Passive "floating" composite anchors for the gradual stabilization of a landslide

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Abstract

The annual frequency of landslide in the North-Eastern Italy is very high due to the hydro-geological conditions of this area. These phenomena often lead to severe damages or even destruction of residential and transport infrastructures with effect on economic development of mountain areas. The search for cost-effective solutions for risk mitigation and slope stabilization becomes fundamental. The paper deals with the application of an innovative technique for landslide stabilization with reinforcements, developed as an improvement of Soil Nailing. The method, named floating composite anchors, consists in the installation in the slope of special passive sub-horizontal reinforcements, obtained by coupling a traditional self-drilling bar with some tendons. After a brief overview on the main technical aspects, the paper presents the application of this new method to a slow-moving landslide occurred in 2010. Two proposal for increasing the slope stability in this site are analyzed with a 3D finite element model, considering floating composite anchors installed in different geometries and various seepage conditions.

1 INTRODUCTION

The North-Eastern part of Italy is subject to high hydro-geological hazard due to its climatic, geological and geomorphological conformation. An increasing occurrence of sliding movements commonly happens in consequence of long and intense rainfalls: for instance, in November 2010, due to an exceptionally intense rainfall that hit the mountain area of the Vicenza Province (500 mm of rain in 3 days), almost 500 new landslides occurred in 48 hours (Bisson et al., 2014).

Therefore, the setting up of low-cost solutions for risk mitigation and slope stabilization is a big challenge for everybody. To this aim, a research program developed by the University of Padova (Italy) in partnership with public administrations, professional and businesses offices in Italy started in 2012. It complains the development and the performance-cost evaluation of a new technique for landslide stabilization, named *composite anchors*.

After a brief introduction to this technique, the paper deals with its application on the Cischele landslide, a slow-moving translational landslide activated in November 2010, which involved the small homonymous hamlet of Cischele (Recoaro Terme, Italy). Due to a limited budget, in 2015 only a partial stabilization of the slope was obtained with the installation of some composite anchors, while now the realization of other anchors on completion are under exam.

1.1 Composite anchors

Self-drilling anchor bars are a good alternative to traditional nailing and anchor techniques (GEO, 2008). To expand their application field and improve their mechanical behavior, a special composite bar was developed (Bisson et al., 2014) by coupling a traditional carbon steel bar with one or more harmonic steel tendons, inserted and cemented inside the central cavity of the bar. An external plate for locking the bar and a protective cover for the tendon head complete the system (Fig. 1). Their installation develops in the following steps:

A. Installation of the self-drilling bar, up to the design depth, by roto-percussion with a disposable drilling bit up; a cement grout is injected from the bit during perforation for supporting the cavity, purging the drilling waste and finally cementing the bar to the soil.
B. Manual insertion of one or more harmonic steel tendons in the central cavity of the bar before the inner grout hardening.
C. Application and connection of the external plate, which has the role of contrasting the movement of external soil surface.

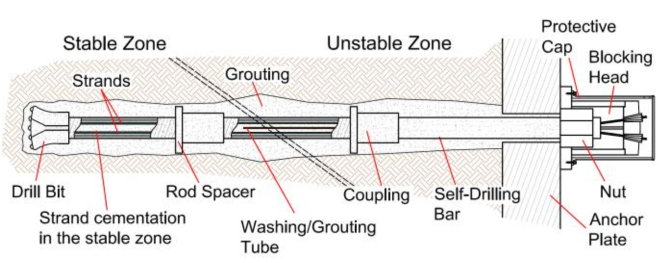


Figure 1. Scheme of a composite anchor.

When realized in this way, the anchors behave like passive elements. A possible variation in the installation procedure, in step B specifically, permits the anchor to become active reinforcement. In this version, the most external portion of the cavity is washed by injection of water from a tube, thus obtaining that the anchors are divided in two parts: the foundation length, where the tendons are linked the bar, and the most external part where the tendons are free. After the grout hardens, the strands are tensioned and connected to the external plate by a special locking head. In this way, the tendons transmit an axial compression to the bar and the soil in depth, thus immediately increasing the stabilizing force along the sliding surface (Bisson et al., 2016).

With respect to anchors constituted by only bars or only strands, composite anchors have many advantages:

- minor cost with the same tensile resistance (Bisson et al., 2013; Bisson, 2015);
- higher durability due to minor cracking and a better corrosion protection;
- easier transport and installation;
- an anchorage length that is adaptable to the real in-situ geological conditions individuated during installation;
- higher flexural inertia and good continuity given by the inner strands.

