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A parametric analysis on the influence of the binder characteristics on the behaviour of passive rock bolts with the Block Reinforcement Procedure

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Abstract

An extensive parametric analysis of 729 typical cases was developed with a calculation procedure allowing to simulate in detail the behavior of the passive bolts and their interaction with the surrounding rock. The parametric analysis allowed to evaluate the effectiveness of the bolts, on the basis of the extent of the stabilization forces produced, in relation to the geometric and mechanical characteristics of the binder used in the realization of the bolts. Different bolt diameters and lengths, binder thickness and elastic moduli and block displacement with respect to the horizontal plane have been considered. It has been possible to detect how such parameters have a great influence on the mechanical behavior of the bolt and on the extent of the stabilizing forces which are applied to the potentially unstable rock block. For this reason, therefore, the definition of the characteristics of the binder (and in particular the thickness of the binder around the steel bar and the elastic modulus of the binder itself) cannot be assessed only in relation to application aspects, but it must be able to consider the effects on the efficiency of the bolt and in particular on the stabilization forces on the potentially unstable rock block.

Key words: rock bolt; rock; binder; elastic modulus; Block Reinforcement Procedure; parametric analysis, rock-bolt interaction

Abbreviations and nomenclature

BRP Block reinforcement procedure

CMC Continuously mechanically coupled

DEFE Doubly enriched finite element

LEM Limit equilibrium method

UCS Unconfined compressive strength

FS Factor of safety

EA Axial stiffness of the bolt

E_{binder} Elastic modulus of the binder surrounding the steel bar in the hole

E_{binder}, ∞ Elastic modulus for the cementitious grout for a time, t, very large;

EJ Bending stiffness of the bolt

E_{st} Steel elastic modulus

i Intersecting line of the sliding surfaces, coinciding with the direction of the block displacement vector

k Link between the transverse displacements, y, of the bolt and the normal pressure, p, which is applied on the perimeter of the bolt (on the wall of the hole) by the surrounding rock

L_a Length of each single bolt inside the unstable block

L_p Bolt length in the stable rock behind the unstable one

M Bending moments

N Axial forces

N_0 Value of the tensile stress applied in the axial direction of the bolt

p Value of the normal pressure which is applied on the perimeter of the bolt

P_{hole} Perimeter of the cross-section of the bolt

T Shear forces

t Time

t_{binder} Thickness of the binder annulus surrounding the bar

T_0 Value of the shear stress applied

v_r Value of the relative axial displacement of the bolt-rock

y Transversal displacements of the bolt

α Parameter characterizing the interaction in the axial direction between bolt and rock

$\alpha = \sqrt{\frac{\beta_c \cdot P_{hole}}{EA}}$

β Parameter that characterizes the interaction in the transverse direction between bolt and rock $\beta = \sqrt[4]{\frac{k \cdot \Phi_{hole}}{4 \cdot EJ}}$

β_c Link between the relative axial displacements, v_r, and the shear stresses, τ, that develop on the perimeter of the bolt

δ Arbitrary displacement to the block

δ_{max} Maximum displacement of the block which the bolt system can support

δ_n Displacement in the axial direction of the bolt

δ_t Displacement in the transversal direction of the bolt

ε_E Constant (inverse dimension of time) indicating the rate with which the elastic modulus evolves from the initial null value to the asymptotic value $E_{grout,\infty}$

γ_{displ} Angle of the block with respect to the horizontal plane

η_{min} Minimum ratio between each local safety factor divided by the respective minimum permissible value required

σ_{yield} Steel yield stress

τ_{lim} Limit shear stress at the bolt-rock interface

υ_{binder} Poisson coefficient of the binder

Φ_{hole} Diameter of the hole

Φ_{bar} Bolt (bar) diameter

ψ_{bolt} Bolt inclination with the horizontal plane

Introduction

In order to control and prevent both major and local instabilities of the rock mass during underground, different support systems such as meshing, sprayed concrete and anchoring are used (e.g. Chen, 2004; Oreste, 2008; Oreste, 2013). Fully grouted bolts are used for instance to prevent rock blocks from falling in fractured rocks in order to ‘lock together’ blocks in heavily jointed rock masses to create a “reinforced arch” around an underground opening that is capable of providing stability to the cavity (Lang, 1961).

A fully grouted bolt intersected by a joint could influence the shearing of a joint increasing the bolt resistance due to an increase in axial, shear forces and bending moments in the bolt rod (Das et al., 2013; Oreste and Dias 2012; Ranjbarnia et al., 2014; 2016).

Rock bolting not only strengthens or stabilizes a jointed rock mass, but also has a marked effect on the rock mass stiffness (Chappell, 1989). Furthermore, where the *in situ* rock stresses increase, rock support is used to prevent the failed rock from disintegration (Li, 2017).

Rock bolts are widely used to reinforce the rock mass and stabilize jointed surrounding rock, because of their ease of installation, versatility and relatively low cost of rebars in comparison to their alternative counterparts (Indraratna and Kaiser, 1990). Passive reinforcing elements have a zero initial load and the mobilized stabilizing load increases with the displacement of the potentially unstable rock block. However, also active bolts can be used, which assure overall stability and provide confinement to the rock mass between the two ends of the element, as the tensile load transfers from the element as an active compressive load to the rock mass increasing the resulting stress confinement in the rock (Carranza-Torres, 2009; He et al., 2015).

Rock bolts generally consist of steel rods with a mechanical or chemical anchor at one end and a face plate and nut at the other (Bawden, 2011). Continuously mechanically coupled

(CMC) bolts rely on a binder that fills the annulus between the element and the borehole wall (see Fig. 1).

The load transfer through the bond between the element and the rock causes tension in the bolt. As a result of the rock bolt deformation, the relative shear force will act on the rock mass and restrain the further deformation of the rock, transferring load from the stable exterior to the interior of the rock mass (Nie et al. 2014).

