensional linear
181 element, i.e. characterized only by the length and by the axial $(EA)_{bolt}$ and bending
182 $(EJ)_{bolt}$ stiffness;
- 183 • Two different zones of the bolt are identified, the crossing zone of the potentially
184 unstable block L_a and the anchorage length in the stable rock portion L_p , beyond the
185 potentially unstable block; the intersection of the bolt with the internal surface of the
186 block allows to identify the point 0, which separates the crossing area from the

187 anchoring area and divides the total length of the bolt into two parts of length L_a and
188 L_p ;

- 189 • Each point of the bolt is connected to the surrounding rock through two different
190 Winkler springs, one normal (perpendicular to the bolt) and the other parallel to it; the
191 first allows to consider the normal reaction of the rock to the transversal
192 displacements of the bolt, the second the shear reaction to the axial (relative)
193 displacements on the bolt-rock interface;
- 194 • The displacement of the rock block in the direction of the slip surface deforms the bolt
195 and activates the reaction of the rock around it, as foreseen by the interaction springs;
196 as the displacement of the block increases, the stresses along the bolt also increase;
- 197 • Upon reaching the limit operating condition of the bolt, when the approach to failure
198 of the steel bar or of the connection of the bolt to the surrounding rock occurs, in
199 correspondence with a certain value of the displacement of the block, the maximum
200 static contribution offered by the bolt to the block stabilization occurs.



201

202 Fig. 1 Diagram of a potentially unstable block of rock in presence of a fully cemented passive
 203 bolt. Key: L_a and L_p are respectively the lengths of the bolt section that crosses the
 204 potentially unstable rock block, and of anchorage in the stable rock; δ is the displacement
 205 vector of the block (parallel to the slip surface); $N_{0,max}$ and $T_{0,max}$ are the stabilizing forces
 206 that the bolt applies to the block of rock.

207

208 The maximum stabilization forces offered by the bolt to the potentially unstable block of rock,
 209 in the limit operating condition, are the forces that must be considered to design of the bolting
 210 intervention, i.e. to define the number and diameter of the bolts necessary to stabilize a rock
 211 block. The stabilization forces offered by the single bolt are two, one is directed in the axial
 212 direction of the bolt ($N_{0,max}$), and the other one ($T_{0,max}$) is directed in a perpendicular
 213 direction to the bolt, in a plane which includes both the bolt and the displacement vector of
 214 the block (δ).

215 Oreste and Spagnoli (2020) have identified some simplified equations capable of providing
 216 the stabilizing forces that a fully cemented passive bolt is able to apply to a potentially
 217 unstable block of rock. This study is based on an extensive parametric analysis, varying all
 218 the main input data (geometric and mechanical) that influence the bolt-rock interaction
 219 problem:

$$220 \quad N_{0,max} = \min \left(\frac{N_{yield}}{F_{s,adm,yield}} \cdot \frac{\xi \cdot (1 + e^{-2\alpha L_a})}{\chi \cdot \tan(\vartheta) + \xi \cdot \eta}; \frac{N_{slip}}{F_{s,adm,slip}} \cdot \frac{\omega}{\alpha} \right) \quad (1)$$

$$221 \quad T_{0,max} = \min \left(\frac{N_{yield}}{F_{s,adm,yield}} \cdot \frac{\rho}{\chi + \frac{\xi}{\tan(\vartheta)} \eta}; \frac{N_{slip}}{F_{s,adm,slip}} \cdot \frac{2 \cdot \tan(\vartheta)}{\lambda \cdot \psi \cdot \alpha} \right) \quad (2)$$

222 Where N_{yield} is the force causing bar failure under a tensile stress $N_{yield} = \sigma_{yield} \cdot A_{bar}$; N_{slip}
 223 is the force which causes the bolt-rock interface to fail for a unit bolt length $N_{slip} = \tau_{lim} \cdot \pi \cdot$
 224 Φ_{hole} ; $(EA)_{bolt}$ is the axial stiffness of the bolt, considering both the steel bar and the binder
 225 annulus, i.e. $(EA)_{bolt} = E_{st} \cdot \left(\frac{\pi}{4} \cdot \Phi_{bar}^2 \right) + E_{binder} \cdot \left[\frac{\pi}{4} \cdot (\Phi_{hole}^2 - \Phi_{bar}^2) \right]$; $(EJ)_{bolt}$ is the
 226 bending stiffness of the bolt, considering both the steel bar and the binder annulus, i.e.

$$227 \quad (EJ)_{bolt} = E_{st} \cdot \left(\frac{\pi}{64} \cdot \Phi_{bar}^4 \right) + E_{binder} \cdot \left[\frac{\pi}{64} \cdot (\Phi_{hole}^4 - \Phi_{bar}^4) \right]; \quad \alpha = \sqrt{\frac{\beta_c \cdot \pi \cdot \Phi_{hole}}{(EA)_{bolt}}}; \quad \beta = \sqrt[4]{\frac{k \cdot \Phi_{hole}}{4 \cdot (EJ)_{bolt}}};$$

$$228 \quad \lambda = \left[\frac{(EA)_{bolt} \cdot \alpha}{(EJ)_{bolt} \cdot \beta^3} \right]; \quad \xi = 2 \cdot (EA)_{bolt} \cdot \alpha \cdot \Phi_{bar} \cdot (1 - e^{-2\alpha L_p}); \quad \chi = 16 \cdot \sqrt{2} \cdot (1 + e^{-2\alpha(L_a + L_p)}) \cdot$$

$$229 \quad (EJ)_{bolt} \cdot \beta^2 \cdot e^{-\frac{\pi}{4}}; \quad \eta = \left(e^{-2\alpha L_a} \cdot e^{\alpha \frac{\pi}{4\beta}} + e^{-\alpha \frac{\pi}{4\beta}} \right); \quad \varrho = 4 \cdot (EJ)_{bolt} \cdot \beta^3 \cdot \Phi_{bar} \cdot (1 +$$

$$230 \quad e^{-2\alpha(L_a + L_p)}); \quad \psi = \left[\frac{(1 + e^{-2\alpha L_a}) \cdot (1 + e^{-2\alpha L_p})}{(1 + e^{-2\alpha(L_a + L_p)})} \right] \text{ and } \omega = \left[\frac{(1 - e^{-2\alpha L_p})}{(1 + e^{-2\alpha L_p})} \right].$$

231

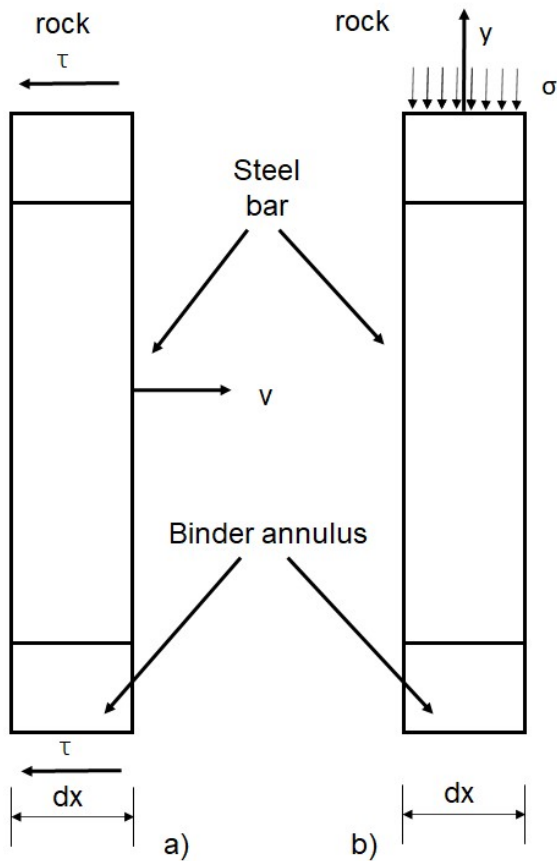
232 Two fundamental parameters condition the values of the stabilization forces $N_{0,max}$ and
 233 $T_{0,max}$ (Figure 2), i.e. β_c and k ; which represent respectively the stiffness of the shear
 234 interaction springs at the bolt-rock interface and the stiffness of the normal interaction
 235 springs.

236 $\tau = \beta_c \cdot v$ (3)

237 where τ is the shear stress that exists at the rock-bolt interface, and v is the relative axial
 238 displacement between the bolt and the surrounding rock.