Composite anchors can be used in consolidation of soil and rock cut slopes, in foundation reinforcements, and in landslide stabilization too.

1.2 Composite anchors on landslides

Passive reinforcements represent a cost-effective technique for landslide stabilization (GEO, 2008; Bisson & Cola, 2014). Since in these applications large installation depths (up to 55 m) and huge axial forces may be requested, composite anchors are a good alternative to reach high strength reducing installation time and costs. In unstable slopes, they can be installed in a *floating* configuration, as recently proposed by Bisson et al. (2014). The technique consists of installing passive sub-horizontal reinforcements, grouted along the entire profile with a sufficient foundation in the bedrock, and coupled with individual external concrete slabs (i.e. the *floating* element). The slabs, having appropriate shape and size, are not in connection among them (Fig.2). If some slope movements occur, axial forces in the passive reinforcements develop because of the shear stresses transmitted by the slow-moving mass at the bars along the soil-grout interface: these axial forces contrast the instability and can reduce the landslide evolution process until it completely stops. Since the axial head force at the connection with the external slab is small, the system does not require a continuous facing or strong and invasive external structures, and, when the slope deforms, the slabs may be also englobed inside the soil. As previously explained, a small pre-tension can be also assigned to the tendons obtaining, therefore, a *partially active* configuration.

As in Soil Nailing, the design capacity of a floating anchor depends on the available frictional strength at the soil-grout interface, as well as the size and the tensile strength of the bar itself. It must therefore ensure that:

A. The tensile strength of the steel bars is sufficient to withstand the maximum developed axial stress; the total stabilizing force Q_a generated by each element is the sum of the head force absorbed by the floating plate Q_p and the integral of friction stresses activated along the soil-grout interface in the moving soil:

$$Q_a = Q_p + \int_0^{L_a} \pi D \cdot \tau_u(x)dx \quad (1)$$

where D is the effective anchor diameter (bar with the cement grout around), L_a the anchor length in the active zone and $\tau_u(x)$ the shear strength at the soil-grout interface at the coordinate x. The latter can be calculated by extending the methods proposed by Bustamante & Doix (1985) for micropiles.

B. The length of each bar within the passive zone, that is, the portion of the bars that extends beyond the potential or actual slip surface, is sufficient to provide a pull-out resistance equal to the total stabilizing force Q_a generated in the bar (GEO, 2008).

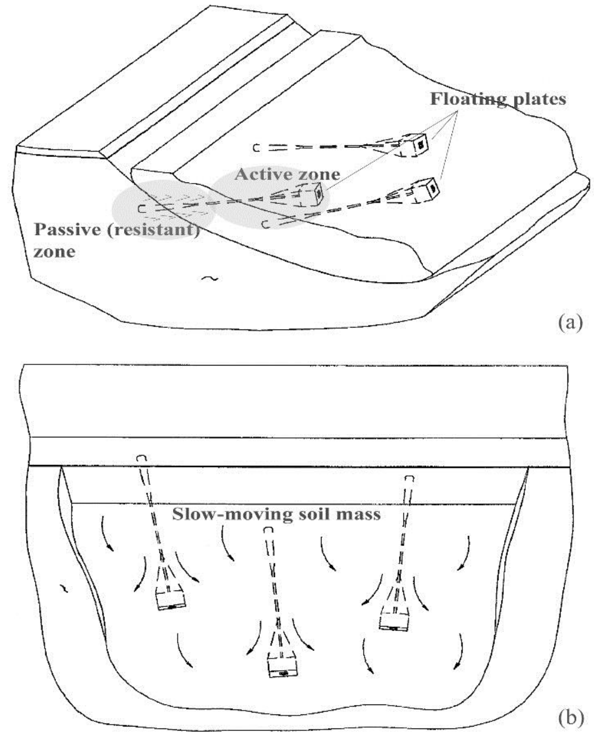


Figure 2. Working scheme of the “floating anchor” technique with composite bars and external slab.

One of the main advantages is that, if the slope movements do not completely arrest with the anchor installation, the soil can slide along the bars, which remain embedded in the slope. In this way, the bars can find a new equilibrium condition without cracks or structural failures and without losing their effectiveness, unlike traditional rigid works, such as gravity or micropile walls. This behaviour permits to progressively calibrate the intervention according to an observational method: if a first installation is not enough to stop the slope, it can be subsequently improved by adding other reinforcements.

