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Performance of ground anchorsbuilt in a flysch deposit

Maria Cristina Di Gregorio[a], RaffaelePapa[b], Gianfranco Urciuoli[b,*], Luciano Picarelli[c], Luigi Zeni[d], Aldo Minardo[d]

[a]*Civil Engineer, Naples, Italy*
[b]*University of NaplesFederico II, Department of Civil, Architectural and Environmental Engineering, Via Claudio 21, 80125 Naples, Italy*
[c]*Second University of Naples, Department of Civil Enigineering, Design, Building and Environment, Via Roma 29, Aversa (CE) 81031, Italy*
[d]*Second University of Naples, Department of Industrial and Information Engineering, Via Roma 29, Aversa (CE) 81031, Italy*

Abstract

The ultimate pull-out tensile load of ground anchors is strongly dependent onsoil nature,grout injection and effective stress state around the bulb. In this paper, the comparison between the results of conventional pull-out testson instrumented anchors built in a flysch formation and those of small scale pull-out tests performed in the laboratory,on undisturbed soil samples recovered at the depth of the anchor bulb,allowed to closely examine the skin friction that can be mobilizedin undrained conditionsat the soil-structure interface.The experiments highlight a strong scale effect, probably depending on the real size androughness ofthe lateral surface of the bulb.In fact, theirregular bulb profiledue to flysch features strongly contributes to the pull-outstrength.

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*Keywords:*Anchor, slope stability, stabilization, skin friction

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1. Introduction

Ground anchorsallow to improvethe mechanical response of retaining structuresbuilt in unstable slopesleadingto the increase of their safety factor and, hence, of the slope. In particular, the role of ground anchors is to transferthrough skin friction the forceinduced by the unstable soil body to the stable formation located beneath the sliding surface. The pull-out tensile load is affected by grout injection,anchorsize, number of strands andsoil properties. Usually, the pull-outforce is the more burdensome aspect of the design that requires a special care.

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* Corresponding author. Tel.: +39 0817683544
E-mail address: gianurci@unina.it

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In flysch deposits the performance of ground anchors is often uncertain because of the following reasons:

- the bulb involves layers of clay shale and of competent rock, which behave quite differently;
- tensile stressesare often applied in undrained conditions; induced excess pore pressures around the anchor then play a prominent role on the anchor behavior.

A problem then raises in the assessment of the ultimate tensile force that is generally roughly solvedthrough a total stress approach using the undrained cohesion $c_u$that is usually measured in the laboratory along compressive stress paths. In contrast, the application of the pull-out force induces in the soil around the anchor a complexstress pathtypically characterized by a decrease of the normal stress in the anchor direction.

This paperreports the results of pull-out tests performed on anchors built in a flysch deposit. An anchor was instrumented with an optical fibre that allowed to determinethe distribution of the mobilized skin friction at the soil-bulb interface. The average value of the skin friction was then compared to the value measured on small scale pull-out tests performed in the laboratory on undisturbed soil samples. All samples were takenat the depth of the bulb.The comparison between these experiments allowed to closely examine the anchor performance.

2. The problem

In December 2013, a landslide took place nearby the town of Castelnuovo di Conza (Fig.1), Southern Italy, interrupting the access road to some houses located in a rural area.Urgent measures were then adoptedto re-establish the normal traffic conditions.In order to stabilize the slope, some retaining walls anchored with injected bulb anchors were built. The design was strongly influenced by site morphology and mechanical soil properties. In particular, two types of retaining walls were built: the first one, reinforced with 30 m long injected bulb anchors, was located in the uppermost part of the slope; the second type, reinforced with 25 m long anchors, was builtat the slope toe. All anchors,having an inclinationof25° to the horizontal, presented a bulb length of 10m.

Fig. 1. Study area In the Southern Italy Apennine

3. Nature and properties of the subsoil

Site investigations included a number of boreholes reaching a maximum depth of 25 m.
A stratigraphic section of the site is shown in Figure 2. The soil profile includes: (*a*) a 6-7 m thick softened clayey cover with marlyinclusions; (*b*) a 5-6 m thick flysch formation locally consisting of highly fissured and sheared clay

shales (Varicoloured Clay); (*c*) a marlybedrock. The groundwater table is located at a depth of 2 m from the ground surface,in the softened cover.

The grain size distribution of the soils *a* and*b* is summarized in Table 1.Their main physical properties and shear strength parameters, measured through traditional triaxial tests, are reported in Tables 2 and 3.

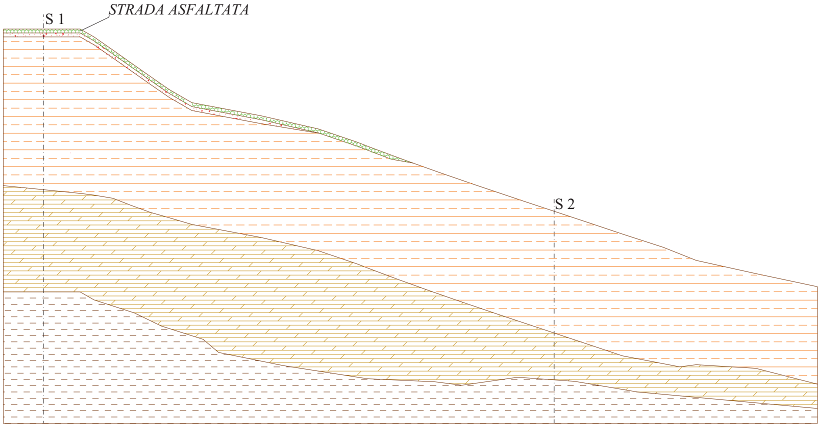

Fig. 2. Stratigraphic section of the slope. From the ground surface: softened clayey cover, highly fissured clay shales, bedrock (marls).