Rock bolts are also used for the stabilization of potentially unstable blocks due to sliding from the walls of rocky excavation fronts on the surface or from side walls of underground works. This type of bolts operates by applying to the potentially unstable blocks two direct forces, the first one, along the axis of the bolt and the second one, perpendicular to the first one and having a direction that depends on the vector displacement of the block (Oreste and Cravero, 2008). Passive bolts are loaded and transmit stabilizing forces with the movements of the rock mass and in particular with the displacement of the potential unstable block. At the time of their installation they have a zero initial load which increases until the block is completely stabilized. The role of the interface with the rock is fundamental for the functioning of the bolt. The physical and mechanical characteristics of the cementitious (or resin) binders are, therefore, decisive, but often neglected in the design phase of the bolt installation procedure.

In this paper a simplified calculation method the Block Reinforcement Procedure (BRP) (Oreste and Cravero, 2008; Oreste, 2009) is used for performing a parametric analysis to study potentially unstable small-medium sized rock blocks on the walls of an underground excavation, reinforced by passive fully grouted bolts. The procedure applies the Limit Equilibrium Method (LEM) and the bolt is schematized as a beam while the bolt-rock interaction considers a continuous bed of Winkler springs (Lancellota and Cavalera 1999), in both the axial and transversal directions. More specifically, the parametric study aimed to analyze in detail the influence of the characteristics of the bolt-rock interface on the behavior of the bolt and, therefore, on its effectiveness in transmitting the stabilizing forces to the potentially unstable block.

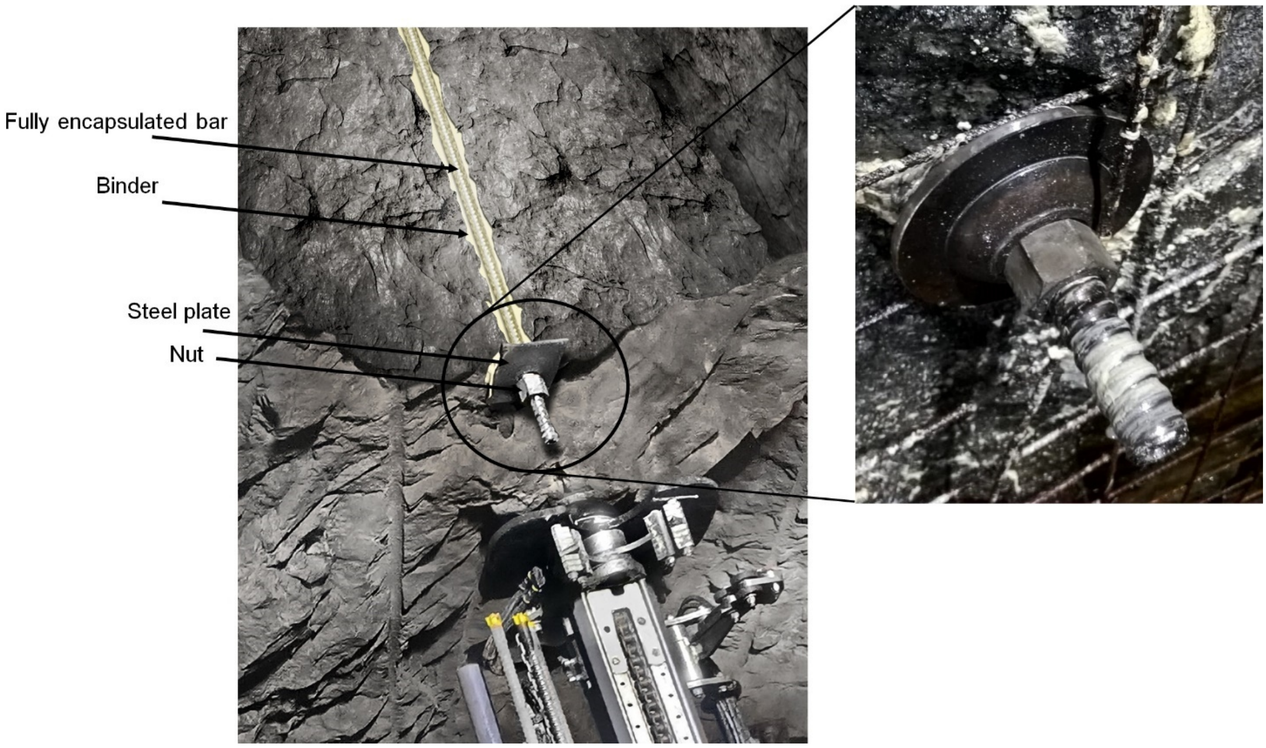

Fig. 1 Picture a fully encapsulated rock bolt

The numerical model used for the parametric analysis

The calculation model used, called BRP, was introduced by Oreste and Cravero (2008) and Oreste (2009). This model maintains the simplicity typical of analytical calculation methods but achieves a satisfactory precision in the analysis of the interaction between fully encapsulated passive bolt and rock, for the stabilization of rock blocks isolated by natural discontinuities. These bolts cross the potentially unstable blocks and reach the stable rock behind them, where they penetrate for a certain length (L_p) (Figure 2). Fig. 2 shows L_a, which is the length of the bolt inside the unstable block (Zone I); L_p, which is the length of the remaining part of the bolt in stable rock (Zone II); A, B, and D are the vertices of the rock block; δ represents the displacement of the block along the sliding direction; δ_n and δ_t are respectively the components of the displacement in the axial and normal direction; x is the axial coordinate along the bolt; γ_{displ} is the angle between the sliding direction and the horizontal plane; ψ_{bolt} is the inclination of the bolt with the horizontal plane.