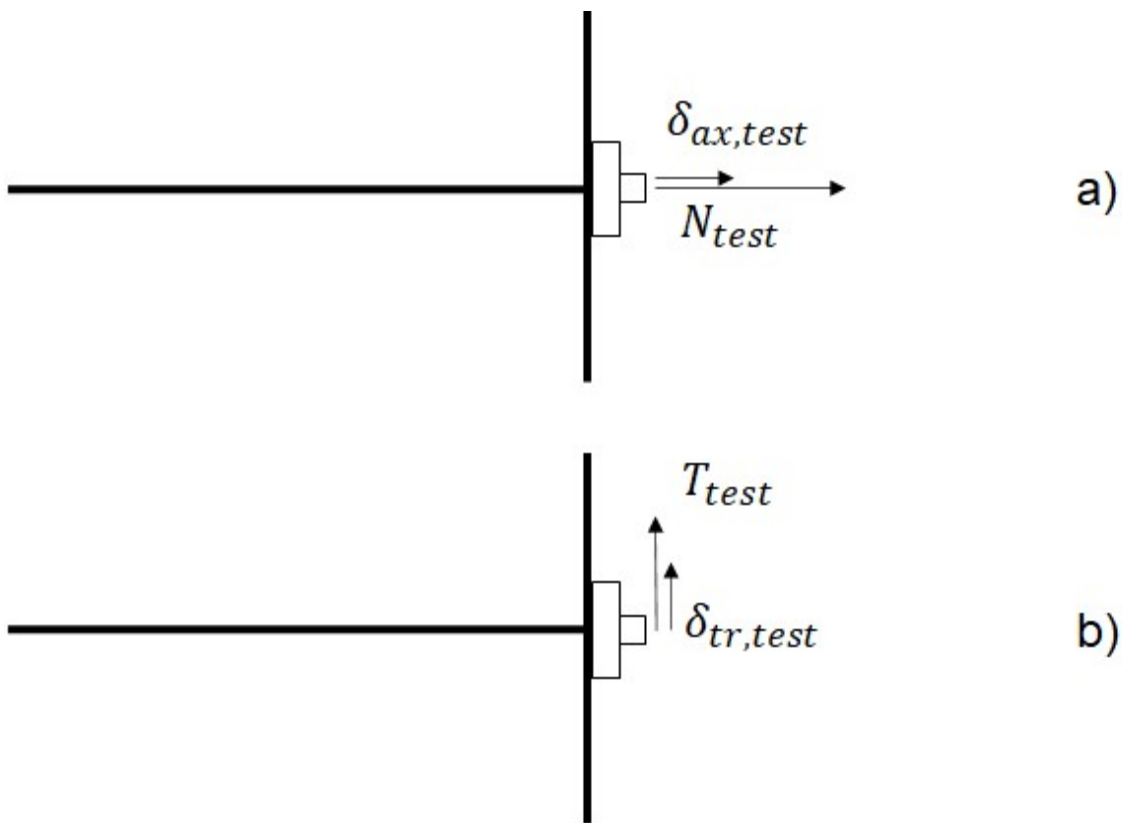
239 $\sigma = k \cdot y$ (4)

240 where σ is the normal (perpendicular) stress applied to the outer surface of the bolt, and y
 241 is the transverse displacement of the bolt (against the rock) as it undergoes deformation due
 242 to the movement of the block.



243
 244 Figure 2. Representation of the stresses applied by the rock (τ and σ) on the external
 245 surface of an infinitesimal element of a dx bolt following the relative displacements (v and
 246 y) of the bolt. Key: a) represents the shear interaction; b) represents the normal interaction
 247 (perpendicular to the bolt); τ is the shear stress applied by the rock on the external surface
 248 of the bolt; σ is normal stress applied by the rock on the external surface of the bolt.

249 Parameters β_c and k describe the rock response during the bolt deformation. They depend
 250 on the elastic modulus of the rock, on the geometry of the bolt (diameter of the bar, thickness
 251 of the binder annulus) and on the elastic modulus of the steel and the binder material. In situ
 252 tests on test bolts (Figure 3) can help in estimating β_c and k starting from the applied forces
 253 and the measurement of the induced displacements, but unfortunately in general there are
 254 very high forces applied on the bolt head and relatively small displacements. The reduced
 255 precision and errors in the measurement of the displacements of the bolt head can lead to
 256 large uncertainties on the two parameters which are fundamental for obtaining a reliable
 257 estimate of the stabilizing forces $N_{0,max}$ and $T_{0,max}$.



258
 259 Figure 3. In situ tests on test bolts for the determination of the parameters β_c and k . Key: a)
 260 is the pull-out test with application of an axial force to the bolt head; b) is the shear test with
 261 application of a transversal force to the bolt head; N_{test} is the applied axial force; T_{test} is the
 262 applied transversal force; $\delta_{ax,test}$ is the measured axial displacement of the bolt head; $\delta_{tr,test}$
 263 is the measured transverse displacement of the bolt head.

264 More specifically, from in situ tests it is possible to determine the parameters β_c and k using
 265 the following two equations:

$$266 \quad \delta_{ax,test} = \frac{N_{test}}{(EA)_{bolt} \cdot \sqrt{\frac{\beta_c \cdot \pi \cdot \Phi_{hole}}{(EA)_{bolt}}}} \cdot \frac{\left(\frac{1+e^{-2 \cdot \sqrt{\frac{\beta_c \cdot \pi \cdot \Phi_{hole}}{(EA)_{bolt}}}} \cdot L_{test}}}{1-e^{-2 \cdot \sqrt{\frac{\beta_c \cdot \pi \cdot \Phi_{hole}}{(EA)_{bolt}}}} \cdot L_{test}}} \right)}{\left(\frac{1+e^{-2 \cdot \sqrt{\frac{\beta_c \cdot \pi \cdot \Phi_{hole}}{(EA)_{bolt}}}} \cdot L_{test}}}{1-e^{-2 \cdot \sqrt{\frac{\beta_c \cdot \pi \cdot \Phi_{hole}}{(EA)_{bolt}}}} \cdot L_{test}}} \right)} \quad (4)$$

$$267 \quad k = \left(\frac{T_{test}}{2 \cdot (EJ)_{bolt} \cdot \delta_{tr,test}} \right)^{\frac{4}{3}} \cdot \frac{4 \cdot (EJ)_{bolt}}{\Phi_{hole}} \quad (5)$$

268 To obtain β_c from equation 4 it is necessary to resort to a numerical solution.

269

270 **The analysis of the bolt-rock interaction through numerical modeling**

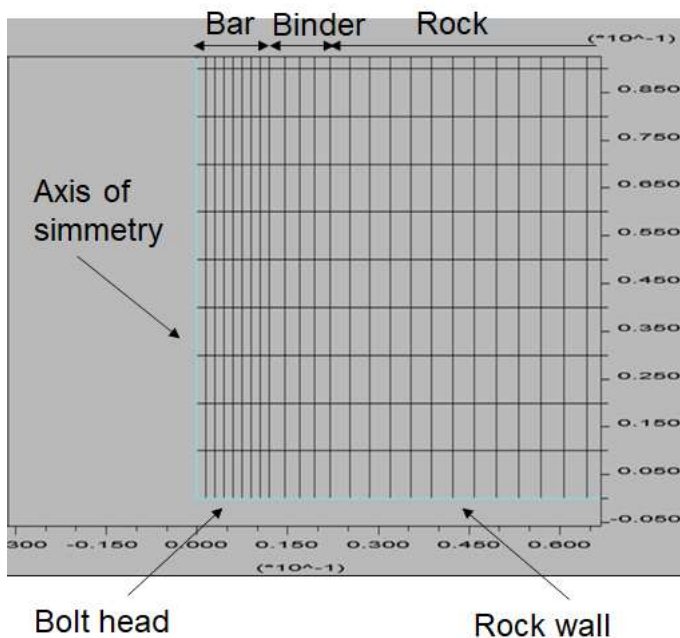
271 It is possible to analyze in detail the complex interaction between the fully cemented passive
 272 bolt and the surrounding rock thanks to numerical modelling. More specifically, through two-
 273 dimensional numerical modeling, the axial interaction (in the axisymmetric configuration)
 274 and the transverse interaction (in a cross section of the bolt) can be simulated.

275 In this work the calculation code FLAC 2D ver 8.1 of the Itasca Company was used. This
 276 code is able to solve the stress-strain problem through a finite difference solution. In the first
 277 case, after applying an axial force N_{test} to the bolt head, the displacement of the bolt head
 278 $\delta_{ax,test}$ can be determined as a result of the calculation. Based on the pair of values N_{test} -
 279 $\delta_{ax,test}$, β_c can be determined (equation 4).