The case illustrated in the follow is a clear example of this reasoning.

2 CISCHELE LANDSLIDE

2.1 Site description

The exceptional rainfall that affected the Vicenza Province in November 2010 activated the movement of some houses and a portion of the road (Fig.3) that connects the Cischele hamlet with the main valley of Recoaro Terme (Italy). The landslide, approximately 120 m wide and 180 m long, with a mean inclination of 24°, is a slow-moving translational phenomenon with a strong correlation between displacements and pore water pressure changes. Many visible fractures, signs of slow and continuous movements, were observed in the houses and walls existing in the area (Fig. 3).

2.2 Geology

The slope is based on the crystalline basement of the Recoaro subalpine area consisting of quartz-Phyllite. Above, there is a layer of Val Gardena Sandstone, a sedimentary rock composed of clastic deposits, such as quartz and feldspars sands and silts. At the top, there is the Bellerophon formation, mainly consisting of a highly stratified limestone, often strongly weathered, with frequent interbedded silty clays in the lower part.

In order to characterize the stratigraphic profile of the landslide area, three continuous core surveys were carried out in 2011 (S1, S2, S3), two in 2012 (S4, S5) and four in 2014 (A, B, C, D) (Fig. 4). In the central part of the slope, a 10-12 m thick cover, constituted by completely weathered Bellerophon Limestone, lies above a clayey silt and sandy clay layer originated by alteration of Val Gardena Sandstone. The attribution of a soil to a specific rock formation is possible thank to the rock fragments still recognizable in the soil. Up to a depth of 20-30 m, a bedrock of low to medium altered phyllite was found. At the landslide toe, below 5 m layer of backfill clay, a strongly altered Phyllite in a reddish silty clay matrix exists, but Val Gardena Sandstone or Bellerophon Limestone are not noticed.

Two inclinometers were installed within holes

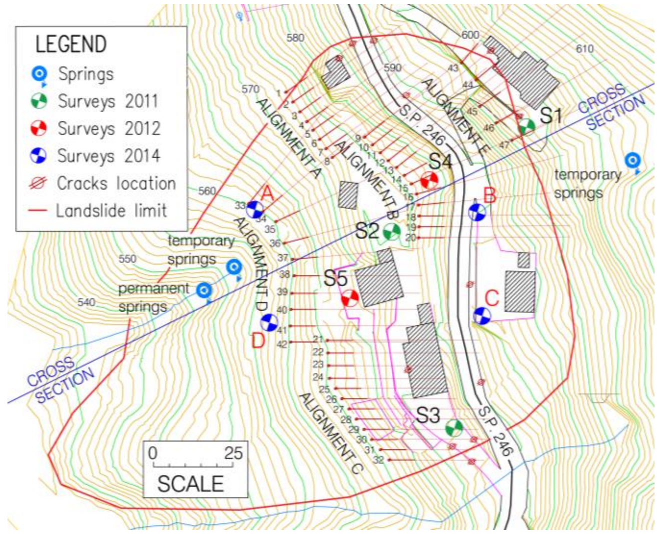


Figure 3. Cischele landslide map with indication of in-situ boreholes and the position of already realized anchors.

S1 and S3. The data acquired in January-May 2011 confirmed the absence of movements in S1, located in the stable zone over the landslide crown. In S3 the total displacement significantly increased from 5 to 13 mm in occurrence of the heavy rains of 13-17 March 2011, thus indicating a close dependence of gravitational movements to the groundwater level inside the landslide body. The movements occurred along with particularly intense rainfalls and the slip surface was individuated at the contact between the Bellerophon formation and the Val Gardena Sandstone.