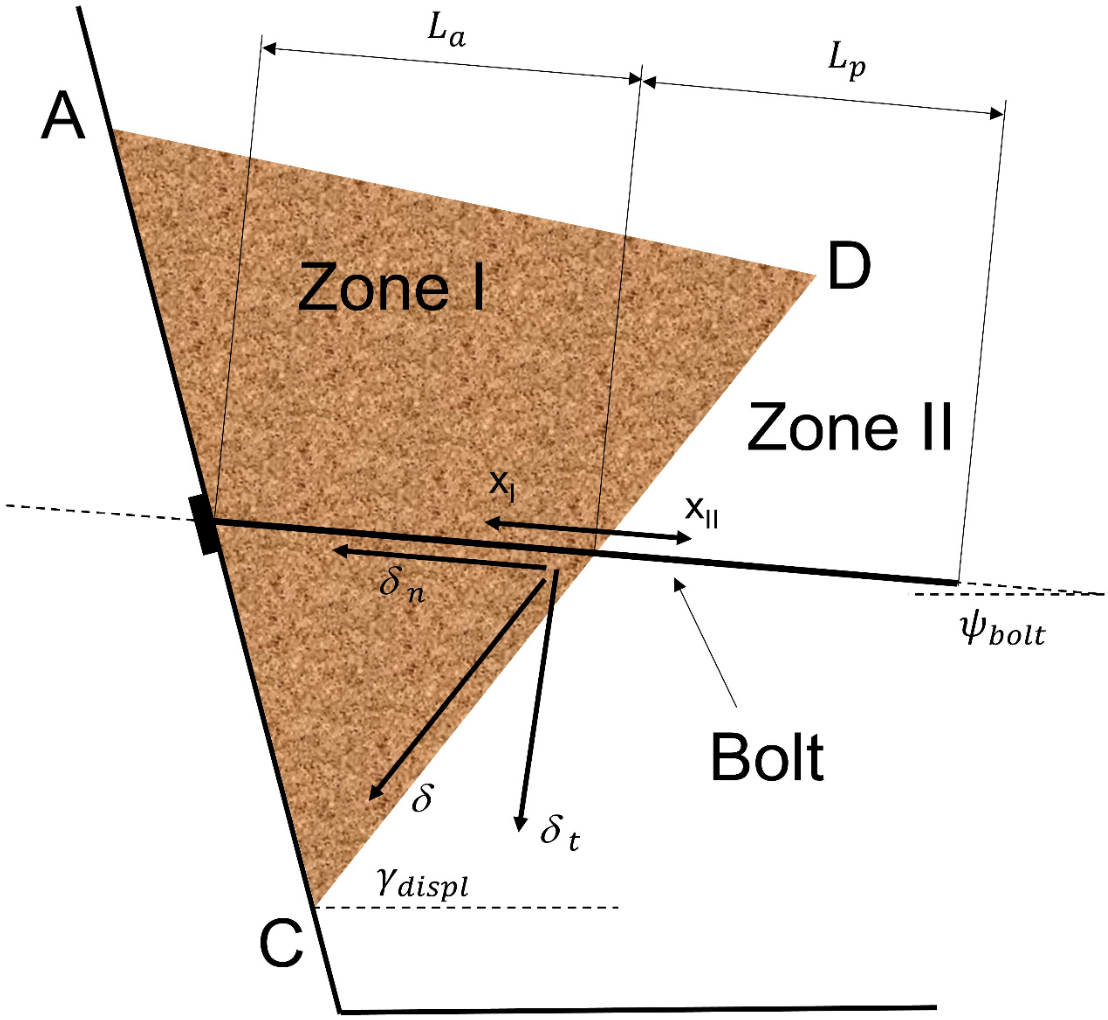

Fig. 2 Schematic representation (not to scale) of the potentially unstable rock block and of the passive bolt passing through it.

The method allows the evaluation of the forces (axial N and shear T) and of the bending moments M developing along the bolt, as a linear function of the (very small) displacements of the block. Then the stabilizing forces, applied by the single bolt to the potentially unstable block, are determined. These are essentially the N and T forces that develop in the bolt at the intersection with the sliding surface. The displacement of the block considered is the maximum one which leads to the limit conditions of the bolts. The main phases of the calculation are as follows (Oreste and Cravero, 2008):

a) definition of the geometry of the problem (number, position, orientation of the bolts with respect to the block, the length of each single bolt inside the block, L_a, and the bolt length in the stable rock behind the unstable one, L_p) (Figure 2);
b) assignment of an arbitrary displacement to the block δ, compatible with the geometry and with the sliding surfaces identified; determination of the two components of the displacement δ for each bolt: one in the axial direction of the bolt δ_n and the other in the transverse direction δ_t (Figure 2);
c) on the basis of the two values of the displacement, δ_n and δ_t, the values of N, T, M and the value of the relative axial displacement of the bolt-rock v_r and the relative transversal displacement along the bolt are then identified;
d) determination of the local safety factors in the bolt and on the bolt-rock interface, in order to verify the working conditions of the bolt in the presence of the arbitrary displacement δ applied to the block;
e) comparison of the local safety factors obtained in the previous point with the required minimum admissible values: the minimum ratio (η_{min}) between each local safety factor divided by the respective minimum permissible value required, among all the installed bolts, allows to determine the maximum displacement of the block which the bolt system can admit: $\delta_{max} = \frac{\delta}{\eta_{min}}$;
f) re-determination of N, T, M, v_r and y in correspondence with the displacement of the block equal to δ_{max}. It is interesting for the evaluation of the block stability to consider the values of N and T at the intersection with the sliding surface of the block (N_0 and T_0): they are also the maximum values of N and T along the bolt. The values N_0 and T_0 are also the forces that each bolt applies to the potentially unstable block: N_0 is the

force applied in the axial direction of the bolt, T_0 is the force applied in the direction of the intersection line between the transversal plane to the bolt and the plane comprising the bolt itself and the block displacement vector;

g) determination of the global safety factor of the block in the presence of bolting, considering the forces N_0 and T_0 that each bolt applies to the potentially unstable block.

The procedure between steps a) and g) is repeated until a configuration of the bolt system is judged satisfactory with respect to the overall safety factor of the block.

To derive the forces N_0 and T_0, which are applied by each bolt to the rock block, the effects of the axial component and of the transversal component of the displacement of the block, δ , are analyzed separately. The axial component δ_n allows to determine the axial force N and the relative axial displacement v_r along the bolt, while the transverse component δ_t allows to determine T, M and the transverse displacement y along the bolt.

