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Strain development measured with DFOS in experimental passive anchors used for landslide stabilization

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Abstract

Distributed optical fiber sensors (DFOSs) as detector of strain and temperature variations are an innovative and very attractive monitoring system because they allow measures distributed along large distances and with medium-high resolution. This paper deals with the monitoring of a new type of self-drilling reinforcements, namely composite anchors, specifically developed for the slope stabilization. They consist in self-drilled bars equipped with some tendons inserted and cemented in inner hole of the bar after installation. Compared to the passive reinforcements with the same external diameters, composite anchors offer a higher tensile strength with small increments of cost. Similar to soil-nailing bars, they are passive reinforcements and the knowledge of the bond strength at the soil-anchor interface is crucial for their design and the evaluation of the long-term stabilization effects; however, the in-situ bond strength measurements performed in the past with traditional sensors have not always produced satisfactory outcomes. The paper presents the preliminary measurements obtained along seven composite anchors installed in a test site on an active translational landslide moving at a displacement rate of 40-100 cm/year. The monitoring system is composed by DFOSs exploiting the optical frequency domain analysis (OFDA) which allows the determination of strain and temperature variation profiles with a spatial resolution of 20 cm. The measures showed that, due to the high displacement rate of the landslide, after only 14 days the anchor traction was about 40% of the maximum strength of bars and arrived at 65% after 1 month. The strain profile clearly showed the localization of the maximum traction close to the sliding surface and that the most external anchor portion is quite unloaded.

Keywords: slope stabilization, passive anchors, distributed optical fibre sensor, soil-anchor interface

1. Introduction

Stabilization of natural or artificial slopes prone to collapse employing structural reinforcements is a standard remediation approach aiming to improve the shear strength and limit sliding motions and consequent hazards over the slip surface. Among the many existing solutions for structural reinforcements (i.e., retaining walls, micropile systems or reticulates, etc.), one of the most versatile is represented by composite anchors (Bisson et al., 2016; Brezzi et al., 2021), which can be applied to different geotechnical works and, in particular, whenever massive forces are required, such as for landslide stabilization. Composite anchors are self-drilling passive sub-horizontal reinforcements composed of 6 m long hollow carbon steel threaded rods, introduced in the soil with the self-drilling technique and connected one to each other with coupling nuts up to reach the desired installation depth (Figure 1). The external threading of rods permits the rapid coupling with nuts and ameliorates the nail-cement-soil coupling to developed high frictional lateral resistance. After installation one or more harmonic steel strands are introduced and cemented inside the rods to improve the mechanical robustness against the pulling force exerted by the surrounding soil mass. In addition, the anchor head is fixed by a nut to a bearing plate (floating plate) made of a precast concrete disk.

When the unstable slope develops some displacements the soil movement triggers the development of shear stress along the interface soil-cement and cement-threaded bar (Figure 2), promoting a synergistic reinforcing effect and activating a traction stress state in the bar that induces the bar to be extracted by the stable deep soil (pull-out mechanism). The external plate can distribute the pulling force, acting on the bar head, over a larger surface. The main mechanisms of the working principle of the composite anchors rely on the coupling effect of the bar to the grout/soil and the ameliorate robustness provided by the integration of the strands to the bar. In

