GFRP anchoring systems for soft-rock geostructures with high cultural and environmental value

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Published in:
Geotechnical Engineering for the Preservation of Monuments and Historic Sites III

DOI:
10.1201/9781003308867-94

Publication date:
2022

Geotechnical Engineering for the Preservation of Monuments and Historic Sites III – Lancellotta, Viggiani, Flora, de Silva & Mele (Eds)

GFRP anchoring systems for soft-rock geostructures with high cultural and environmental value

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ABSTRACT: Structural instability of soft rock geostructures composed of carbonate rocks (such as chalk and calcarenites) and volcanic (tuff) is a serious problem especially when it develops in inhabited centers. Because of the carbonate rich geology, geohazards such as sinkhole and cliff instability are a real threat for inland and coastlines regions of both southern Italy and other regions across the world. The areas affected by such threat often coincide with cultural heritage sites because of their evocative landscape and they represent important nation landmarks, as the white cliffs of Dover in the UK. One of the problems related to the safety of these famous landmarks is the identification appropriate intervention measures able to preserve the originality and beauty of the site. For example, the use of standard shotcrete or rock anchors would result inappropriate as the steel plates of the anchors and the reinforced portions covered by shotcrete would alter the exposed surface significantly. In this paper a novel anchoring system aimed to overcome the above limitations is proposed and its performance is demonstrated by an intensive field testing campaign. By using Glass Fiber Reinforced Polymers (GFRP) bars combined with various types of consolidants, it is shown that that the same level of reinforcement, guaranteed by using standard grouted DYWIDAG steel bars, can be achieved with a setup characterized with lighter, more transparent and corrosion resistant materials.

1 INTRODUCTION

Rockbolts are the most effective and economical method used in mining and tunneling engineering to support underground excavations or to stabilize a jointed rock mass. Regardless of the intervention measure, they are usually made of carbon steel and are therefore susceptible to corrosion (Manquehual et al. 2021). This chemical process causes steel to lose its cross-sectional area and form corrosion products on its surface due to interactions with the environment. Consequently, corrosion can reduce the strength capacity of rock bolts and diminish the bond strength with the surrounding material over time (Dorion & Hadjigeorgiou 2014). Whilst they are aesthetically preferred to shotcrete, the corrosion of the steel face plates may result inappropriate when stabilizing cultural heritage sites.

Because of its good mechanical properties (Jabbar & Farid 2018; Liu et al. 2014; Patil 2014) high corrosion resistance (Jabbar & Farid 2018; Kemp 2003) and its light weight, Glass Fiber Reinforced

Polymer (GFRP) bars are widely used as an alternative material to the steel rebars. Thanks to these characteristics GFRP bars are also becoming widespread in Geotechnical Engineering practice as an alternative to classical steel bars/tendons (Wang et al. 2018; Zhang et al. 2018). The GFRP, however, has low shear strength and low ductility. Recently, GFRP bars were also used as soil nails in Hong Kong (Cheng et al. 2009) and as Screw Anchors for stabilizing slopes in different types of soils (Zou et al. 2016). The limitations of GFRP bar as soil nails are that pressure grouting is complex, and that the connection of bars used for longer soil nails is cumbersome.

The Apulian region is characterized by strong tourist impact above all due to the beautiful cost and the vertical cliffs in carbonate rock formations. Many zones of this region must hence be preserved for their important cultural heritage. Because of the long term hydro-mechanical interaction with the sea, and due to rainfall water infiltration from the ground surface, the Polignano a Mare coastline has suffered from weathering effects causing partial collapses (Ciantia et al. 2015a, 2015b). For example, part of *Grotta Palazzese* cave vault detachment in 2006 and 2014 caused the closure of the touristic location for several years. Such event was the main reason behind the need of finding stabilization techniques able to both preserve the cultural heritage of the cave and guarantee a high safety factor despite the ongoing weathering mechanisms (Castellanza et al. 2018). Such needs are the main drive of the field test campaign presented in this work. The exposure to an aggressive marine environment, making the use of steel bars unsuitable and the need to avoid use of shotcrete or other less aesthetic surface reinforcement solutions. The test campaign was hence designed to compare the anchoring performance when using either GFRP or DYWIDAG bars of various diameter anchored with different types of consolidating materials. The anchor performance was assessed in both the *Calcare di Bari* limestone and *Calcarenite di Gravina* calcarenite performing tension pull-out tests according to UNI EN 14490:2010. In this contribution, the main results of the 16 pull test performed in the two sites in the proximity of the *Grotta Palazzese* cave joint to the potential failure mechanisms identified are presented.