280 Figure 4 shows the detail of the numerical model developed to analyze the axial interaction
 281 of the bolt; in this model, only half of the bolt and the surrounding rock is represented,
 282 exploiting the axisymmetric symmetry of the problem (vertical y-axis represents the axis of

283 the steel bar). The model allows the study of the axial interaction with great precision and
284 has the following main characteristics:

- 285 • Total number of elements: 60000
- 286 • Thickness of the rock considered around the bolt: 1.5 m
- 287 • Length of the bolt simulated in the model: 2 m
- 288 • Overall length of the model in the axial direction of the bolt: 4 m
- 289 • Number of elements dedicated to the semi-section of the steel bar: 8
- 290 • Number of elements dedicated to the annular binder: 4



291

292 Figure 4. Detail of the two-dimensional axisymmetric numerical model developed to study the axial
293 interaction between the bolt and the surrounding rock. Key: the left edge represents the axis of
294 symmetry of the bolt, the lower one the rock face where the head of the bolt is located; the first 8
295 elements represent half of the steel bar in the analyzed section, the next 4 the annular binder that
296 connects the steel bar to the surrounding rock.

297

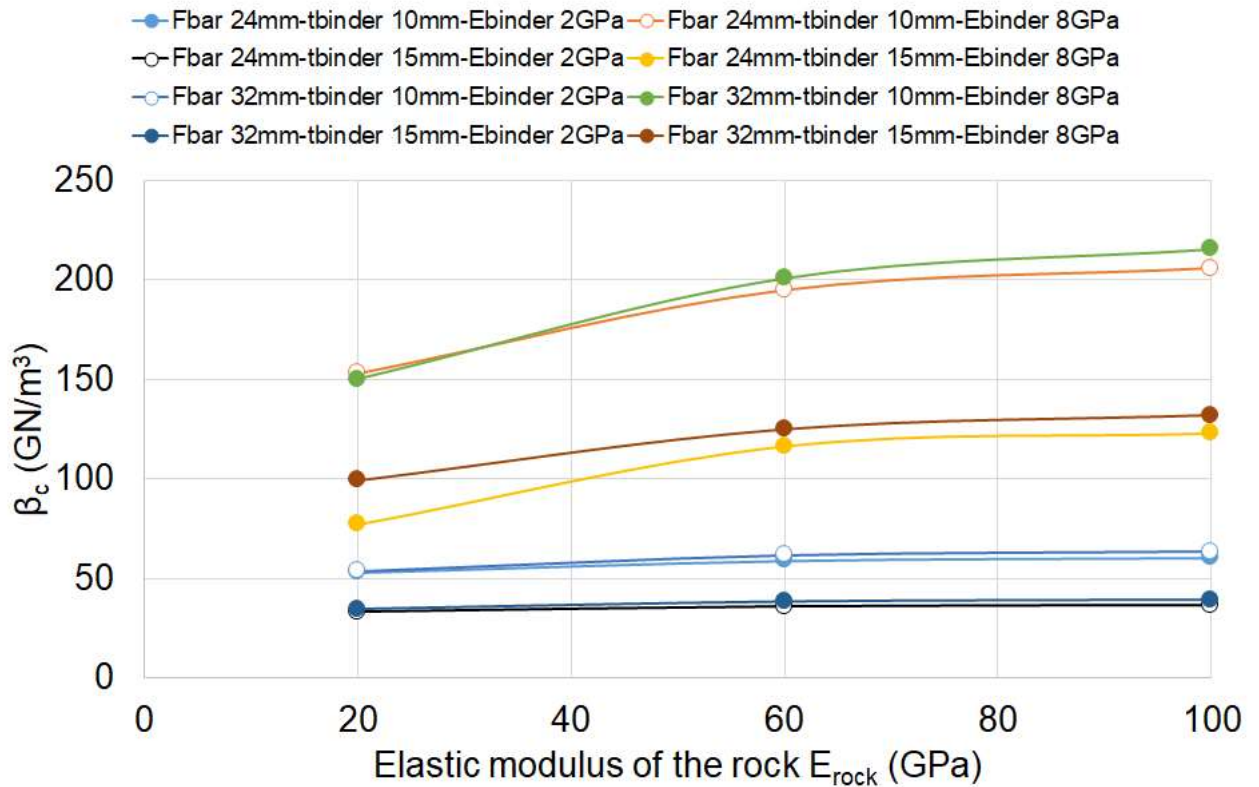
298 Different values of the diameter of the steel bar, of the thickness of the annular binder, of
299 the elastic models of the rock and of the material that constitutes the annular binder were
300 analysed:

- 301 • Diameter of the steel bar Φ_{bar} : 24 mm and 32 mm
- 302 • Thickness of the annular binder t_{binder} : 10 mm and 15 mm
- 303 • Elastic modulus of rock E_{rock} : 20 GPa, 60 GPa, 100 GPa
- 304 • Elastic modulus of the material constituting the annular binder E_{binder} : 2 GPa and 8
305 GPa

306

307 The considered cases, 24 in total, allow us to investigate the axial interaction of the bolt for
308 all possible cases that may arise in reality when passive bolting (fully grouted) is adopted in
309 rock masses. More specifically, a bar with a small diameter (24 mm) and a large diameter
310 (32 mm), a reduced (10 mm) and high (15 mm) thickness of the annular binder, a rock with
311 low (20 GPa), intermediate (60 GPa) and high (100 GPa) mechanical characteristics, a
312 material constituting the binder having an elastic modulus 2 GPa (resin) and 8 GPa
313 (traditional cementitious grout) were considered.

314 For each of the 24 cases analyzed it was possible to determine the parameter β_c . Figure 5
315 shows the graph that allows to synthetically represent the values calculated on the basis of
316 the results of the numerical modeling.



317

318 Figure 5. Trend of the parameter β_c , which governs the axial interaction of the passive bolt,
 319 as the elastic modulus of the rock varies, for different combinations of the diameter of the
 320 bar (Φ_{bar}), the thickness of the binder (t_{binder}), the elastic of the material that constitutes
 321 the binder (E_{binder}).

322 From the analysis of Figure 5, the following observations can be made:

- 323 • The diameter of the bar has, in general, a small influence on the axial interaction
 324 parameter β_c , with the sole exception of the case of weak rock, high thickness of the
 325 annular binder and bar-rock connection with traditional cementitious grout (in this case
 326 β_c increases by about 30% when going from a small (24 mm) to a large (32 mm) bar
 327 diameter. In the case of using the resin as a bolt-rock connection material, the stiffness
 328 of the rock has no effect on the axial interaction parameter β_c

- 329 • The thickness t_{binder} of the annular binder has an important effect on the interaction
 330 parameter β_c : as it decreases from 15 mm to 10 mm, β_c increases considerably by 60-
 331 65%, mostly with the use of traditional cementitious grout
- 332 • With the use of traditional cementitious grout ($E_{binder}=8$ GPa) there are no significant
 333 increases in β_c for values of the elastic modulus of the rock E_{rock} above 60 GPa; for
 334 lower values of the elastic modulus of the rock ($E_{rock}=20\div 60$ GPa) β_c grows considerably
 335 with E_{rock} .

336 The results, therefore, can be summarized as follows. In the case of using resins for the bar-
 337 rock connection, β_c essentially depends on the thickness t_{binder} :

$$338 \quad \beta_c \cong 103.3 - 4.48 \cdot t_{binder} \quad (\text{with } \beta_c \text{ expressed in GN/m}^3 \text{ and } t_{binder} \text{ in mm}) \quad (6)$$

339 In the case of using traditional cementitious grout, β_c depends on both E_{rock} and t_{binder} :

$$340 \quad \beta_c \cong (277.5 - 15 \cdot t_{binder}) + 1.125 \cdot E_{rock} \quad (\text{with } \beta_c \text{ expressed in GN/m}^3, \quad t_{binder} \text{ in mm and}$$

$$341 \quad E_{rock} \text{ in GPa, for } E_{rock} \leq 60 \text{ GPa}) \quad (7)$$