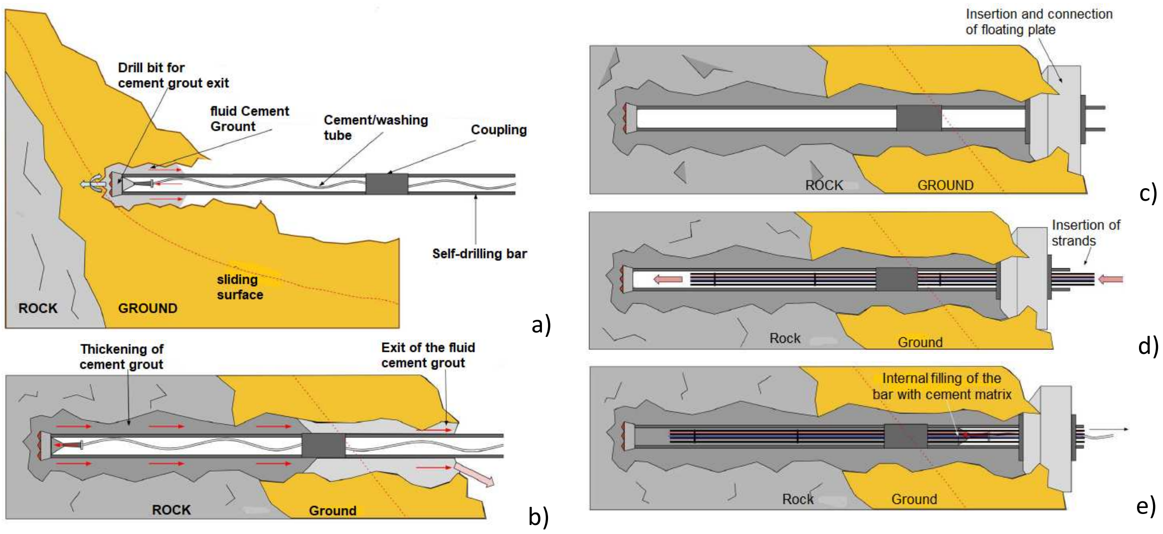


Figure 1: Plot of pore water pressure measured by Piezometer 1.

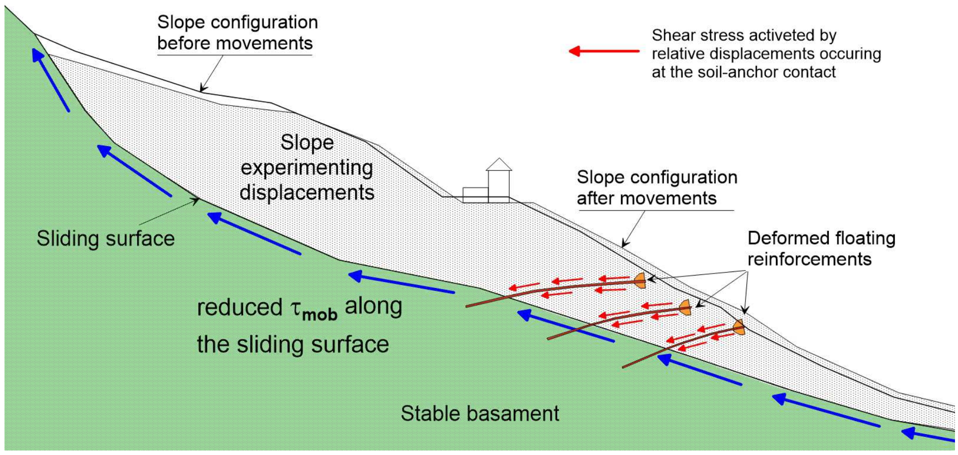


Figure 2. Working scheme of the 'floating anchor' technique with composite bars and external slab.

order to verify how the composite anchors develop their action with time some measures with electrical strain gauges were initially proposed to assess the performance of both the axial force in the anchor and the friction force at the soil-anchor interface, with very poor results. Then a first positive, yet limited to a proof-of-concept, application of high resolution distributed fiber optic sensors based on OFDR has been proposed (Cola et al., 2019). In that work, only two measurement sessions were carried out on three anchors within a short time period, during which no evident landslide activation was observed. Moreover, due to the reduced distance range of the employed technique (i.e., 70 m), the anchors were instrumented with dedicated fiber cables and interrogated in sequence. Noticeably, OFDR was also proposed to monitor anchor bearing plates (Know et al, 2018) and short grouted steel anchors (Monsberger and Lienhart, 2019).