The rains generate a very rapid rise in the water table, with also the appearance of a number of temporary springs on the slope surface. For instance, in 13-17 March 2011 a cumulative rainfall

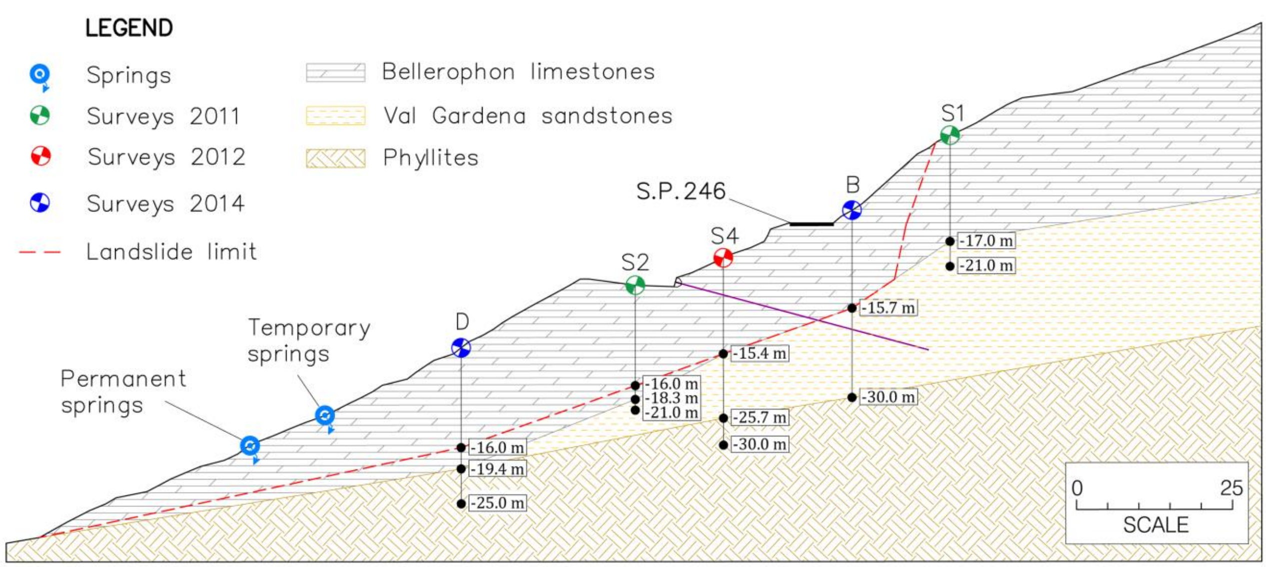


Figure 4. Geological cross section of Cischele landslide with position of boreholes and anchors (Bisson, 2015).

a)

b)

Figure 5. Installation of composite anchors at Cischele landslide (2014): *(a)* Bar and strands already infixed; *(b)* External concrete plates of alignment B visible at the ground surface near the house and below the road.

of 231 mm, with a peak of 141 mm on 16 March, occurred: the open-pipe piezometer installed in S2 showed a water table rising 3 m in some hours, with a delay of some hours respect the rain. After the event, the water level returned to the normal level within 2-3 days, evidencing a relatively high permeability of the slope mass.

2.3 Soil properties and basic stability analysis

To estimate the resistance parameters of the involved soils, the frictional angles obtained from direct shear tests on samples of silt and sand, taken in the Bellerophon and Val Gardena formations in S1 and S2, were considered. Additional friction angle values were obtained by N_{SPT} recorded in S4 between 3.5 and 12.5 m of depth, adopting the empirical relationships proposed by Schmertmann (1975). Finally, some 2D back-analysis with limit equilibrium method that have been realized by the designers on some sections of the slope to complete the material parameters identification.

2.4 First stabilization works

The first proposal of stabilization works focalized on a water control system with a regularization of meteoric water in the upstream side of the road, coupled with a large diameter draining well to lower the water table. Due to the high cost of this solution and the limited budget at disposal of the public agencies, the latter ones opted to substitute the drainage well with floating anchors with composite bars. Given the complexity of the geological context and many uncertainties that affect the slope stability, this solution allowed to carry out the work in successive stages, applying the observational method, as provided in the Italian Technical Law (NTC, 2008). The intervention may also be integrated in progress with other anchors if subsequently it would be proved not sufficient.

From June to December 2014 a first group of 32 composite anchors were set up (Fig.5). They are 40-50 m long and formed by a 76 mm bar coupled with 7x0.6” pre-tensioned strands. The pre-tension is limited to 250 kN per anchor to obtain the *partially active* configuration. Thanks to the presence of inner tendons, the nominal tensile strength of anchors increases from 1160 to 2840 kN with an increment of cost less than 20% with respect to the self-drilling bar alone.