2 FIELD TESTING CAMPAING

2.1 *Geological settings*

The anchor pullout tests presented in this study are all perfomremd in Polignano a Mare. Figure 1a, taken from Spalluto (2012), reports the geology and the succession crops of the area. The coastal stretch is characterized by the outcropping of two main formations: well stratified micritic limestones of the *Calcare di Bari* (CB) formations (Callovian pp.-early Turonian) are overlaid by discontinuous calcarenite deposits of the *Calcarenite di Gravina* (CG) formation (upper Pliocene–early Pleistocene). The latter, mainly constituted by biocalcarenites, is transgressive on the former through an angular erosional unconformity and thin conglomerate deposits (Andriani & Walsh 2002; Festa 2003; Spalluto 2012).

These two formations are mainly composed of calcium carbonate ($CaCO_3 > 95\%$) but, because of the different microstructure and porosity are characterized by a different hydro-mechanical behavior

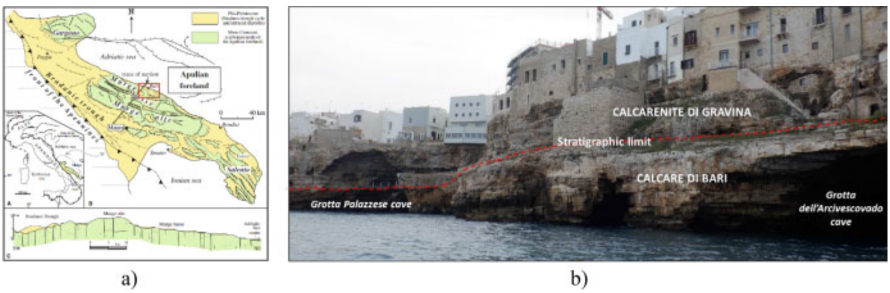


Figure 1. a) Location of the Apulian foreland in a synthetic structural map of Italy (Spalluto 2012); b) Stratigraphic limit between CB limestone and CG.

(Andriani & Walsh 2002, 2007). While the CG can be considered a soft rock (UCS < 5 MPa), the CB is a much stronger rock (UCS > 10 MPa) (Castellanza et al. 2018; Ciantia et al. 2015a, 2015b).

2.2 *Site investigation and filed test locations*

The field-testing campaign was performed in two different locations on the Polignano a Mare coastline (Figure 2). Both locations were chosen to be close to the two main cavities which experienced partial collapses in the past and that require urgent in safety measures. The first (FT1) is in the proximity of the *Grotta Palazzese* cave, where both *Calcarenites of Gravina* (CG) and *Calcare di Bari* (CB) limestones are outcropping (Figure 3). In filed test 2 (FT2), which is in correspondence of the *Grotta dell'Arcivescovado* cave, only the *Calcare di Bari* (CB) limestone is outcropping (Figure 4). Risk assessment and preliminary site preparation were coordinated and performed by Favellato SPA.

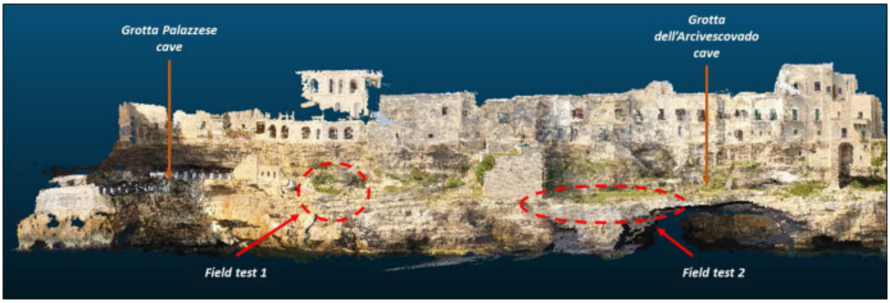


Figure 2. Field tests location. Image reconstruction from drone acquisition.

2.2.1 *Field test 1 (FT1)*

As detailed in Figure 3, three different zones were identified and selected for the pull tests. Zone 1, in the upper region, is characterized by pure and intact CG outcrops. In Zone 2 only intact CB limestones are present while Zone 3 is characterized by a very fractured CB limestone.