In December 2020 seven composite anchors were installed in an active landslide, extending over an area of 57,000 m^2 in the Recoaro Terme municipality (North-East of Italy), known as Fantoni landslide. They were instrumented with a Brillouin based-distributed optical fiber sensors system. The system overcomes the limitations of the previous attempts and represents the first implementation of an extensive and effective smart soil anchor system for landslide monitoring and remediation. It combines the intrinsic remediation function of anchors with the monitoring feature of DFOSs, enabling a double level of inspection. First, DFOSs provides an indication of the properness of the anchor's design and the effectiveness in remediation and health over time itself. Second, they promote the anchor itself as a sensor, by which it is possible to monitor and characterize the landslide movements and geometry.

In this paper, we will describe the system, providing the installation procedure details. We will then show and discuss some of the results that have been collected during the measurement campaign.

2. Design and installation of DFOS equipped soil composite anchors

Figure 3a shows the position of the seven anchors installed on Fantoni landslide. In the Figure, the respective lengths and inclination angles with respect to the horizon are also indicated. The lengths were adapted in site during perforation in order to be at least for 8 m in the strong bedrock. The anchors are formed by a hollow bar of 76 mm with 4 tendons cemented inside. Among the seven anchors, six of them (A.1 - A.6) were instrumented with a unique armored corrugated optical fiber cable for strain measurement (BruSens® V9, Solifos), approximately 500 m long, introduced in the cavity together with the tendons (Figure 3b). The cable is installed in a loop configuration, that means that the cable enters and exits in each anchor, starting from the A.1 in the photo, moving to the other (A.2, A.3, etc.) up to return again to the first one: in this position there are the connectors for linking the cable to the analyser device. The portion of cable between the anchors was hung at steel wires laid between each bar head and then protected. That allowed close and easy access to both ends of the thread for the double-ended measurement. In this case the analyser device is carried out in the site to perform the measurements, but in other cases, if there are some houses in the site, it is possible to perform the reading in continuous automatic way.

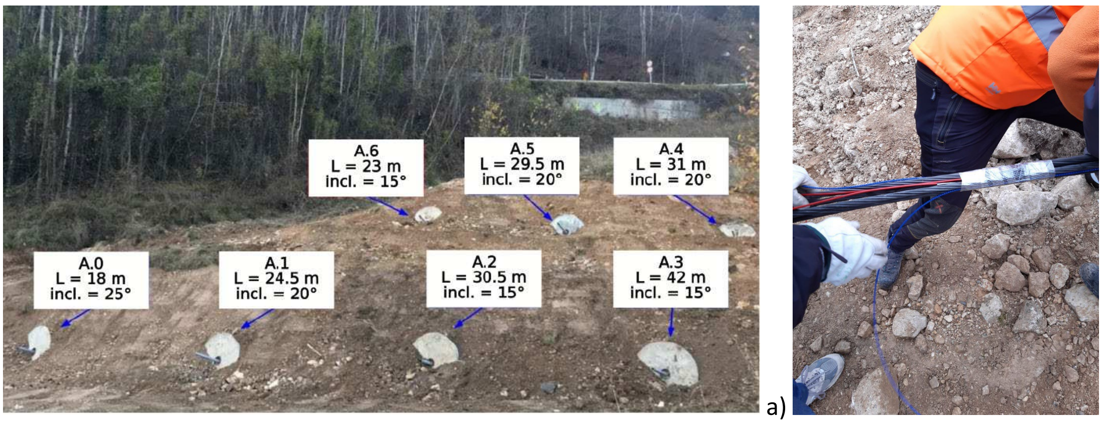
Anchor A.6 was also instrumented with an additional cable for temperature compensation (BRUSens® DTS STL PA, Solifos), a specifically cable realized with the fiber hosted in a gel-filled stainless-steel loose tube in order to avoid that the optical core in the fiber is affected by mechanical strain.