More specifically, N_0 and T_0, are determined with the following equations:

$$N_0 = EA \cdot \alpha \cdot \left(-\frac{\left(1-e^{-2\cdot\alpha\cdot L_p}\right)\cdot e^{-2\cdot\alpha\cdot L_a}}{2\cdot\left[1+e^{-2\cdot\alpha\cdot(L_a+L_p)}\right]} - \frac{\left(1-e^{-2\cdot\alpha\cdot L_p}\right)}{2\cdot\left[1+e^{-2\cdot\alpha\cdot(L_a+L_p)}\right]} \right) \cdot \delta_{n,max} \quad (1)$$

$$T_0 = EJ \cdot \beta^3 \cdot \delta_{t,max} \quad (2)$$

where:

EA is the axial stiffness of the bolt;

EJ is the bending stiffness of the bolt;

L_a is the crossing bolt length in the block;

L_p is the bolt length in the stable rock behind the block;

α is a parameter characterizing the interaction in the axial direction between bolt and rock

$\alpha = \sqrt{\frac{\beta_c \cdot P_{hole}}{EA}}$;

P_{hole} is the perimeter of the cross-section of the bolt;

β_c is the link between the relative axial displacements, v_r, and the shear stresses, τ, that develop on the perimeter of the bolt (on the wall of the hole); β_c depends in general on the characteristics of the material surrounding the steel bar and on the elastic modulus of the rock;

β is a parameter that characterizes the interaction in the transverse direction between bolt and rock $\beta = \sqrt[4]{\frac{k \cdot \Phi_{hole}}{4 \cdot EJ}}$;

k is the link between the transverse displacements, y, of the bolt and the normal pressure, p, which is applied on the perimeter of the bolt by the surrounding rock;

Φ_{hole} is the diameter of the hole.

Equation 2 is valid for sufficiently high values of L_a and L_p (greater than or equal to 1m). The characteristics of the material that is used to connect the steel bar to the rock (usually cement grout or resin, e.g. Littlejohn and Bruce 1977; Henning and Ferreira 2010) affect the axial stiffness of the bolt (EA), the transverse stiffness (EJ), the parameter β_c of interaction in the axial direction and the parameter k which links the trasversal displacements y to the pressure p applied to the perimeter of the bolt. They prove to be very important in the functioning mechanism of the bolt and in particular in the evaluation of the stabilization forces that the bolt succeeds in transmitting to the rock block.

Axial and transverse stiffness can be obtained from the following expressions (Oreste and Cravero 2008):

$$EA = E_{st} \cdot \left(\frac{\pi}{4} \cdot {\Phi_{bar}}^2\right) + E_{binder} \cdot \left[\frac{\pi}{4} \cdot \left({\Phi_{hole}}^2 - {\Phi_{bar}}^2\right)\right] \tag{3a}$$

$$EJ = E_{st} \cdot \left(\frac{\pi}{64} \cdot {\Phi_{bar}}^4\right) + E_{binder} \cdot \left[\frac{\pi}{64} \left({\Phi_{hole}}^4 - {\Phi_{bar}}^4\right)\right] \tag{3b}$$

where:

Φ_{bar} is the bolt diameter;

E_{st} is the steel elastic modulus;

E_{binder} is the elastic modulus of the binder surrounding the steel bar in the hole.

In the case in which the elastic modulus of the rock is considerably higher than the elastic modulus of the material that surrounds the steel bar (for example cement mortar), it is possible to assume the simplified hypothesis of non-deformable rock, which leads to the following estimation of β_c (and therefore, of α) and of k (and therefore of β):

$$\beta_c \cong \frac{1}{t_{binder}} \cdot \frac{E_{binder}}{2 \cdot (1+\nu_{binder})} \tag{4a}$$

$$k \cong \frac{E_{binder}}{t_{binder}} \tag{4b}$$

where:

t_{binder} is the thickness of the binder annulus surrounding the steel bar;

υ_{binder} is the Poisson coefficient of the binder (generally assumed equal to 0.15).

When using both cement grout or resin, the elastic modulus evolves over time from the moment the material is injected into the hole. For resins, curing evolution over time is faster, whereby setting occurs within few hours, while for cement grouts are more slowly, where cement hydration is completed within several weeks (see Spagnoli 2018 for detailed information). In both cases it is however possible to use the following negative exponential equation to estimate the trend of the elastic modulus over time (Fig. 3):

$$E_{binder} \cong E_{binder,\infty} \cdot (1 - e^{-\varepsilon_E \cdot t}) \tag{5}$$

where:

E_{binder}, ∞ is the elastic modulus of the binder for a time t very large;

ε_E is a constant (having the inverse dimension of time) indicating the rate with which the elastic modulus evolves from the initial null value to the asymptotic value E_{binder}, ∞. The constant ε_E can be evaluated by knowing one or more E_{binder} intermediate values associated with certain values of time t.