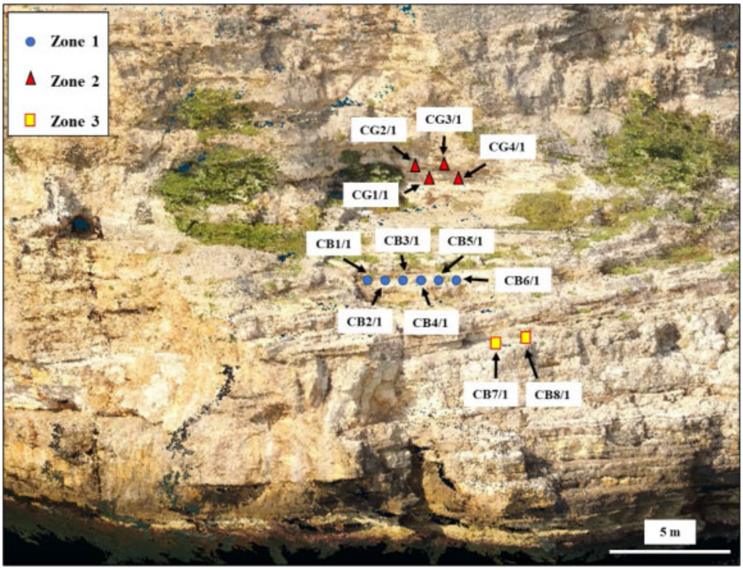


Figure 3. Location pull tests in FT1. Image reconstruction from drone acquisition.

2.2.2 *Field test 2 (FT2)*

As detailed in Figure 4, two different zones were identified and selected for the pull tests. Zone 1, in the upper region, is characterized by pure and intact CG outcrops. In Zone 2 only intact CB limestones are present while Zone 3 is characterized by a very fractured CB limestone.

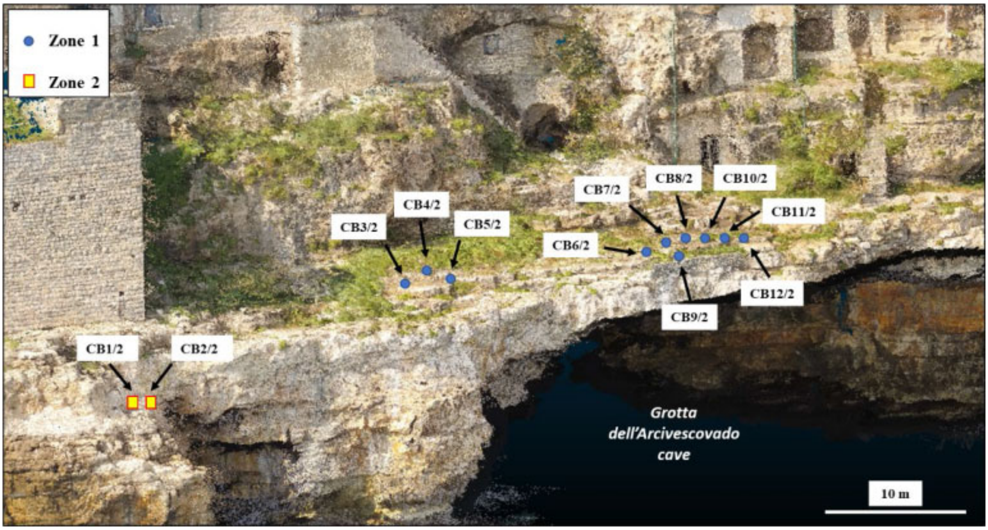


Figure 4. Location pull tests in FT2. Image reconstruction from drone acquisition.

2.3 *Pull test characteristics*

As mentioned previously, two types of bars were used in this field-testing campaign. On one side GFRP bars of variable diameter were used to determine their pullout capacity performance and exploit their lightweight and corrosion resistance properties. On the other classic DYWIDAG bars used as benchmark to compare the performance of the GFRP bars. Whist DYWIDAG bars are already threaded one extremity of each of the GFRP bar used had to be modified to allow a proper anchoring of the pulling system. Depending on the bar type a threaded steel tube was glued to the external or internal surface of the GFRP at one extremity using an epoxy resin. Figure 5 shows some images of such details while