The head of each anchor was connected with a prefabricated frustoconical reinforced concrete slab, with an outer diameter of 1.5 m (Fig.5). The reinforcements were arranged in three rows (alignments A, B and C) with horizontal spacing of 5 m: two rows in the Northern portion of the landslide, below the road, and one in the Southern portion, downstream of the housing (Fig.3).

It is important to note that these reinforcements were only a part of all the reinforcements planned for a complete stabilization of the landslide and the reaching of an adequate safety factor. The complete intervention required at least a number of anchors three times larger, but, at that moment, the administration had not the entire budget for installing all the need anchors.

2.5 Monitoring and managing after the first intervention

After the intervention, slope displacements and water level were monitored for 4 years. The period 2015-2017 was relatively dry (total rain was about 1700 mm/year) with only an intense rain event in March 2016 (240 mm of rain in 1 day). On the contrary, 2018 was very wet, with a total rain of about 3000 mm (in 2010 was 3700 mm) and a very extreme event in November (800 mm of rain in 3 days). In March 2016 the water level rising was of the same order of that observed in 2011 (4-5m); unfortunately, due to a damage occurred at the monitoring system, no data about the water level were recorded in November 2018.

The displacement profiles measured at inclinometer B (Fig. 6) evidences that the landslide is still active, and it experiments some accelerations in occurrence of rain events. Nonetheless, the accumulated displacements are small, especially considering the increment related to the extreme rain event of November 2018.

It seems possible to conclude that the landslide is partially stabilized but not completely arrested. Moreover, some in progress damages are evident on the building in the Northern part of the slope. Consequently, the administration is now planning a supplementary installation of anchors, but in order to choose the optimal anchor configuration a 3D Finite Element model of the slope is previously realized.

3 FEM ANALYSIS

The 3D FE model of the site is constructed using Midas GTS NX 2019 v1.2. The slope geometry (Fig 7) is created on the base of information collected in all the boreholes. All the volumetric elements (e.g. soils, plates and buildings), are simulated using *Brick elements*, while anchors are modelled using 1-D *Embedded Truss elements*. The adopted material models are:

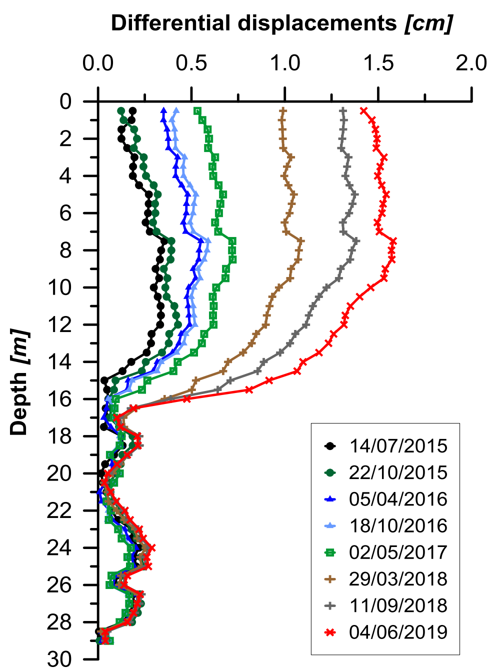


Figure 6. Vertical profile of landslide displacements recorded at inclinometer B from 2015 to now.

- <u>Soils</u>: isotropic elasto-plastic model with Mohr-Coulomb criterion;
- <u>Buildings, plates and anchors</u>: isotropic-elastic model.

Table 1 lists all the material parameters. Note that they are chosen according to the results of laboratory tests for the Bellerophon and Val Gardena soils, and according to literature for the Phyllite (Hoek et at., 1998).

To evaluate the influence of seepage on overall stability, the ground water table is varied from -20 m to -5 m below the slope surface, with a step of 5 m. Of course, this condition is not completely in accord with the in-situ observation, because, as previously described, some springs appear on the ground during rains. However, it is adopted for numerical convenience, knowing full well that any choice involves very large approximation errors, especially in a 3D model and when only few data are available, as in this case. It is also important to note, that the limit conditions is assumed for a water table at -10 m, the maximum level observed in site also during very extreme rain events: the water table at -5 is simulated in order to have an evaluation of the safety condition for an extra-exceptional case.

Three different situations are investigated:

- without any intervention (*case 1*);
- with the already realized anchors (*case 2*);
- with a hypothetical new group of 40 m long anchors (*case 3*), distributed in two rows as indicated in Figure 7 with a spacing ≈ 5÷7 m.