Indeed, since the anchor A.0 was selected to perform a pull-out test, it was equipped with a separate fiber cable for strain measurement, 80 m-long. The results of this test are not shown here for brevity.

The installation procedure exploits the feature of composite anchors to install the optical sensing fiber inside the bar cavity, together with the strands. Subsequent cementation of the cavity ensures the connection between the bar and the fiber, thus becoming an integrated system for acquiring deformations and temperature along the bar. Furthermore, compared to other types of anchors (Monsberger and Lienhart, 2019), the bars can be instrumented with the optical fiber directly in the field, allowing the fiber integration on long bars and a greater chance for the fibers to survive the installation and operation.

The group of strands constitutes the support for the installation of the fibers, which is carried out in two steps: first, the hollow bars are installed on-site using the self-drilling technique; hence, four harmonic steel strands, to which optical fiber cables are anchored and kept in place with opportunely designed centering devices, are inserted into the internal cavity of the bar. Metal pulleys were soldered at the bottom of the composite bars to support the cable loop. Then the strands and the fibers are cemented inside the rods by pouring a special mortar through a central injection tube.

Figure 4a shows the cross-section of the smart soil: this scheme refers to the anchor A.6, with two optical fiber cables included, one for strain measurement and the other for temperature compensation. Two cross-sections are represented for each cable, given that the cables are installed in a loop configuration. The cables have been then interrogated using a Brillouin Optical Frequency Domain Analyzer (BOFDA) from FibrisTerre (Germany) with a maximum sampling and spatial resolution of 5 and 20 cm, respectively, and a strain and temperature measurement accuracy of 2 με and 0.1°C.



a) b)

Figure 3. a) Smart soil anchors installed at Fantoni landslide in November 2020 (North-East of Italy); b) Fiber cables introduced with the tendons in the cavity.

3. Measurement campaign and discussion

The installation was completed at 2 December 2020. Excluding the fiber embedded in the anchor A.0, which was destroyed during the pull-out test performed at 04/03/2021, the other cables within anchors A.1-A.6 were repeatedly measured. As of today, they are still operative.

Strain and temperature have been calculated from the Brillouin Spectral Shift (BSF) measured in the cables and employing the temperature and strain coefficient provided by the cables' manufacturer. As mentioned above, the temperature is exclusively measured by the cable integrated into the anchor A.6. Still, it is used to compensate for the thermal effects affecting the strain measured in all the anchors, despite the different locations. In doing so, we assume that the temperature gradient is almost uniform over the area where the anchors are installed. That is a reasonable assumption given the soil homogeneity in the area, at least at a shallow depth, where the temperature varies mostly. Moreover, given that the other anchors are longer than A.6, we have assumed the temperature to be constant below the depth of A.6, where we do not have temperature data. The negligible temperature variation measured in A.6 at a depth of some meters below the ground supports this choice.

Due to limited space, only a selection of strain curves is here presented and commented. Figure 4 shows the temperature compensated strain measured in the anchors A.1, A.3 and A.6 during six measurement sessions, the first of which was taken two weeks after the installation of the anchors (i.e., 02/12/2020 when the reference measurements were collected).

Given the loop configuration of the cable, the strain field is probed twice at each depth and, in Figure 4, the strain measured in both the ascending and descending cable sections is represented in the plot, employing a bidirectional x-axis. As one can see, the ascending and descending sections of all bars show almost the same strain, testifying that the two sections are well aligned within the bars, and the cables are not significantly twisted around the strands. In fact, tight control of the fiber alignment, especially in long bars, is challenging for anchors instrumented on the field.