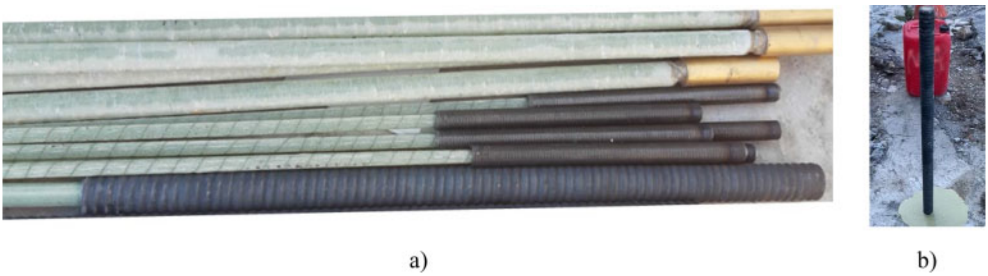


Figure 5. a) Threaded steel tube glued on the GFRP bars with epoxy resin; b) *Silicajet EXP/4* grouted *Glasspree* GFRP bar with threaded steel tube glued externally in CB limestone.

Tables 1 and 2 summarize the mechanical and geometrical characteristics of the DYWIDAG and GFRP bars used.

Table 1. DYWIDAG bar details.

Type	Diameter (mm)	Yield stress (MPa)	Yield load (kN)	Ultimate load (kN)	Young Modulus (GPa)
Y1050H	26.5	950/1050	525	580	205

Table 2. GFRP bar details.

Type	Diameter (mm)	Guaranteed Tensile Strength (MPa)	Min guaranteed ult. tensile force (kN)	Young Modulus (GPa)
Glasspree Ø16	16	850	>170	46
Glasspree Ø25	25	800	>392	46
GFRP Hollow Bar	32	800	>350	40

2.3.1 *Consolidants*

In FT1 two types of consolidants were used to anchor the bars in the CB limestone and only one type for the tests in the CG calcarenite. A bi-component organo-mineral and thixotropic resin, *MasterRoc RBA 380*, and a premixed cement mortar, *MasterEmaco T 1200 PG*, were used in the limestone, as both materials have low hardening times. For the tests in the calcarenite a lime-based mortar, *MasterInject 222*, was used instead, as the holes were made with an inclination of 45 degrees upwards and the use of resins resulted to be impractical. In FT2, on the other hand, the 8 different types of consolidants listed in Table 3 were used:

Table 3. Details of the consolidant materials used.

Consolidant	Fabricant	Chemical composition/ characteristics	Compressive (MPa)*	Interface shear strength (MPa)**	Young Modulus (GPa)
Masterinject 222	MasterBuilders	pozzolanic lime grout	>10	>4	6 ± 1
MasterEmaco T 1200 PG	MasterBuilders	reinforced cement mortar	>80	>25	43
MasterRoc RBA 380	MasterBuilders	TIX polyurea silicate resin	>35	/	/
MasterEmaco A 640	MasterBuilders	expansive cement mortar	>40	>15	30 ± 2
MasterEmaco S 1120 TIX	MasterBuilders	TIX cement mortar	>35	/	22
MasterRc 710 TIX	MasterBuilders	TIX cement mortar	>40	/	22
Stabilcem T	Mapei	TIX cement mortar	>40	>17	30
Silicajet EXP/4	Mapei	two-component organo-mineral resin	/	/	/

*Determined according to UNI 1015-11; UNI 12190:2000
**Determined according to RILEM-FIP-CEB

2.4 *Definition of holes characteristic*

The choice of the diameter of the holes was made in relation to the diameters of the bars used. For, 32 mm holes were drilled while for both the Ø25 and Ø32 bars a 51 mm hole was used (Figure 6). All the bar (D) and hole (D_h) diameters are reported in Table 3. All anchoring lengths were fixed to one meter.

Figure 6. Favellato SPA technician preparing the holes in the limestone.

2.5 *Positioning and bar grouting*

Field test 1

In FT1 12 bars were installed (4 in CG and 8 in CB limestone) and pulled to failure or to the maximum capacity of the jacking system (100 Tons). Of the 4 bars installed in the calcarenite, 2 were Ø32 GFRP hollow tubular bars and 2 were 26, 5 Ø DYWIDAG bar. The holes in zone 2 in Figure 3 (in CG calcarenite) with an upward inclination of approximately 45° were filled using a bespoke injection system (Figures 7a and 7b). First the bars were inserted into the holes for a length of 1 m with a tube for the injection of the consolidating material. Both the bar and the tube were fixed to the rock face using an ultra-fast cement mortar (*Lampocem* from Mapei) that helped to seal the hole preventing the consolidants to leak out during the injection. Once cured a very fluid lime-based mortar (*MasterInject 222* – Pozzolanic lime grout, cement-free) was injected through the preinstalled tube.