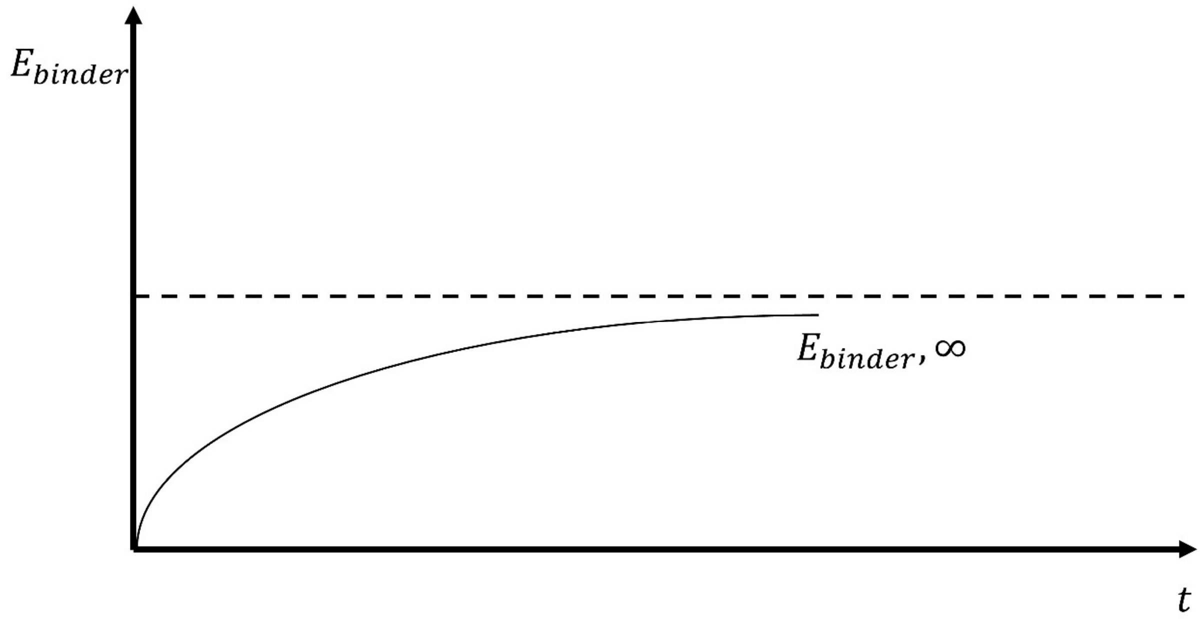

Fig. 3 Sketch of the evolution over time of the elastic modulus of the binder according to the simplified trend of the negative exponential law.

By estimating the time t at which the dislocation of the block occurs and, therefore, the loading of the bolts, it is possible to determine from the equation 5 the value of the elastic modulus E_{binder} to be used in the calculations (equations 3 and 4) for the analysis of passive bolts used in the stabilization of rock blocks.

Results and discussion

To study in detail the role of the mechanical properties of the binder used to connect a steel bar of a fully encapsulated passive bolt to the surrounding rock, a parametric analysis of 729 cases has been developed by varying six fundamental parameters of the calculation, i.e. 3^6 cases:

1. The diameter of the steel bar (Φ_{bar}= 18mm, 27mm, 36mm);
2. The thickness of the binder ring around the bar (t_{binder}= 8mm, 12mm, 16mm);
3. The length of the bolt in the unstable block (L_a = 1m, 2m, 3m);
4. The total length of the bolt ($L_{tot} = L_a + L_p$= 4m, 5m, 6m);
5. The elastic modulus of the binder (E_{binder} = 4GPa, 8GPa, 12GPa)
6. The displacement of the block with respect to the horizontal plane (γ_{displ} = 30°, 45°, 60°).

The first four parameters concern the geometry of the bolt (the characteristics of its cross section and those related to the longitudinal development, with reference to the crossed rock block); the fifth is the parameter related to the stiffness of the binder; finally, the last one concerns the angle of the vector-displacement of the block, coinciding with the intersection line of its two sliding planes (Figure 4). A, B and C are the vertices of the block on the vertical rock face; D: vertex inside the rock mass; i: intersecting line of the sliding surfaces, coinciding with the direction of the block displacement vector. It has to be pointed out that normally annulus values of 16mm are not used, but it was discussed in the analysis to show the impact on the axial and shear forces obtained with the model. Besides, the model is also applicable for length values larger than those presented above (for instance for cable bolts).

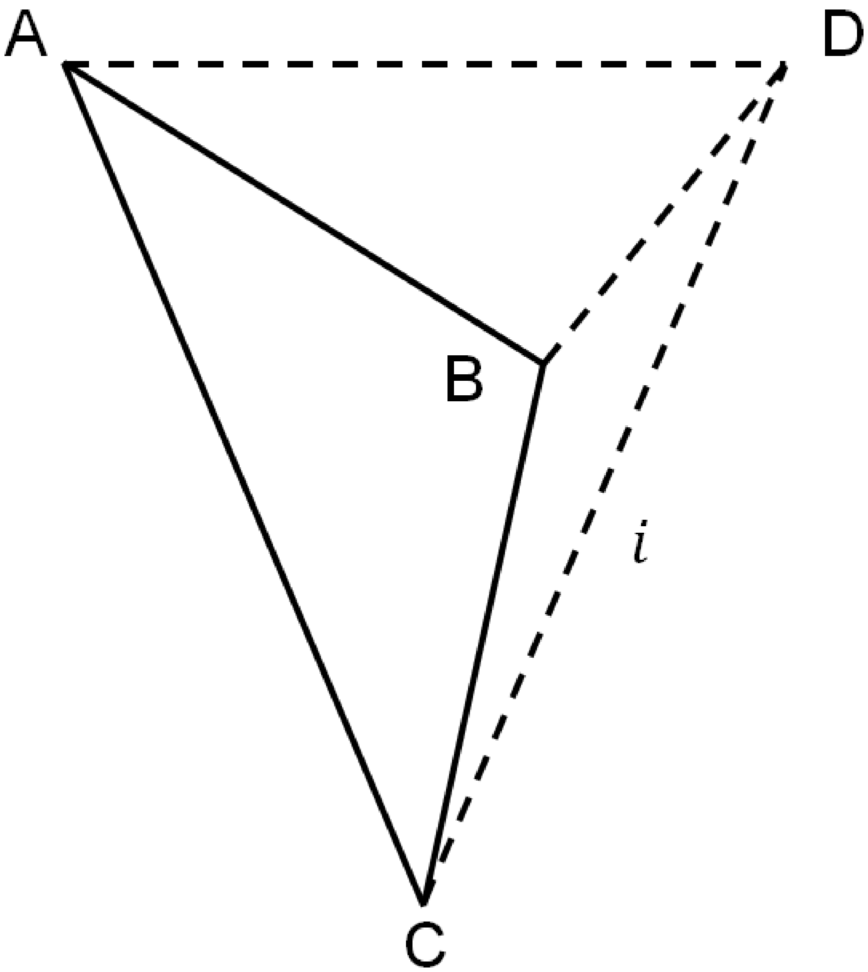

Fig. 4 Sketch of the pyramidal block considered in the calculations.