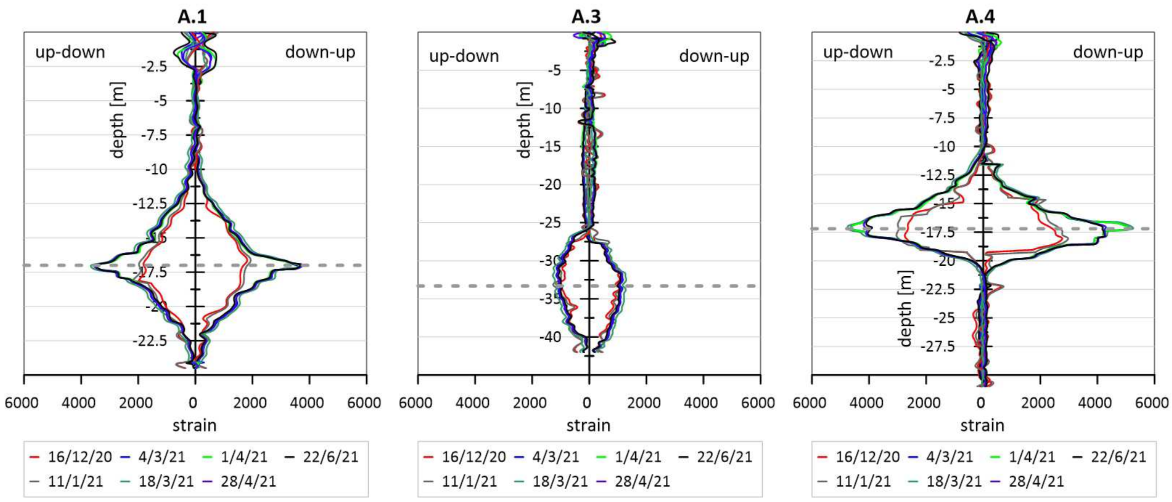


Figure 4: Strain measured in anchors A.1 (left) and A.3 (center) and A.4 (right) with time (d/mm/yy). The plots employ a bidirectional x-axis, where the half-left and -right parts of the x-axis refer to the portion of the fiber from the top to the bottom of the anchors and viceversa, respectively.

The strain measured in anchors A.1 and A.4 and their evolution over time are representative of the behaviour of quite all the anchors, except A.3. These anchors clearly show a marked strain peak, approximately at 16.5 m and 17.4 m for A.1 and A.4 respectively. The peak value was well defined in the first interrogation and rapidly increased (for A.1 the peak strain doubles) from the 1° to the 2° measurement, one month later: then it remained almost fixed. Interestingly, for all anchors, the strain is significant over a limited length, with the strain peak located within the length of the bar. Moving toward the surface and the inner part from the peak position, the strain decreases up to zero with a quite constant gradient. This gradient directly measures the friction exerted at the soil-bar interface. The remaining parts of the bars show a negligible strain and, therefore, we may conclude that they do not contribute to the retaining force, but they may be activated if further soil movement would occur.

On the contrary, a smoother strain profile characterizes anchor A.3, with a smaller and less marked strain peak at a larger depth (approximately 32 m). Moreover, also the maximum strain has a value lower than the other anchors. It may be justified thinking that in this position the landslides displacements are minor and they did not completely activate the resistance at the interface soil-anchor and, consequently, the traction in this anchor.

Comparing the position of the maximum elongation with the data collected in site during installation, it is evident that the peak of strain is close to the passage from the upper low resistant soil to the more resistance deep material, constituted, in this case, by a medium weathered volcanoes rock. It is possible to suppose that in this position the anchors cross the landslide sliding surface, and the landslide movement pulls the bar, activating the interface soil-anchor frictional resistance. This behaviour was not observed in the previous application (Cola et al., 2019) because, in that case, the measurement campaign carried out was too brief and no landslide movements have occurred in the meanwhile. The same analysis carried out for all the anchors allows for determining the depths of the sliding surface with respect to the ground. These depths are reported in Table 1: they decrease towards the right side of the slope and are more prominent for the anchors in the lower row. Together with the position and height of the bars and the relative inclination angle, these data may consent to identify and reconstruct a 3D map of the sliding surface.