Figure 7. a) VTR bars blocked by *Lampocem* before injection; b) injection of *MasterEmaco 222* through injection tube in CG.

A few meters below the above described calcarenite anchors a bank of CB limestone was chosen (Zone 1 in Figure 3) and injected, by pour (see Figure 8). 4 different bars with different diameters, for a total of 8 holes were filled with either an organomineral resin (*MasterRoc RBA 380*) or a quick-setting cement mortar (*MasterEmaco T 1200 PG*).

Figure 8. Pouring to two different materials.

Two bars (CB7/1 and CB8/1) were anchored in Zone 3 where the limestone was more fractured with respect to the one found in Zone 1. During the casting phase of the consolidant, it was noticed that the rock had some fractures along the lateral surface of the hole. To overcome this difficulty, since the material used was thixotropic, to properly grout the bar it was sufficient to pause the casting for a few seconds to then proceed again with the filling and subsequent insertion of the bar.

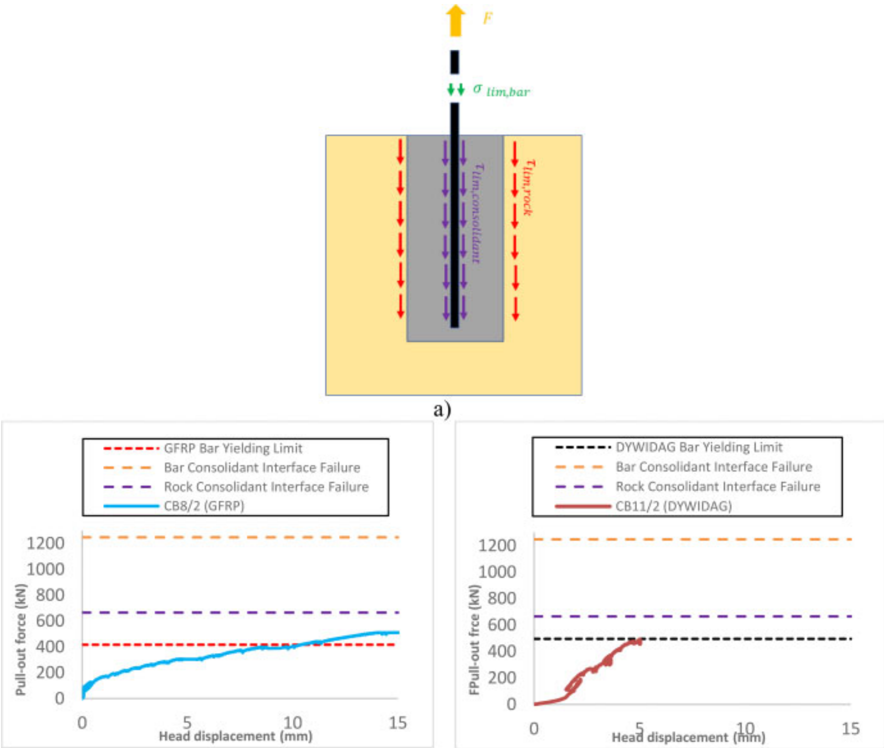
Field tests 2

In FT2, 12 anchors were installed (all in CB limestone), with 8 different types of consolidating materials. Except for the CB1/2 and CB2/2 bars (Zone 2), where the consolidant material was injected with the same bespoke method used in FT1 and described above (Figure 9a), all the other bars were grouted by casting the chosen material (Figure 9b).

Figure 9. a) Technician during injection *MasterEmaco A 60* in CB1/2; b) anchor in FT2 zone 1.

3 PULL-OUT TESTS

All the pull-out tests were performed using Hallow piston Hydraulic cylinder Jack brought under pressure by a manual pump, connected to a load cell to measure the applied tensile force. Depending on the estimated capacity the 100ton capacity or 30ton capacity hallow piston was used. Data acquisition was carried out digitally, using 3 digital displacement transducers connected to a data logger to which a connection to the pump was also added to also view the applied force. By connecting the data logger to a portable PC, it was possible to view and record in real time the displacement and force signals of the transducers. The results of the pull test of the CB8/2 and CB11/2 anchors are reported in Figure 11. In the figure the failure loads related to rock-consolidant shear failure, bar consolidant shear failure and yielding of the bar are also reported. For the anchoring length of 1 m and for tests in CB limestone, failure is expected to occur because of the yielding of the bar. The two tests reported in Figure 10 could not reach failure as the maximum load of the piston was reached in both cases. The main difference that clearly visible is the much stiffer response of the DYWIDAG compared to the GFRP one. Because of technical issues related to the data acquisition system it was not possible to perform all test with a digital data acquisition. For these latter, to measure and record displacements an analog displacement transducer was used (Figure 11). The force was also recorded manually. As detailed in Table 3 some tests were performed after 18 hours of curing time. Others were performed after 40 days. The field-testing campaign will be completed by the end of 2022 (about one year after installation) will be performed.