The BRP calculation procedure was used to study the behavior of the bolts. Some simplifying hypotheses are the basis of the study:

a. The potentially unstable rock block is pyramidal and is positioned on a vertical wall; appears to be symmetrical with respect to the vertical plane passing through its inner vertex D (Figure 4) and perpendicular to the rock face;
b. The block moves with a simple translation in the direction of the intersection line i;
c. The bolt is a single element, horizontal and perpendicular to the rock face;
d. The bolt has a linear and elastic behavior, dictated by normal stiffness (EA) and by flexural stiffness (EJ);

e. The interaction of the bolt with the surrounding rock is analyzed through linear and elastic Winkler springs, both in the direction transverse to the bolt, and in the axial direction;
f. The stiffness of the rock is considerably larger than the stiffness of the binder; for this reason, the rock is considered infinitely rigid and does not influence the interaction parameters α and β.

The other parameters necessary for the calculation were arbitrary considered constant in the parametric study and they are:

- Poisson ratio of the binder (ν_{binder} = 0.15);
- Elastic modulus of steel (E_{st} = 210GPa);
- Steel yield stress (σ_{yield} = 400MPa);
- Limit shear stress at the bolt-rock interface (τ_{lim} = 2MPa);
- Local safety factors of the bolt, against the failure of the steel bar or failure of the bolt-rock interface ($FS_{,bar}$ = 1.25; $FS_{,pullout}$ = 1.25).

The forces distribution along the bolt N, M and T for L_a=3m, L_{tot}=6m, E_{binder}= 8GPa, γ_{displ}=60°, Φ_{bar}= 27mm and t_{binder} = 8mm is shown in Fig. 5. The origin of the distance axis on Fig. 5 is positioned on the intersection with the sliding surface of the block. Because of the flat trend of the lines at a certain distance from the origin, the graph has been cut. The study allowed to derive the values of N_0 and T_0 that the bolt applies to the potentially unstable rock block, in each of the 729 cases examined. In each graph obtained, the results of 27 analyzes are summarized. In particular, in these graphs, the values N_0 and T_0 are plotted with varying the elastic modulus of the binder.

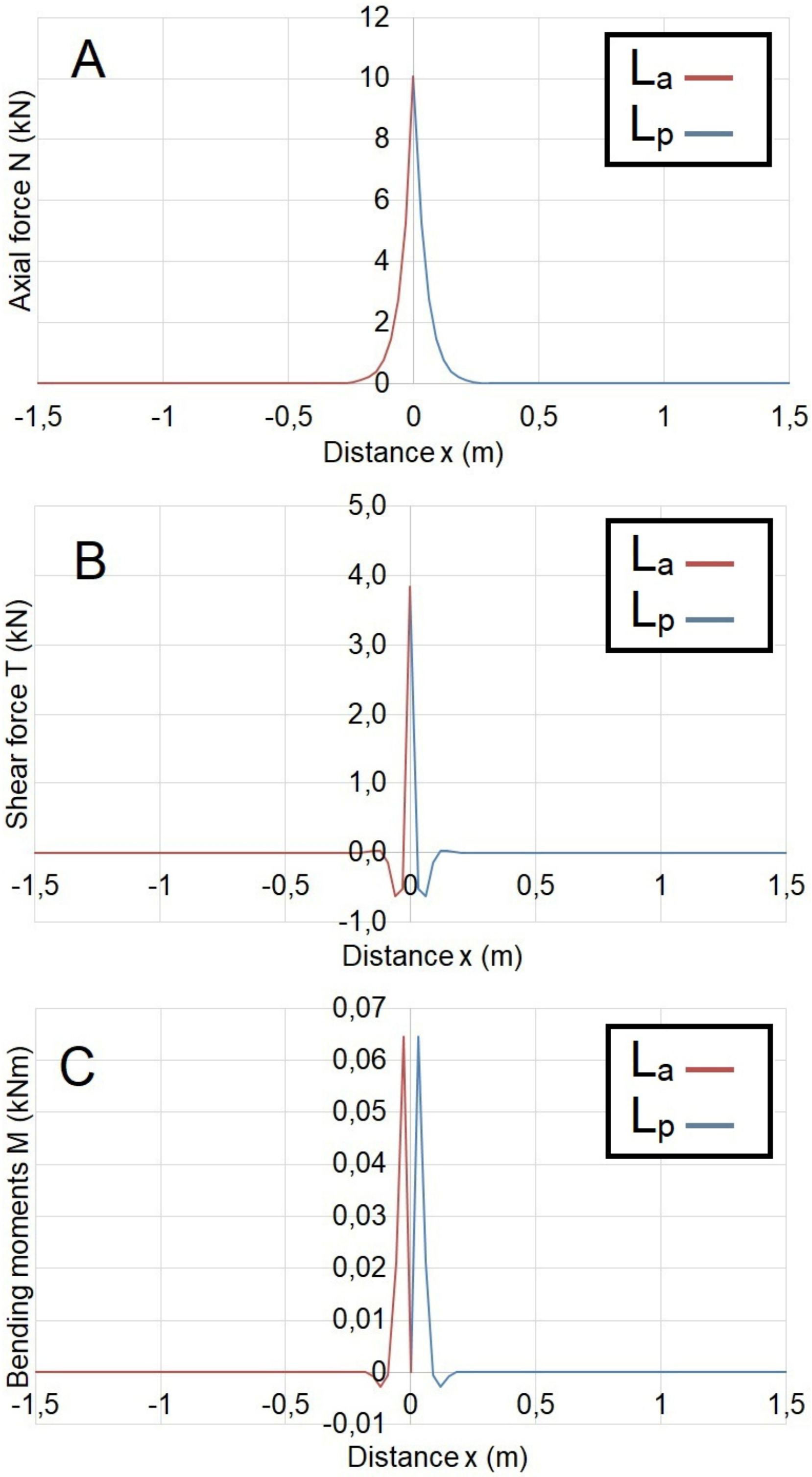

Fig. 5. Trend of the axial force N (A), shear force T (B) and moment M (C) for a bolt with L_a=3m, L_{tot}=6m, E_{binder}= 8GPa, γ_{displ}=60°, Φ_{bar}= 27mm and t_{binder} = 8mm.