	Lower row				Upper row		
Anchor	**A.0**	**A.1**	**A.2**	**A.3**	**A.4**	**A.5**	**A.6**
Maximum strain (%)	0.29(*)	0.38	0.43	0.12	0.44	0.25	0.26
Maximum Force (kN)	1225	1312	1361	855	1371	1186	1196
Depth of maximum strain (m)	12.5	16.5	21.5	32.5	18	13.5	11.5

Table 1: Maximum strain and maximum force measured for each anchor at 21/09/2021 and depth at which these are. (*) Data measured at 04/03/2021.

Anchor A.4 presents the maximum strain (about 4400 με) which is within the elasticity range of the optical cable (approx 10000 με). The same is well above the mechanical yielding strain of the hollow bar (approximately 2000 με) but within the yield strain of the strands (approximately 2000 με). In general, these features represent a validation that the design of the anchors is appropriate; most notably, the distributed optical fiber sensors make this validation possible.

In order to move from the strain to the axial force of anchors and evaluate their stabilization contribution a simple strain-force relationship could be assumed for the anchors, hypothesizing linear behaviour between the yielding point (Figura 5a). In particular, the data given by the manufacturers for the bar and the strands are:

- Bar: yielding strain, 0,23%; force at yielding, 952 kN; failure strain, 5%; maximum traction, 1159 kN.

- Strand: traction at 0,2%, 46.4 kN; yielding strain, 1%; force at yielding 1%, 232 kN; failure strain, 5%; maximum traction, 260 kN.

Considering that the contribution of strands and bar can be added and that the number of strands introduced in the anchors are 4, it is possible to calculate the axial traction present in the anchors according to the last reading. These axial tractions are listed in Table 1.

To track the strain evolution in the bar during the measurement campaign, we estimated the differential elongation accumulated over three portions, 1 m long, of anchor A.1 located around the strain peak position, at distances of 15.5, 16.5, and 17.5 m respectively from the external plate. The calculated curves are represented in Figure 5b: they further confirm that (i) the landslide movement considerably slowed down since the installation of the anchors (ii) an evident increase of deformation is observed around the strain peak position (around 50%, with respect to adjacent portions of the bar).

Of course, in the future these data have to be put in relation with the kinematical evolution of the landslide, in order to verify if the fact that the anchor elongation has remained quite constant for all the 2021 year is due to

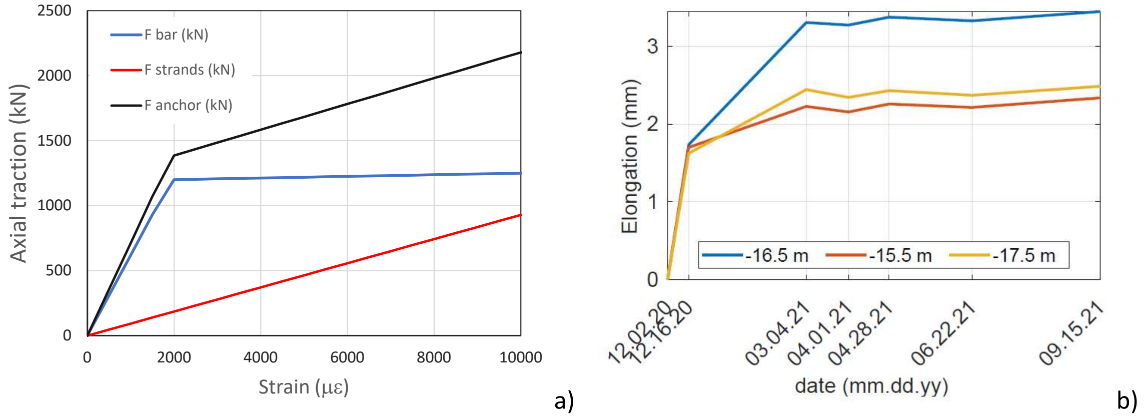


Figure 5: a) Schematized force-strain behaviour of the bar, strands and composite anchor; b) Partial elongation of anchor A.1 over 1 m of bar length, calculated at different depth around the peak strain position