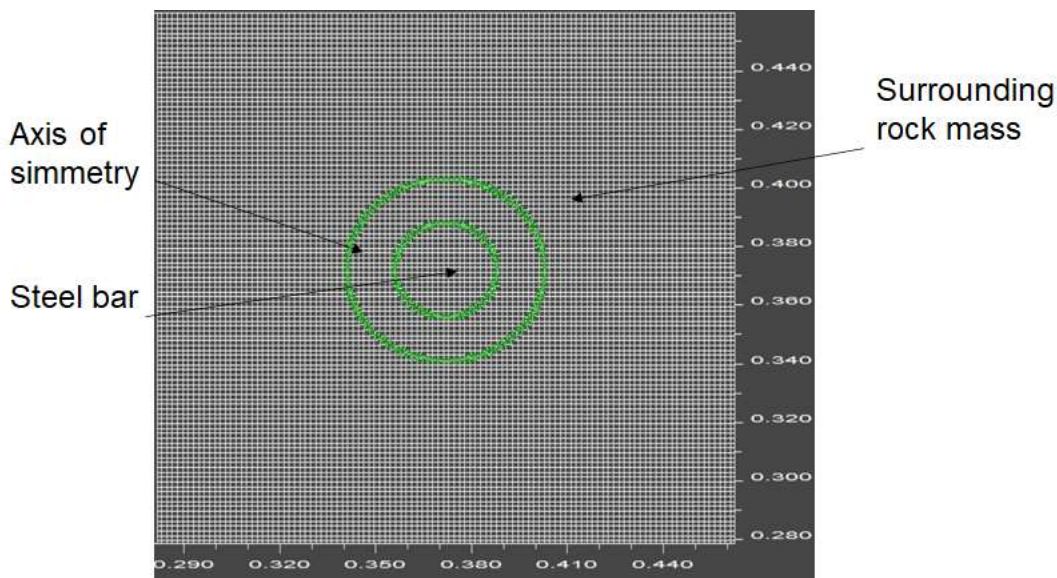
342 In the latter equation (for traditional cementitious grout), in the only case of weak rock
 343 ($E_{rock} \leq 20$ GPa) and high thickness of the annular binder ($t_{binder}=15$ mm), β_c must be
 344 increased by 15% when considering a intermediate diameter steel bar (28 mm) and 30% for
 345 large diameter bar (32 mm). Furthermore, for E_{rock} greater than 60 GPa (rock with high
 346 mechanical characteristics), the values of β_c calculated for $E_{rock}=60$ GPa can be adopted
 347 without making significant errors.

348 As regards the transverse interaction, a two-dimensional numerical model of the cross
 349 section of the bolt has been developed; after applying a shear force T_{test} to the bolt (at the
 350 center of the steel bar), the displacement of the bar axis $\delta_{tr,test}$ was calculated. The pairs of
 351 values $T_{test}-\delta_{tr,test}$ then allow to determine the interaction parameter k (equation 5).

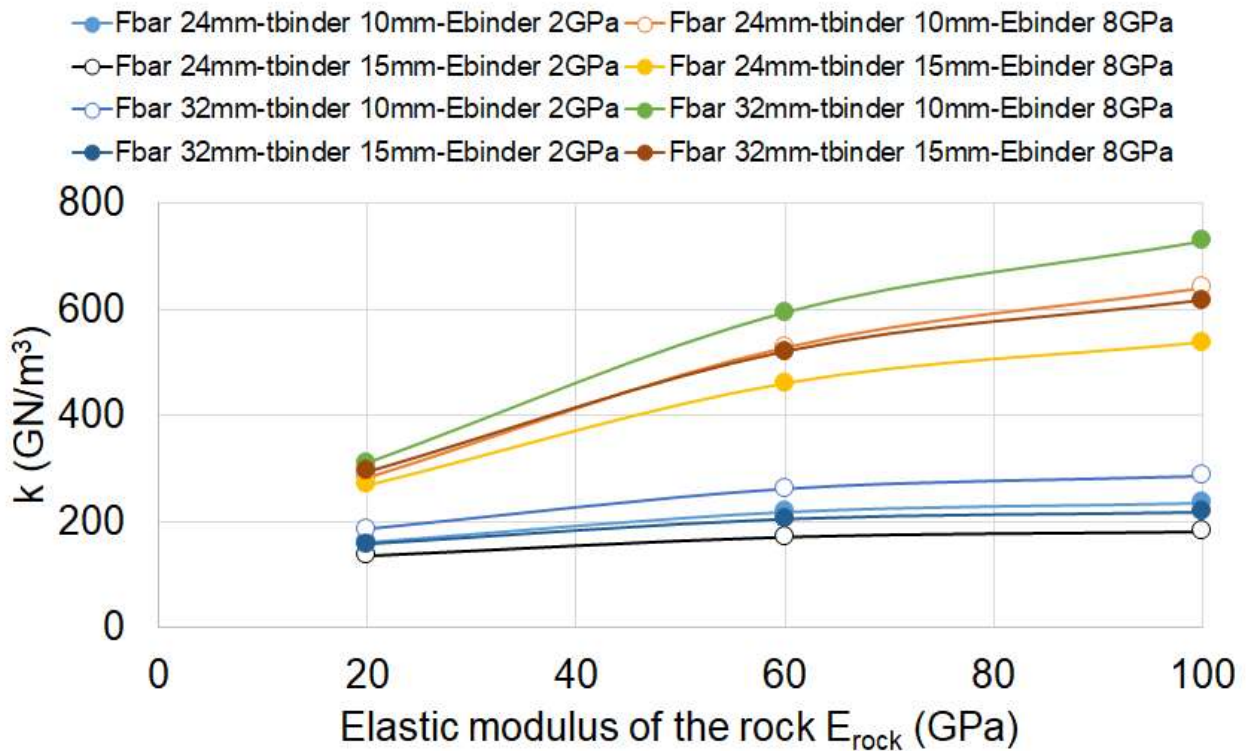
352 Figure 6 shows the detail of the numerical model used, which considers the entire cross
353 section of the bolt and the surrounding rock. It is able to analyze in great detail the
354 transversal interaction of the bolt and has the following main characteristics:

- 355 • Total number of elements: 200000
- 356 • Thickness of the rock considered around the bolt: 0.5 m
- 357 • Average dimension of each numeric element: 1.5 mm x 1.5 mm; 14/19 numerical
358 elements were used to simulate the steel bar along its diameter ($\Phi_{bar}=24/32$ mm);
359 6/9 numerical elements have been used to represent the binder annulus along its
360 thickness ($t_{binder}=10/15$ mm)

361 The same 24 cases considered in the analysis of the axial interaction were analyzed also in
362 the transversal one, by varying the diameter of the bar, the thickness of the binder around
363 it, the elastic modulus of the rock and the elastic modulus of the binder. The obtained results
364 of the numerical calculation have been summarized in Figure 7.



366 Figure 6. Detail of the two-dimensional transversal numerical model developed to study the
367 transversal interaction between the bolt and the surrounding rock. The average size of the
368 numerical elements used is 1.5 mm x 1.5 mm.



369

370 Figure 7. Trend of the parameter k , which governs the transversal interaction of the passive
 371 bolt, as the elastic modulus of the rock varies, for different combinations of the diameter of
 372 the bar (Φ_{bar}), the thickness of the binder (t_{binder}), the elastic of the material that constitutes
 373 the binder (E_{binder}).

374 From the analysis of Figure 7, the following comments can be made:

- 375 • The parameter k tends to grow with E_{rock} according to a parabolic trend (the influence of
 376 E_{rock} is greater for traditional cementitious grout, $E_{binder}=8$ GPa, less for resins, $E_{binder}=2$
 377 GPa)
- 378 • The values of k are 2÷3 times greater when the binder is made up of traditional
 379 cementitious grout compared to the case of a binder made up of resins
- 380 • k tends to increase as the diameter of the bar increases and the thickness of the binder
 381 decreases
- 382 • the influence of Φ_{bar} and t_{binder} on k depends on the rock's elastic modulus E_{rock} : it is
 383 smaller for low E_{rock} , it increases for high E_{rock}

384 For each type of binder (traditional cementitious grout or resin), thickness of the binder
385 annulus (10 or 15 mm) and diameter of the bar (24 or 32 mm) considered, it was possible
386 to obtain the equations of the parabola which best describes the results of the numerical
387 calculation in terms of k (GN/m³) as the elastic modulus of the rock E_{rock} (GPa) varies:

388 binder made of traditional cementitious grout:

389 $\Phi_{bar}=24$ mm; $t_{binder}=10$ mm: $k \cong -0.04156 \cdot E_{rock}^2 + 9.450 \cdot E_{rock} + 111.625$ (8)

390 $\Phi_{bar}=24$ mm; $t_{binder}=15$ mm: $k \cong -0.03594 \cdot E_{rock}^2 + 7.675 \cdot E_{rock} + 129.875$ (9)

391 $\Phi_{bar}=32$ mm; $t_{binder}=10$ mm: $k \cong -0.04688 \cdot E_{rock}^2 + 10.875 \cdot E_{rock} + 111.250$ (10)

392 $\Phi_{bar}=32$ mm; $t_{binder}=15$ mm: $k \cong -0.04063 \cdot E_{rock}^2 + 8.900 \cdot E_{rock} + 133.250$ (11)

393

394 binder made of resin:

395 $\Phi_{bar}=24$ mm; $t_{binder}=10$ mm: $k \cong -0.01281 \cdot E_{rock}^2 + 2.475 \cdot E_{rock} + 116.625$ (12)

396 $\Phi_{bar}=24$ mm; $t_{binder}=15$ mm: $k \cong -0.00813 \cdot E_{rock}^2 + 1.550 \cdot E_{rock} + 108.250$ (13)

397 $\Phi_{bar}=32$ mm; $t_{binder}=10$ mm: $k \cong -0.01625 \cdot E_{rock}^2 + 3.200 \cdot E_{rock} + 128.500$ (14)

398 $\Phi_{bar}=32$ mm; $t_{binder}=15$ mm: $k \cong -0.01094 \cdot E_{rock}^2 + 2.075 \cdot E_{rock} + 120.875$ (15)

399

400 **Estimation of the stabilization forces produced by the passive bolt on the basis of the**
401 **mechanical parameters of the bolt-rock interaction**

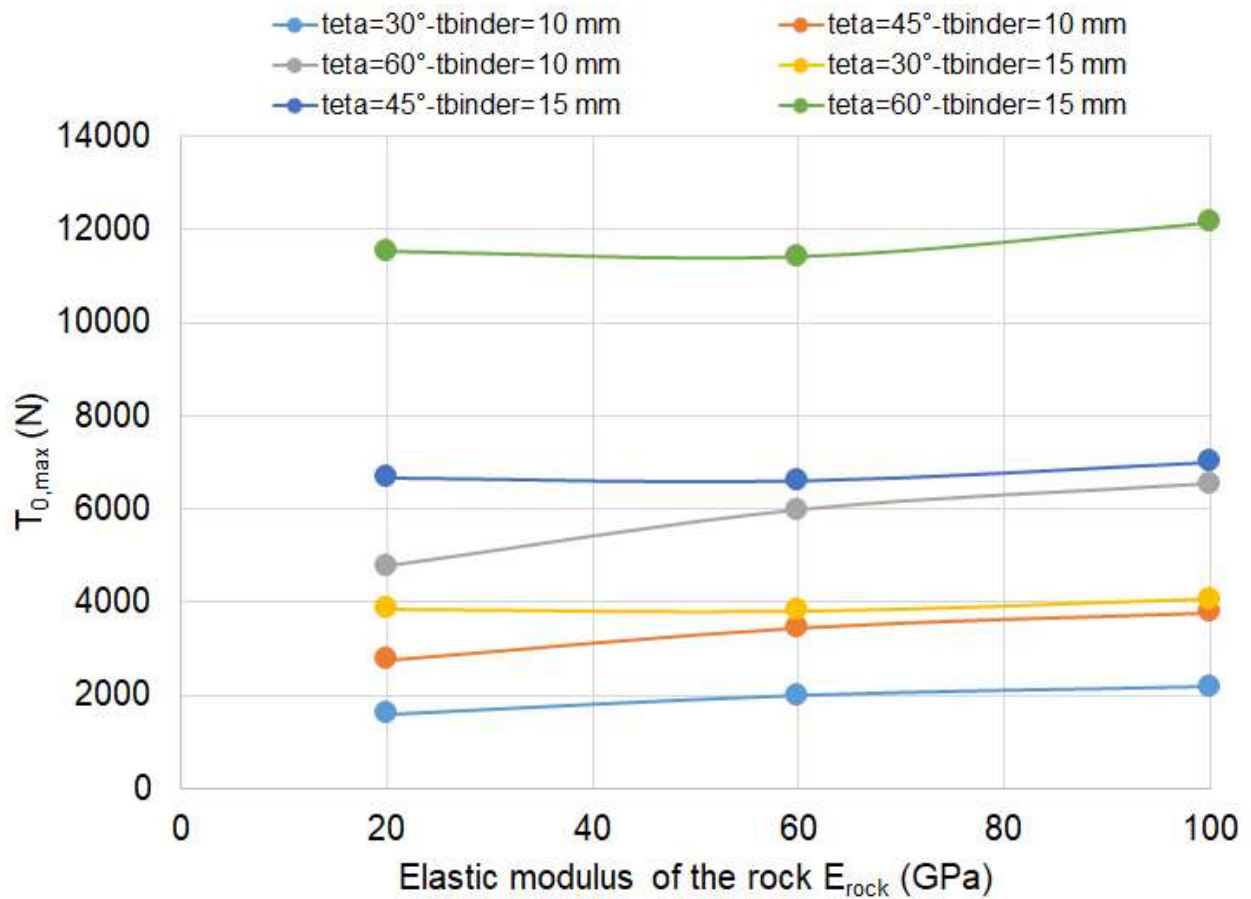
402 Thanks to the results obtained from the numerical modeling and the determination of the
403 mechanical parameters of bolt-rock interaction in the axial (β_c) and transversal (k) direction,
404 it is possible to proceed to the estimation of the stabilization forces on the basis of equations
405 1 and 2 (Oreste and Spagnoli, 2020). More specifically, it is possible to have a reliable

406 estimate of the stabilization force acting in the axial direction ($N_{0,max}$) and transversal
407 upwards ($T_{0,max}$), acting perpendicularly to the bolt with a vector belonging to the plane
408 encompassing the bolt itself and the block displacement vector δ (Fig. 1).

409 The following Figures (8-13) show the values of $T_{0,max}$ and $N_{0,max}$ as the elastic modulus of
410 the rock E_{rock} varies, for traditional cementitious grout, ($E_{binder}=8000$ MPa) and resin
411 ($E_{binder}=2000$ MPa), in the cases of steel bar with diameter Φ_{bar} 20 and 32 mm and
412 thickness of the binder annulus t_{binder} of 10 and 15 mm. These graphs assume a fundamental
413 design role, allowing the correct design of the fully grouted passive bolts in the different
414 conditions that can be encountered in engineering practice, guaranteeing the stabilization
415 of the potentially unstable blocks of rock, quickly defining the characteristics and the number
416 of bolts that are necessary.

417 These graphs were obtained assuming the following parameters present in equations 1 and
418 2:

- 419 • Length of the bolt in the two areas L_a (block crossing area) and L_p (anchor length in
420 the stable rock behind the block): 2 m
- 421 • Elastic modulus of steel E_{steel} : 210 GPa
- 422 • Limit shear stress τ_{lim} at the bolt-rock interface: 2.5 MPa
- 423 • Steel yield strength σ_y : 450 MPa
- 424 • Safety factors considered as minimum admissible against yield failure of the steel bar
425 ($F_{s,adm,yield}$) and pullout failure at the bolt-rock interface ($F_{s,adm,slip}$): 1.3.