From the analysis of the figures it is possible to see how the maximum axial tensile force N_0 increases, as well as increasing the diameter of the bar, and:

- N_0 decreases as the elastic modulus of the binder increases;
- N_0 increases as the thickness of the binder annulus increases;
- N_0 is independent of the inclination with respect to the horizontal of the block displacement vector.

Furthermore, there is no influence of the length L_a and the length L_{tot} on the value of N_0, when the values of the lengths in the unstable zone and in the stable rock are greater than or equal to 1 m. For this reason, the graphs that refer to the case of L_a = 2m and L_{tot} = 4m (Figure 6) can also be considered representative of the other 8 L_a-L_{tot} combinations.

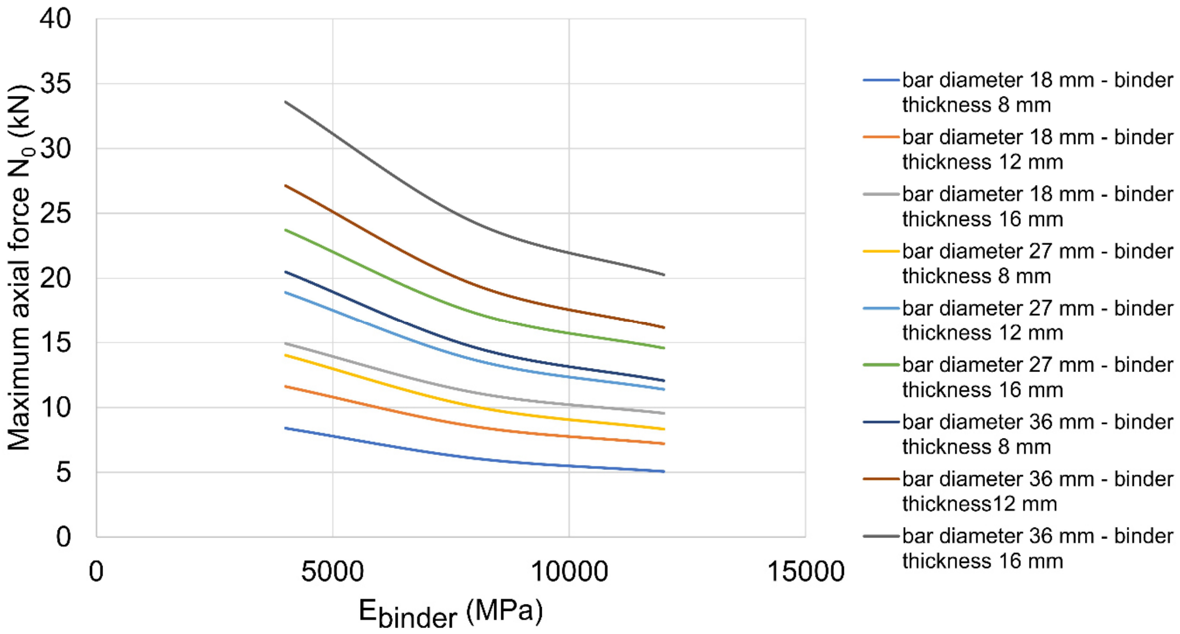

Fig. 6. Trend of the axial tensile force N_0 with variation of the elastic modulus of the binder, the diameter of the steel bar, the thickness of the binder for the displacement vector angle, γ_{displ}, of 30°.

From the analysis of the graphs of Figure 6 it can be seen how the characteristics of the binder (elastic modulus and thickness) have a great influence on the axial force N_0. In fact, this force can even increase by 250% depending on the thickness of the grout and its elastic modulus. It is also possible to observe that the values of N_0 tend to increase for increasing annulus grout thickness (from 8 to 16mm).

As for the maximum shear force T_0 value, it increases with the diameter of the bar, but also:

- It decreases with the increase of the elastic modulus of the binder (in a non-linear way);
- It increases as the thickness of the grout annulus increases;
- It increases as the inclination of the vector-displacement of the block increases.

Also for T_0 there is no influence of length L_a and length L_{tot}. The three graphs that refer to the case of L_a= 2 m and L_{tot} = 4 m (Figure 7) can, therefore, be considered representative for all the values L_a and L_{tot}, provided they have a value greater than 1m.

For bar diameters of 18mm and with relatively small grout thicknesses (8 mm), the value of T_0 remains negligible for any E_{binder} value. When the bar has high diameters and the thickness of the grout is considerable (16mm), on the other hand, T_0 can vary with the elastic modulus of the binder.