b) c)

Figure 10. Potential failure modes (a) and pull-out force vs head displacement curves for CB8/2 (b) and CB11/2 (c).

Figure 11. a) Pull test with 1000 kN capacity Hallow piston; b) pull test with 300 kN capacity hallow piston.

Table 4. Anchors pull test details.

ID test	Bar type	D (mm)	D_h (mm)	Consolidant	Curing time	F_{max} (kN)	Comments
CA-2/1	DYWIDAG	26.5	55.3	*Masterinject 222*	40 (days)	400	failure looked to appear at interface rock-binder
CB-1/1	GFRP	16	35.4	*MasterEmaco T 1200 PG*	18 (hours)	>140*	failure pull test bar attachment system
CB-2/1	GFRP	16	35.3	*MasterRoc RBA 380*	18 (hours)	100	failure at interface rock-binder
CB-4/1	GFRP	25	54.1	*MasterRoc RBA 380*	18 (hours)	120	failure at interface rock-binder
CB-5/1	GFRP	25	54.4	*MasterEmaco T 1200 PG*	18 (hours)	340	failure looked to appear at interface rock-binder
CB-6/1	DYWIDAG	26.5	34.4	*MasterEmaco T 1200 PG*	18 (hours)	>300	Hallow piston max load
CB-7/1	GFRP	16	34	*MasterEmaco T 1200 PG*	18 (hours)	>140*	failure pull test bar attachment system
CB-8/1	GFRP	16	34.2	*MasterRoc RBA 380*	18 (hours)	>120*	failure pull test bar attachment system
CB-1/2	DYWIDAG	26.5	33.6	*MasterEmaco A640*	40 (days)	>430**	Hallow piston max load
CB-2/2	GFRP	25	53.7	*Masterinject 222*	40 (days)	>100*	failure pull test bar attachment system
CB-4/2	DYWIDAG	32	46	*Silicajet EXP/4*	40 (days)	235.7	failure looked to appear at interface rock-binder
CB-6/2	GFRP	16	33.8	*MasterRoc 710 TIX*	40 (days)	>122.4*	failure pull test bar attachment system
CB-8/2	GFRP	25	52.6	*MasterEmaco A640*	40 (days)	>511**	Hallow piston max load
CB-9/2	GFRP	25	54.1	*MasterEmaco S1120 TIX*	40 (days)	340	failure looked to appear at interface rock-binder
CB-10/2	GFRP	16	34.2	*MasterEmaco A640*	40 (days)	>128*	failure pull test bar attachment system
CB11/2	DYWIDAG	26.5	53	*MasterEmaco A640*	40 (days)	>488**	Hallow piston max load

*Maximum force achieved because the bars attachment system for traction test have been underestimated
**Maximum force achieved for safety reason

4 CONLUSIONS

This article reports the results of a series of pull-out tests on soft rock anchors. The test campaign was designed to compare the anchoring performance when using either GFRP or DYWIDAG bars of various diameter anchored with different types of consolidating materials. DYWIDAG bars are widely used in the engineering field as they are economical and have always guaranteed excellent results in terms of safety in the short term. However, being made up of iron alloys, they have a short life as they are subject to corrosion, especially in marine environments. On the other hand, GFRP bars, already widely used in construction, mostly as tie rods, in such extreme environments offer an almost infinite resistance to corrosion. The results of this field-testing campaign the anchor performance was assessed in both the *Calcare di Bari* limestone and *Calcarenite di Gravina* calcarenite. The main results of the 16 pull test performed in the two sites in the proximity of the *Grotta Palazzese* cave show that GFRP bars are a good alternative to DYWIDAG as they can provide similar capacity with a more ductile behaviour. Such feature is important when stabilising rock masses prone to brittle failure mechanisms. Moreover, in addition to being more corrosion resistant, GFRP have lighter color that is more aesthetic and may be preferred when stabilizing cultural heritage cliffs such as the one considered in this work.

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