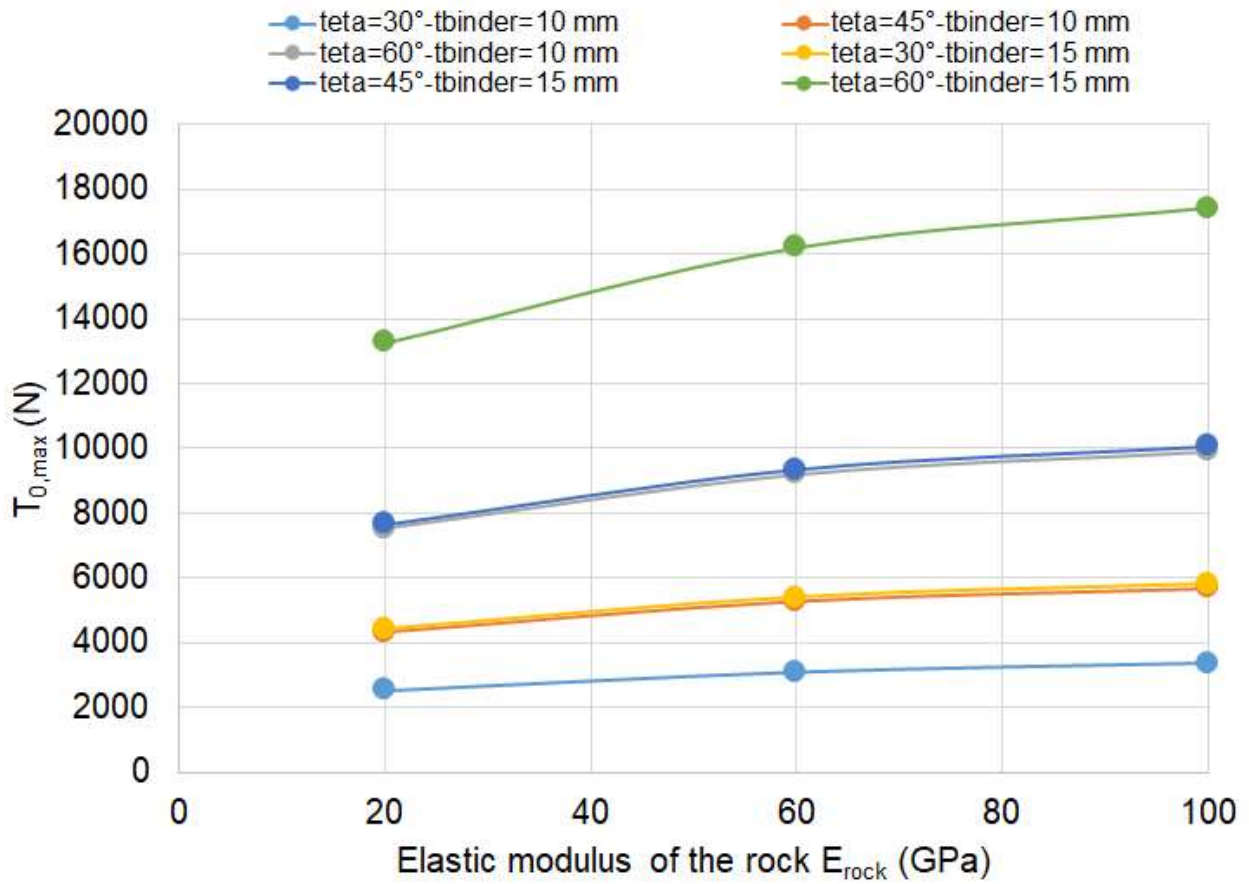
426

427 Figure 8. Trend of the transversal stabilization force $T_{0,max}$, as the elastic modulus of the
 428 rock E_{rock} varies, for different combinations of the thickness of the binder annulus (t_{binder})
 429 and of the angle ϑ which forms the displacement vector of the block δ with the direction of
 430 the bolt axis. Case of a traditional cementitious binder ($E_{binder}=8$ GPa) and diameter of the
 431 bar $\Phi_{bar}=24$ mm.

432

433

434

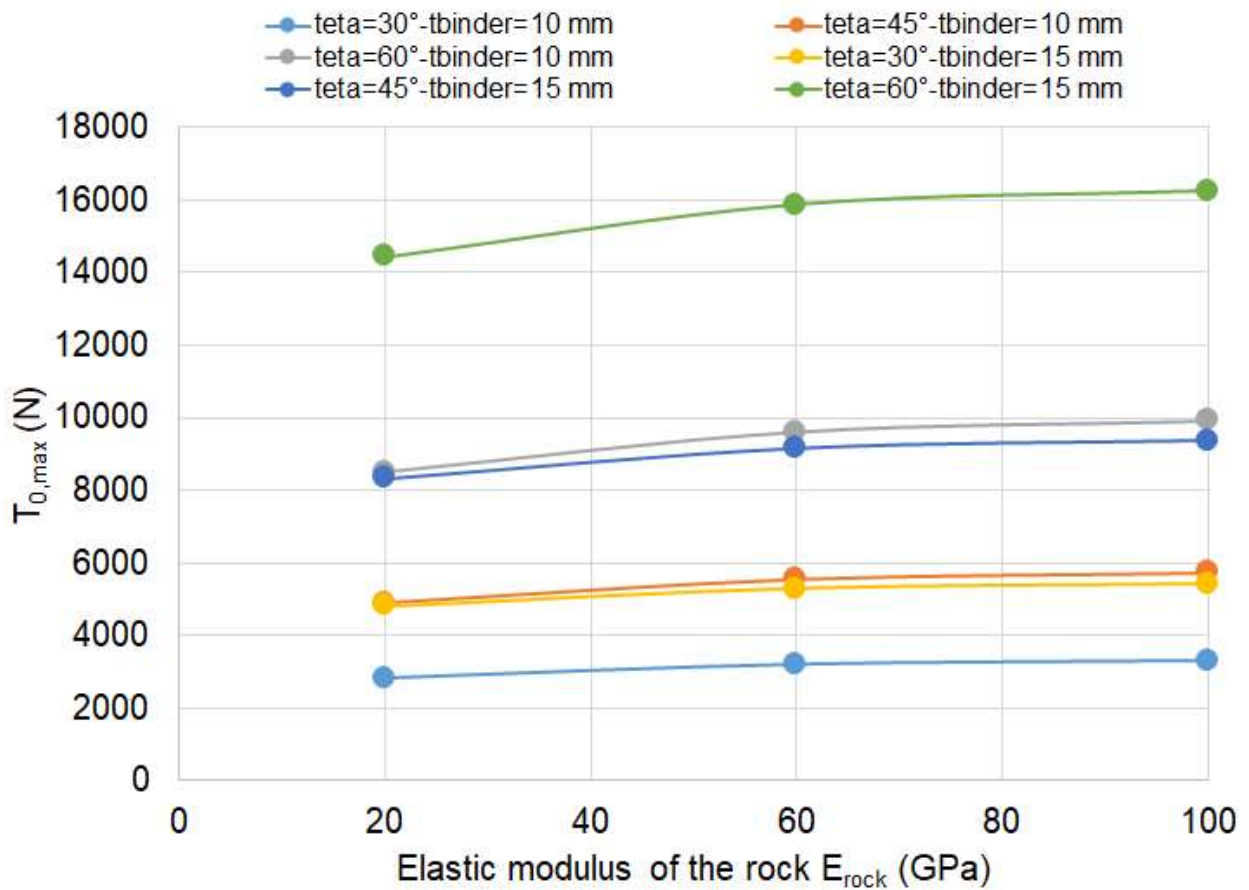


435

436 Figure 9. Trend of the transversal stabilization force $T_{0,max}$, as the elastic modulus of the
 437 rock E_{rock} varies, for different combinations of the thickness of the binder annulus (t_{binder})
 438 and of the angle ϑ which forms the displacement vector of the block δ with the direction of
 439 the bolt axis. Case of a traditional cementitious binder ($E_{binder}=8$ GPa) and diameter of the
 440 bar $\Phi_{bar}=32$ mm.

441

442



443

444 Figure 10. Trend of the transversal stabilization force $T_{0,max}$, as the elastic modulus of the
 445 rock E_{rock} varies, for different combinations of the thickness of the binder annulus (t_{binder})
 446 and of the angle ϑ which forms the displacement vector of the block δ with the direction of
 447 the bolt axis. Case of a resin binder ($E_{binder}=8$ GPa) and diameter of the bar $\Phi_{bar}=24$ mm.