the capability of the installed anchors to stopped the landslide or a consequence of particular dry period. To this aim, in the site two inclinometers and an innovative photogrammetric technique have been used to check the trend of the landslide displacements. In particular, one standard inclinometer was installed before the realizing the anchors. It was located close to the position chosen for the subsequent installation of anchors in order to check the mobility of the landslide before and after the installation. Unfortunately, in the 2 months before the anchor installation the landslide developed large displacements (see Figure 6a) and the inclinometer was rapidly put out of service for excessive deformation. The day after the installation a strong snowy storm occurred in the region and the area remain covered by snow for 3 months. Another inclinometer probe was installed only at 4/3/2021 in a new borehole parallel to the first. In this second installation an electrical probe for continuous reading is installed at the depth of the sliding surface previously determined. The displacements accumulated in this second installation are shown in Figure 6b. They demonstrate that during the measurement campaign the landslide was moving very slowly (less then 4mm/y) if compared with the displacement rate before anchor installation (about 0.8 m/y). These measurements have to continue in the future for further analysis and verifications.

4. Conclusions

The paper presents the preliminary results of a monitoring activity carried out on an experimental site where some composite anchors were installed in an active landslide to reduce its kinematical evolution. For the first

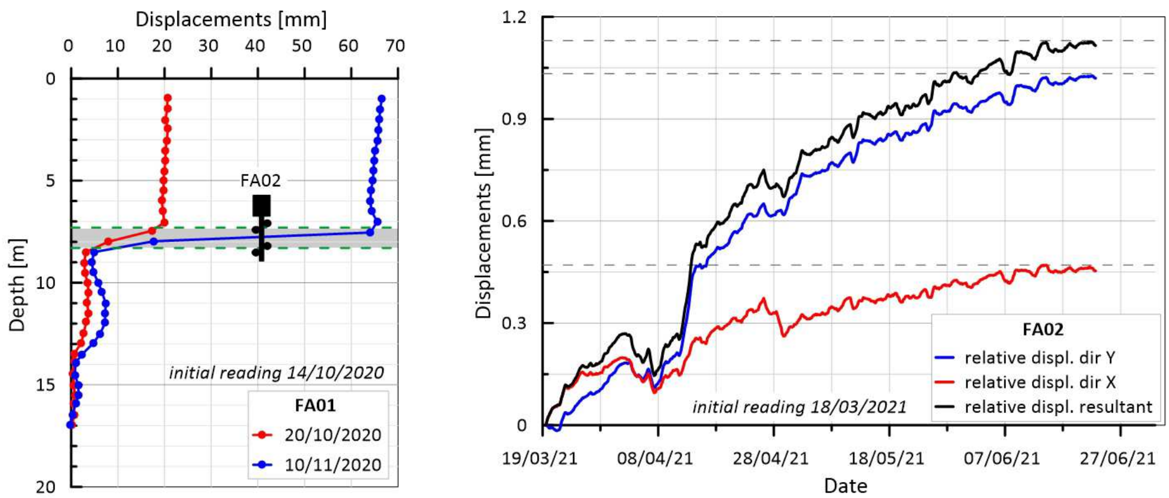


Figure 6: Landslide displacement recorded at the: manual inclinometer FA01 in two months before the installation of anchors (left); automatic inclinometer probe FA02 installed in March 2021 close to FA01 (right). The vertical position of FA02 is indicated in the plot a).

time these anchors are monitored with a new patent system that uses the fiber optic technology. A Distributed optical fiber sensor was installed within the anchors for measuring the developing of the traction in time and along the length of the anchors. Up to now the system has given good results and upon an extensive validation, the system may become a standard practice to evaluate the effectiveness of these anchors with time.

Acknowledgements

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