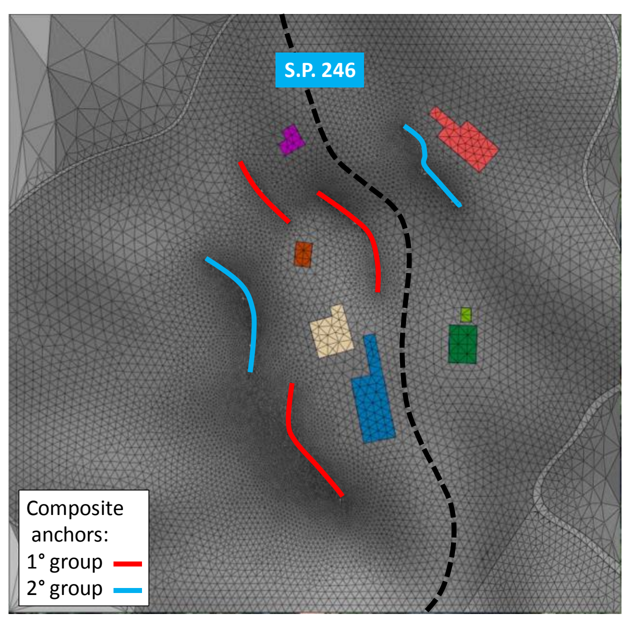


Figure 7. FEM model geometry and mesh.

Table 1. Soil parameters for FEM analyses.

Material	**E [MPa]**	**φ [°]**	**c [kPa]**
Bellerophon Limestone	20	23	5
Val Gardena Sandstone	500	36	10
Phyllites	20’000	45	100
	E [MPa]	**ε_{el}**	**H [MPa]**
Anchors	200’000	0.43%	1’321

Legend: E=Young modulus, φ=friction angle, c=cohesion, ε_{el}=limit elastic range, H=plastic modulus.

Table 2. Safety factors obtained in the different cases from SRM analyses.

Water table position [m]	**Safety Factor, FS**		
	case 1	***case 2***	***case 3***
-20	1.19	1.26	1.31
-15	1.18	1.25	1.27
-10	1.12	1.20	1.25
-5	*less than 1*	1.04	1.06

For each case and each water table position, an SRM analysis is completed to evaluate the safety factor (Midas, 2019, Griffiths & Lane, 1999). The critical values of the Strength Reduction Factor SRF obtained in various conditions, and assumed here as the safety factor FS, are listed in Table 2.

It is possible to note that without interventions the slope becomes unstable when the water table rises above -10 m of depth, according with the in-site observation performed in March 2011.

Of course, the anchors have a stabilization effect, as the FS increases in all the cases. The already realized anchors (*case 2*) permit to increase the FS value corresponding to a water table at -10 m of 7% (FS increases from 1.12 to 1.20). When the water table reaches -5 m, the slope approaches the instability condition, even if the FS value is above unit (FS = 1.04).

The additional anchors (*case 3*) would permit to further increase the safety factor, reaching a more stable condition for every water table position examined. All the cases with water level up to -10m may be considered stable according to the Italian rule (NTC, 2018), which required a minimum safety degree of 1.25. Anyway, the slope when the water table is at -5 m is still stable, even if the safety factor value is not completely satisfactory according to NTC 2018.

Figure 8 compares the distribution of total displacements for *cases 1*, *2* and *3*, for the same analysis conditions, i.e. water table at -10 m and