448

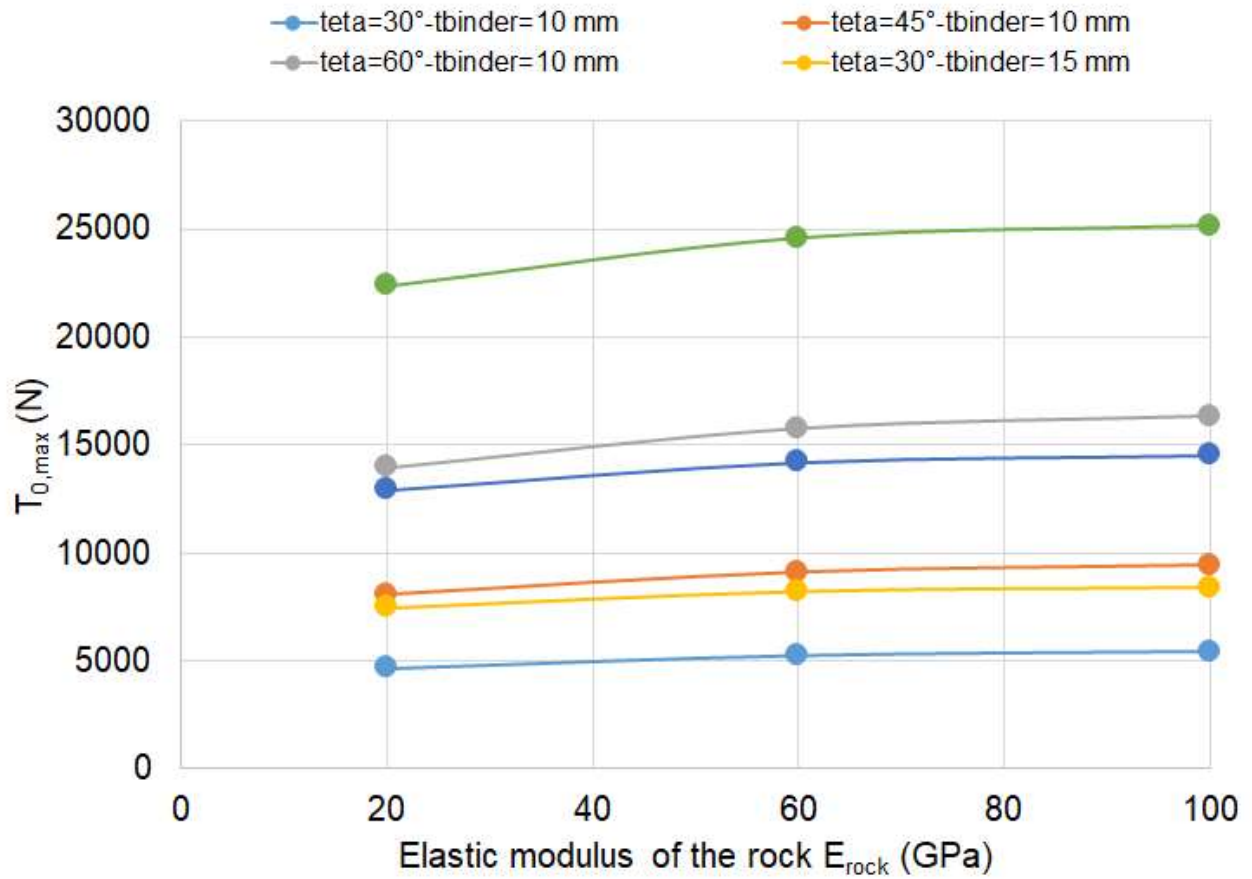
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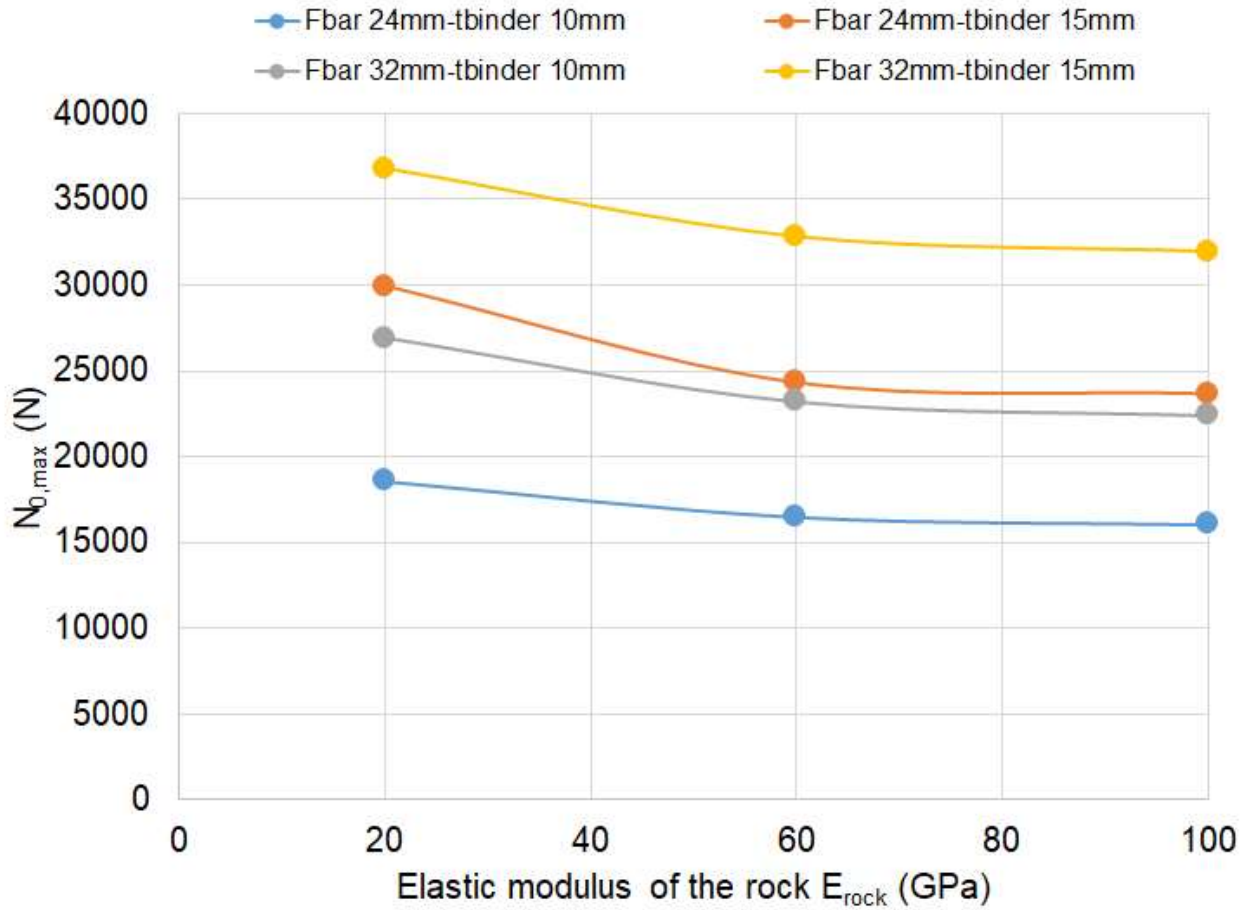
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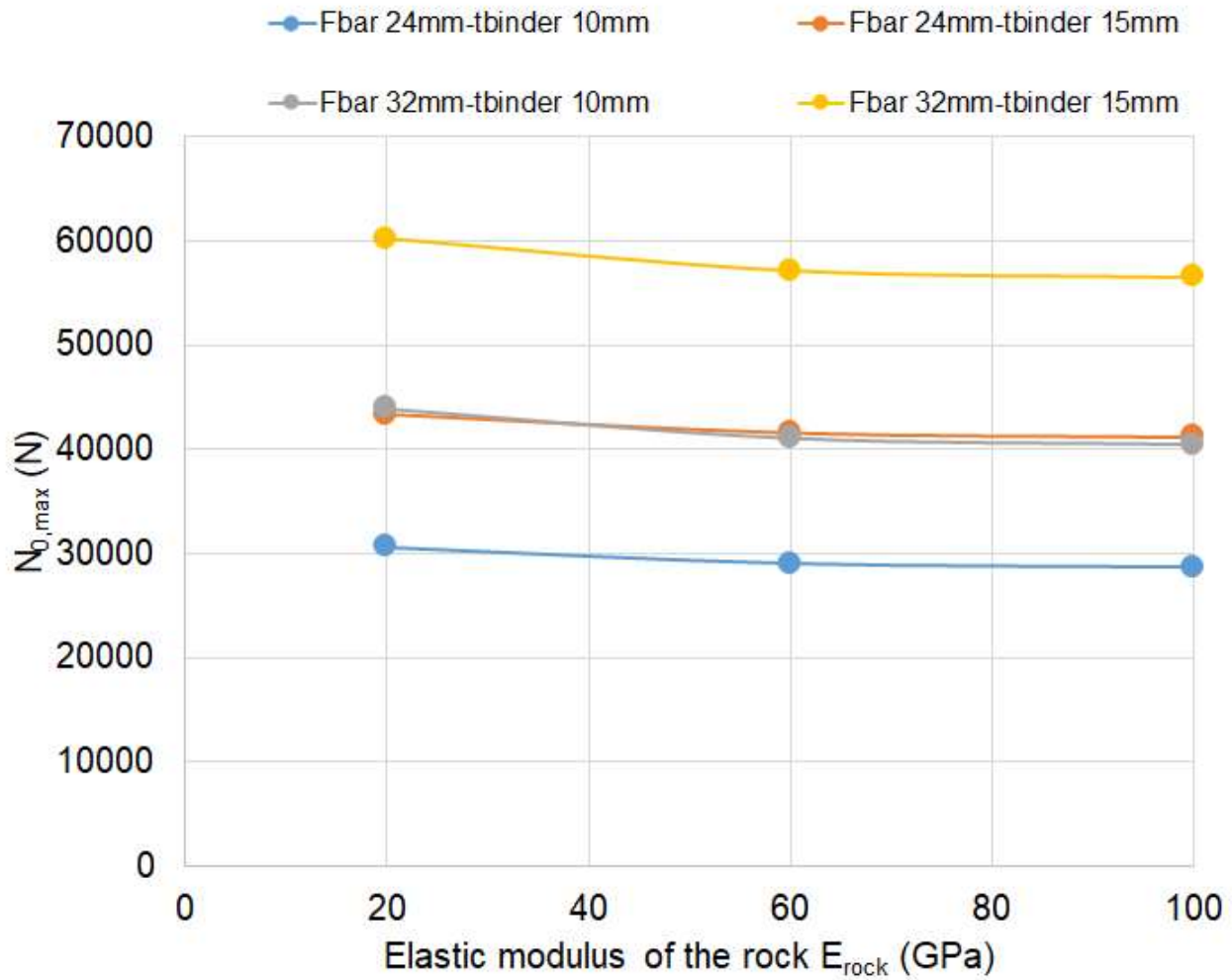
455 Figure 11. Trend of the transversal stabilization force $T_{0,max}$, as the elastic modulus of the
 456 rock E_{rock} varies, for different combinations of the thickness of the binder annulus (t_{binder})
 457 and of the angle ϑ which forms the displacement vector of the block δ with the direction of
 458 the bolt axis. Case of a resin binder ($E_{binder}=8$ GPa) and diameter of the bar $\Phi_{bar}=32$ mm.