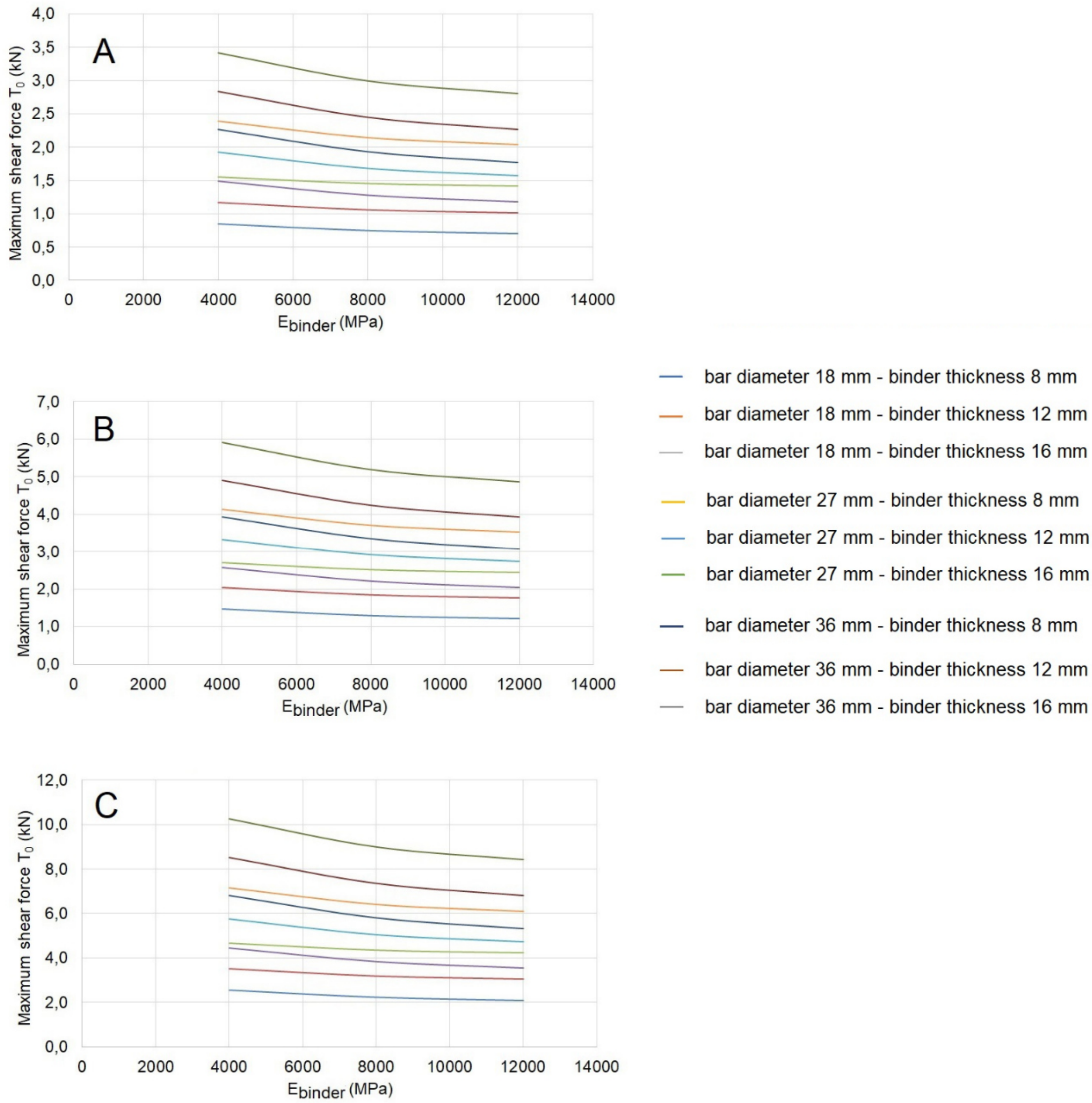

Fig. 7. Trend of the shear force T_0 with variation of the elastic modulus of the binder, the diameter of the steel bar, the thickness of the binder, for three different values of the angle of the displacement vector γ_{displ}: 30° (A), 45° (B), 60° (C) for L_a = 2m and L_{tot} = 4m.

Conclusions

Passive rock bolting is a rock reinforcement system widely used both above ground and in the underground excavations. Its functioning mechanism is complex, as its loading and, therefore, the stabilizing effects are activated with the movement of the rock.

In the present work we tried to evaluate the effects of the mechanical and geometric characteristics of the grout on the behavior of the bolt. The cementitious (or resinous) binder used to connect the steel bolt bar to the rock, in fact, play a fundamental role also in the development of the stabilizing forces that the bolt transmits to the potentially unstable rock blocks.

For this purpose, an extensive parametric analysis was performed, varying some fundamental parameters of the fully encapsulated passive bolts. The calculation method used is the BRP (Oreste and Cravero 2008; Oreste 2009), which allows to analyze in detail the behavior of fully encapsulated passive bolts in the stabilization of blocks that tend to move on a rock face. In the parametric analysis the geometric and mechanical parameters representing the grout around the steel bar and, more precisely, the thickness and the elastic modulus of the binder, were changed.

Furthermore, different values of the total length of the bolt and of its crossing length in the block, the diameter of the steel bar and of the inclination of the vector-displacement of the block with respect to the horizontal plane were considered. 729 different analyzes were developed to represent the typical cases that can be encountered in practice. From the results of the calculation it was possible to detect how the stabilizing forces that the bolt applies to the potentially unstable block depend markedly on the elastic modulus and on the thickness of the binder itself on the edge of the steel bar. In particular, the axial force and the transversal force applied by the bolt to the block decrease as the elastic modulus of the binder increases and they increase as the binder thickness increases. Ultimately, it has been possible to observe a fundamental role of the binder on the behavior of the bolt and on its effectiveness in the stabilization of the potentially unstable blocks on the rock walls. The definition of the characteristics of the grout must be implemented not only in relation to execution problems (speed up of the bolts installation, simplification of the execution phases, guarantees of the final product), but also in relation to the efficiency of the bolting in the stabilization of rock blocks, by achieving high values of stabilization forces. From the parametric analysis performed in this research, larger bolt and larger annulus thickness values provided better results in terms of axial and shear forces, however it is recommended that the mechanical properties (i.e. compressive strength and elastic module) of the pure grout are not overperforming as it seems that larger values have a negative impact on N_0 and T_0.

Conflict of interests

Authors declare they have no conflict of interest.

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FIGURE CAPTION

Fig. 1 Picture a fully encapsulated rock bolt

Fig. 2 Schematic representation (not to scale) of the potentially unstable rock block and of the passive bolt passing through it.

Fig. 3 Sketch of the evolution over time of the elastic modulus of the binder according to the simplified trend of the negative exponential law.

Fig. 4 Sketch of the pyramidal block considered in the calculations.

Fig. 5. Trend of the axial force N (A), shear force T (B) and moment M (C) for a bolt with L_a=3m, L_{tot}=6m, E_{binder}= 8GPa, γ_{displ}=60°, Φ_{bar}= 27mm and t_{binder} = 8mm.

Fig. 6. Trend of the axial tensile stress N_0 with variation of the elastic modulus of the binder, the diameter of the steel bar, the thickness of the binder for the displacement vector angle, γ_{displ}, of 30°.

Fig. 7. Trend of the shear force T_0 with variation of the elastic modulus of the binder, the diameter of the steel bar, the thickness of the binder, for three different values of the angle of the displacement vector γ_{displ}: 30° (A), 45° (B), 60° (C) for L_a = 2m and L_{tot} = 4m.