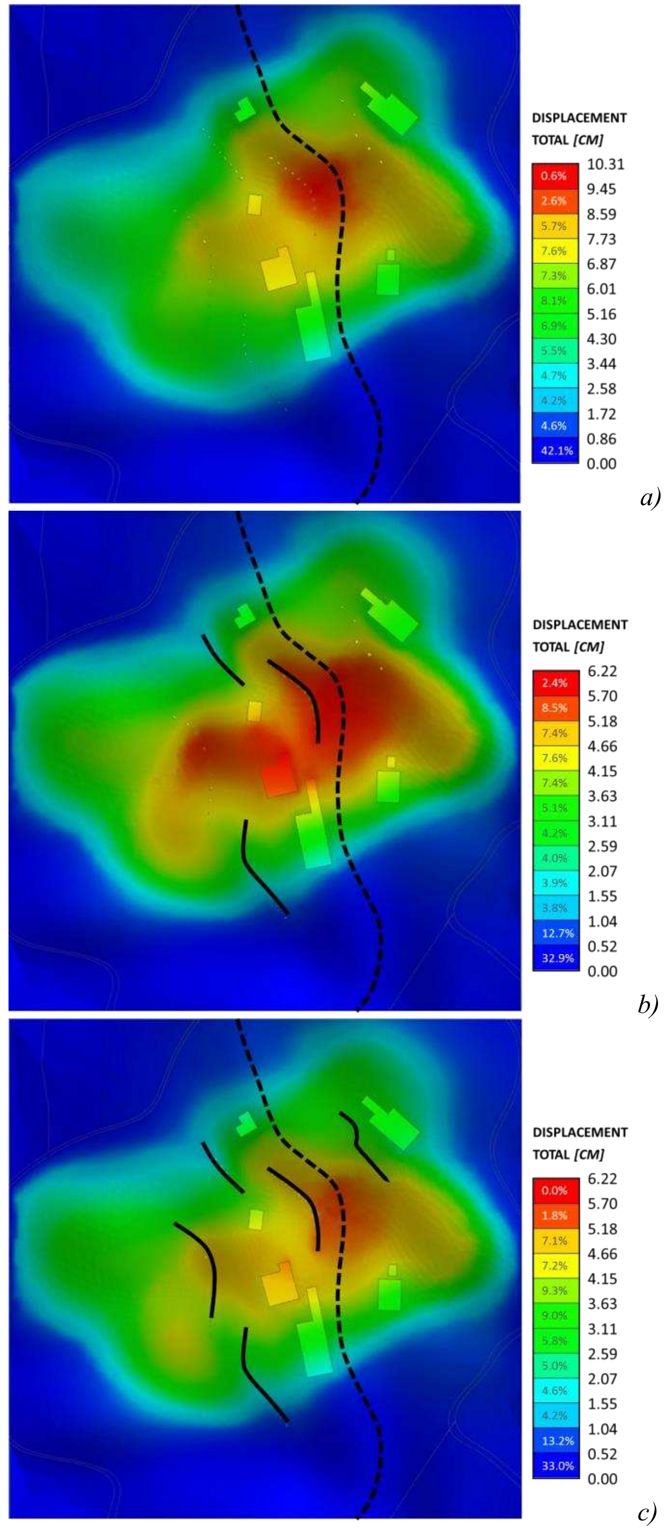


Figure 8. Contour plot of the total displacements for *(a) case 1*, *(b) case 2* and *(c) case 3* in analysis conditions *WT = -10 m* and *SRF = 1*. Note: *case 1* has a different contour range.

resistance parameters not reduced (SRF = 1). Note that in the figures, contour ranges of *case 2* and *case 3* are the same, but different from that adopted for *case 1*. It is evident that, at same analysis condition, the entity of displacements reduces with the anchor installation: the maximum displacement changes from 16.4 cm with no anchors to 6.1 cm with the first group of reinforcements and to 5.4 cm with the second group.

In an SRM analysis, the displacement entity corresponding to the critical SRF has not a real meaning, but their map allows to evaluate the areas more susceptible to instability and to compare their extension in various conditions. Figure 9*b* presents the displacements distribution on the most critical section resulted for the *case 3* with WT at -10 m and FS = 1.25 (the section is also indicated in Figure 9*a*). It is evident that the installation of the new group of anchors stabilizes the central portion of the landslide, i.e. the zona close to the road, but two unstable areas remain in the upper and lower parts of the section, where the reinforcement effect is minor. For a complete stabilization of the slope, it will need at least other 8-10 anchors respect those planned by the administration.

3.1 Conclusion

The paper presents a partial stabilization of a landslide with composite floating anchors, a new type of passive reinforcements. The advantages of these reinforcements are flexibility of installation, high geotechnical performance, and ability to adapt their actions in relation with the displacements that the slope can develop if the stabilization is not completely successful. The availability of a 3D FE model permits to better exploit the advantages of composite anchors, analysing their spatial distribution on the slope, in order to optimize the stabilization effects with the lowest cost.

Reference lists

Bisson A., Cola S., Dalla Gassa G. (2013). Comportamento elastoplastico di ancoraggi compositi, IARG 2013, Perugia (Italy). ISBN: 9788890642135.