459



460

461 Figure 12. Trend of the axial stabilization force $N_{0,max}$, as the elastic modulus of the rock
 462 E_{rock} varies, for different combinations of the thickness of the binder annulus (t_{binder}) and
 463 of the angle ϑ which forms the displacement vector of the block δ with the direction of the
 464 bolt axis. Case of a traditional cementitious grout ($E_{binder}=8$ GPa).



465

466 Figure 13. Trend of the axial stabilization force $N_{0,max}$, as the elastic modulus of the rock
 467 E_{rock} varies, for different combinations of the thickness of the binder annulus (t_{binder}) and
 468 of the angle ϑ which forms the displacement vector of the block δ with the direction of the
 469 bolt axis. Case of a resin binder ($E_{binder}=2$ GPa).

470

471 From an examination of the figures, it can be seen that:

- 472 • The elastic modulus of the rock E_{rock} does not always have a significant influence on
 473 the value of the force $N_{0,max}$
- 474 • the angle ϑ , the thickness of the binder annulus, the diameter of the bar and the type
 475 of binder used, greatly influence the value of the force $N_{0,max}$

- 476 • as the rock's elastic modulus E_{rock} increases, the stabilization force $N_{0,max}$ tends to
477 decrease; this reduction is more evident when traditional cementitious grout is used
478 as binder material
- 479 • the angle ϑ has no effect on $N_{0,max}$, whose value, however, is influenced by the
480 diameter of the bar, the thickness of the binder annulus and above all by the type of
481 binder material used (traditional cementitious grout or resin)

482 The same graphs shown in this paragraph can be used for different values of the diameter
483 of the bar, thickness of the binder annulus, angle ϑ and elastic modulus of the rock: in these
484 cases, linear interpolation can be used to estimate the stabilization forces for values different
485 from those considered in the study, without committing significant errors. If, for example, it
486 is necessary to determine the stabilization force $T_{0,max}$ in the case of a bar diameter Φ_{bar} of
487 28 mm, thickness of the binder annulus t_{binder} of 13 mm, angle ϑ of 50° and $E_{rock}=50$ GPa,
488 adopting the traditional cementitious grout, the following values of $T_{0,max}$ can be obtained
489 from Figures 8 and 9:

490

491 $T_{0,max} (\Phi_{bar}=24 \text{ mm}; t_{binder}=10 \text{ mm}; \vartheta =45^\circ; E_{rock}=20 \text{ GPa}) =2759 \text{ N}$

492 $T_{0,max} (\Phi_{bar}=24 \text{ mm}; t_{binder}=10 \text{ mm}; \vartheta =45^\circ; E_{rock}=60 \text{ GPa}) =3452 \text{ N}$

493 from which we have by interpolation:

494 $T_{0,max} (\Phi_{bar}=24 \text{ mm}; t_{binder}=10 \text{ mm}; \vartheta =45^\circ; E_{rock}=50 \text{ GPa}) =3278 \text{ N}$

495

496 $T_{0,max} (\Phi_{bar}=24 \text{ mm}; t_{binder}=10 \text{ mm}; \vartheta =60^\circ; E_{rock}=20 \text{ GPa}) =4778 \text{ N}$

497 $T_{0,max} (\Phi_{bar}=24 \text{ mm}; t_{binder}=10 \text{ mm}; \vartheta =60^\circ; E_{rock}=60 \text{ GPa}) =5978 \text{ N}$

498 from which we have by interpolation:

499 $T_{0,max} (\Phi_{bar}=24 \text{ mm}; t_{binder}=10 \text{ mm}; \vartheta =60^\circ; E_{rock}=50 \text{ GPa}) =5678 \text{ N}$

500

501 and then again by interpolation:

502 $T_{0,max} (\Phi_{bar}=24 \text{ mm}; t_{binder}=10 \text{ mm}; \vartheta =50^\circ; E_{rock}=50 \text{ GPa}) =4078 \text{ N}$

503

504 Proceeding in the same way for $\Phi_{bar}=32 \text{ mm}$ and $t_{binder}=10 \text{ mm}$ we have:

505 $T_{0,max} (\Phi_{bar}=32 \text{ mm}; t_{binder}=10 \text{ mm}; \vartheta =50^\circ; E_{rock}=50 \text{ GPa}) =6286 \text{ N}$

506

507 For $\Phi_{bar}=24 \text{ mm}$ and $t_{binder}=15 \text{ mm}$ we obtain:

508 $T_{0,max} (\Phi_{bar}=24 \text{ mm}; t_{binder}=15 \text{ mm}; \vartheta =50^\circ; E_{rock}=50 \text{ GPa}) =8231 \text{ N}$

509

510 For $\Phi_{bar}=32 \text{ mm}$ and $t_{binder}=15 \text{ mm}$ we obtain:

511 $T_{0,max} (\Phi_{bar}=32 \text{ mm}; t_{binder}=15 \text{ mm}; \vartheta =50^\circ; E_{rock}=50 \text{ GPa}) =11109 \text{ N}$

512

513 And, therefore, by interpolating the last 4 values of $T_{0,max}$ in pairs, we have:

514 $T_{0,max} (\Phi_{bar}=28 \text{ mm}; t_{binder}=10 \text{ mm}; \vartheta =50^\circ; E_{rock}=50 \text{ GPa}) =5182 \text{ N}$

515 $T_{0,max} (\Phi_{bar}=28 \text{ mm}; t_{binder}=15 \text{ mm}; \vartheta =50^\circ; E_{rock}=50 \text{ GPa}) =9670 \text{ N}$

516

517 And finally:

518 $T_{0,max} (\Phi_{bar}=28 \text{ mm}; t_{binder}=13 \text{ mm}; \vartheta =50^\circ; E_{rock}=50 \text{ GPa}) =7875 \text{ N}$

519

520 **Conclusions**

521 Fully grouted passive bolts take load when the block of rock tends to move, sliding along
522 one or more surfaces formed by the natural discontinuities of the rock. The bolt is able to
523 apply two stabilizing forces to the block: an axial force and a transversal one, perpendicular
524 to the axis of the bolt, with vector belonging to the same plane of the bolt itself and the
525 displacement vector of the rock block. In this paper it was possible to provide simplified
526 equations able to determine the two stabilizing forces of the passive bolt.

- 527 • These equations require the determination of the two fundamental mechanical
528 parameters governing the bolt-rock interaction: the shear interaction parameter β_c at
529 the bolt-rock interface and the normal interaction parameter k at the same interface.
- 530 • The interaction parameters are difficult to determine through specific in situ tests.
- 531 • For this reason, an accurate analysis through numerical modeling is necessary. Two
532 different highly detailed numerical models have been developed, one for the study of
533 the shear interaction and the other for the normal interaction between the bolt and
534 the rock.
- 535 • Numerous cases were considered, varying the diameter of the steel bar, the
536 thickness of the binder annulus, the mechanical characteristics of the rock and of the
537 binder material.
- 538 • The parametric analysis was developed considering fields of variability of each
539 geometric and mechanical parameter, typical of the real cases that can be
540 encountered.
- 541 • From the study it was possible to identify the interaction parameters for all the cases
542 analyzed and also to define equations that are able to estimate them when the main
543 geometric and mechanical parameters that characterize the functioning of fully
544 grouted passive bolts vary.

- 545 • Thanks to the knowledge of these parameters, it has been possible to directly
546 evaluate the stabilization forces of the single bolt and develop diagrams that allow
547 their determination as the diameter of the steel bars, the thickness of the binder
548 annulus, the mechanical characteristics of the rock and the binder vary material
549 (either cementitious grout or resin).
- 550 • These diagrams are a useful tool to allow an accurate design of such interventions in
551 the stabilization of potentially unstable blocks of rock.

552 **Conflict of interests**

553 Authors declare they have no conflict of interest.

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