Bisson, A. (2015). *"Floating anchors for landslide stabilization"*. University of Padova (Italy). PhD Dissertation.

Bisson A., Cola S. (2014). *"Ancoraggi flottanti per la stabilizzazione di movimenti franosi lenti"*. XXV Convegno Nazionale di Geotecnica AGI: La geotecnica nella difesa del territorio e delle infrastrutture dalle calamità naturali, 4-6 giugno, Baveno, Vol. 2, 327-334, Edizioni AGI, ISBN 9788897517054.

Bisson A., Cola S., Tessari G., Floris M. (2014). *"Floating anchors in landslide stabilization: the Cortiana case in North-Eastern Italy"*. Engineering Geology for Society and Territory, Vol. 2, pp. 2083-2087. Zurich: Springer.

Bisson A., Cola S., Carollo I. (2016). *"Ancoraggi compositi pretesi: analisi delle sollecitazioni indotte nel terreno"*. 6° IAGIG: L'ingegneria geotecnica al servizio delle grandi opere: necessità e opportunità, 20-21 Maggio 2016, Verona (Italy), pp.24-27.

Bustamante M. & Doix B. (1985). *"Une méthode pour le calcul des tirants et des micropieux injectés"*. Bulletin de liaison des laboratoires des ponts et chaussées, 140, pp. 75-95.

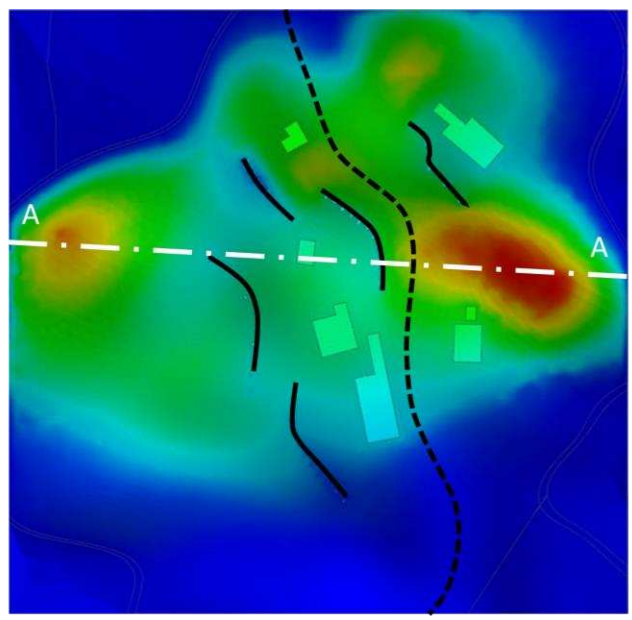
GEO (Geotechnical Engineering Office). (2008). *"Geoguide 7: Guide to Soil Nail Design and Construction"*. Hong Kong: The Government of the Hong Kong Special Administrative Region.

Griffiths D.V. & Lane P.A. (1999). Slope stability analysis by finite elements. Géotechnique 49(3), pp. 387-403.

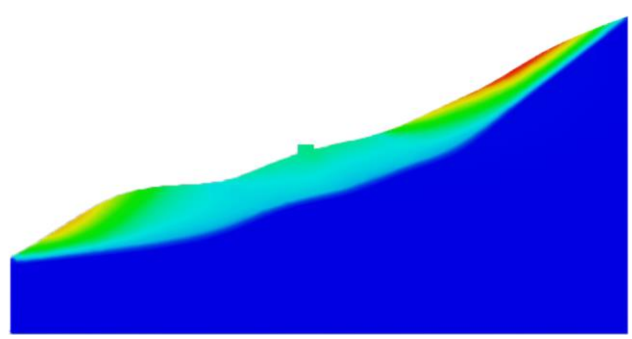
Hoek, E., Marinos, P., Benissi, M. (1998). Applicability of the Geological Strength Index (GSI) classification for very weak and sheared rock masses. The case of the Athens Schist Formation. Bulletin of Engineering Geology and the Environment, 57(2), 151-160

MIDAS, 2019. *"Midas GTS NX Reference Manuals"*.

NTC 2018. Ministero delle infrastrutture e dei trasporti. Gazzetta Ufficiale, Decreto Ministeriale 17-01-2018.



a)



b)

Figure 9. *(a)* Contour plot of the total displacements and *(b) A-A* section detail (*case 3*, WT = -10 m and FS = 1.25).