Table 1. Grain size distribution of samples.

Borehole	Sample	Clay(%)	Silt (%)	Sand (%)	Gravel (%)
S1	C1	25.0	43.0	32.0	0.0
S1	C2	24.5	73.0	2.5	0.0

Table 2. Physical properties.

Lithotypes	γ(kN/m^3)	γ_{sat}(kN/m^3)	w_p (%)	w_L (%)	I_P (%)
A	19. 0	19.5	-	-	-
B	21.0	23.0	22.8	43.6	20.8
C	21.0	-	16.0	36.0	20.0

Table 3. Shear strength parameters.

Soils		ϕ'(°)	c′ (kPa)
A	Clayey silt	21.5	22.0
B	Flysch	26. 0	19.0
C	Bedrock	22.0	28. 0

Legend: γ bulk unit weight; γ_{sat} saturated unit weight; w_P plastic limit, w_L liquid limit; I_P plasticity index; ϕ' internal friction angle; c′ cohesion.

4. Pull-out strength of the anchors

The pull-out resistance $q_s$of ground anchors may be determined from the results of in situ tests or by calculations based on the following expression:

$$q_s = \tau = \frac{T}{\pi \cdot d \cdot l} \tag{1}$$

where τ is the skin friction at the bulb-soil interface, T the ultimate pull-out value, *l* and *d* respectively the bonded length and hole diameter.

The skin friction resistanceis given by the Mohr-Coulomb criterion:

$$\tau = K \cdot \sigma_v^{'} \cdot \tan\delta \tag{2}$$

where K is an earth pressure coefficient and σ'_v,the average effective overburden pressure at the bulb depth.

The angle of shaft friction δ is usually assumed to be less than the angle of internal friction of the soil, ϕ'. The value of the coefficient K depends on several interrelated factors such as soil features, construction method andgrout injection pressure.

5. Determination of the skin friction from laboratory tests

In structurally complex soils, the selection of the soil parameters for the design is alwaysa challenge. In fact, typically, these soils are extremely heterogeneous and anisotropic[1,2,3]. Therefore, it was decided to measure the skin friction at the bulb-soil interface through small scale pull-out tests. To this aim, a number of undisturbed sampleswere recoveredat the same depth of the bulb.The tests were carried out in amodifiedtriaxial apparatus (Fig. 3).

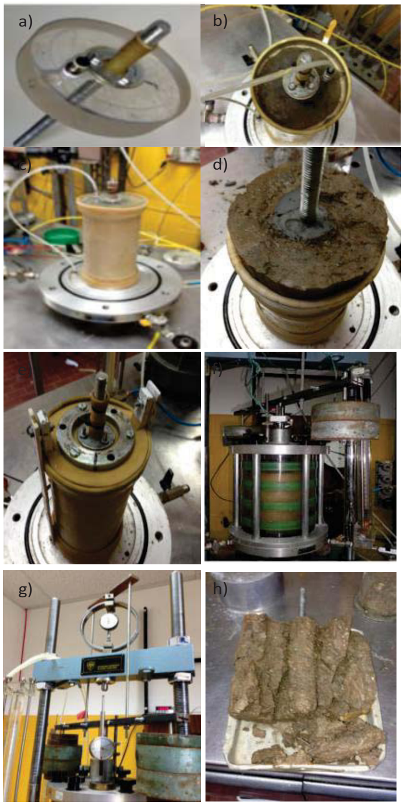

Fig. 3. Pull-out test apparatus: a) plexiglass plate for injection; b) top plan view of the plate connected to the cell; c) front view of the plate; d) setting of the cement inthe cell; e) plate for the pull-out test and steel bars; f) loading system; g) loading ring and micrometer; h) injection bulb.

A number of specimens having height, *h*, of 20 cm and diameter, *d*, of 10 cm were adopted. A hole with *h* = 15-17 cm and *d* = 3 cm was then drilled in the middle of the specimen and a small diameter (d=10 mm) anchor bar was then installed and cemented:an anti-shrinkagecement mixture was used with a water-cement ratio of 0.6.

In order to simulate the injection process, a special upper plate was adopted (Fig. 3a). This allowed to inject the grout through a tube connected to an external pressure generator (Fig. 3b and 3c). The specimen was then put into a latex membrane and installed in the triaxial cell. During the injection process a confining pressure, p′=100 kPa (difference between the cell pressure and the backpressure), was adopted in order to simulate the stress field. Finally, the base of the cell was equipped with a porous stone in order to allow the consolidation process induced by the cell pressure thus simulating the field effective stress and then, to measure the pore pressure variations during the pull-out phase, through a pressure transducer.

The consolidation phase lasted about 7 days.The cement hardening phase lasted 21 days (Fig. 3d). Later on, a plate was installed on the top of the specimen in order to perform the pull-out test directly in the cell (Fig. 3e). The plate consists of two overlapped concentric steel rings that, at the same time, allowto isolate the specimen from the water and to perform the test (pull-out). Also, two steel bars were connected to the head and at the base of the specimen to prevent any lifting upward of the specimen during the test. To balance the water pressure, a load was applied at the specimen head (Fig. 3f).

The pull-out rate was set at 0.1mm/min.The displacement was measuredwith a micrometer placed at the head to the specimen nearby the piston. The pull-out was measured by a dynamometer (Fig. 3g). Finally, a pressure transducer installed at the base of the specimen allowed to measureany pore pressure variation.

At the end of the testthe length of the injected bulb was carefully measured (Fig. 3h), unraveling the specimen.

6. Experimental results

The tests were performed on three undisturbed samples.Even though they had beentaken very close to each other,the three samples displayed a different lithology confirming the great difficulty in the characterization of these formations.

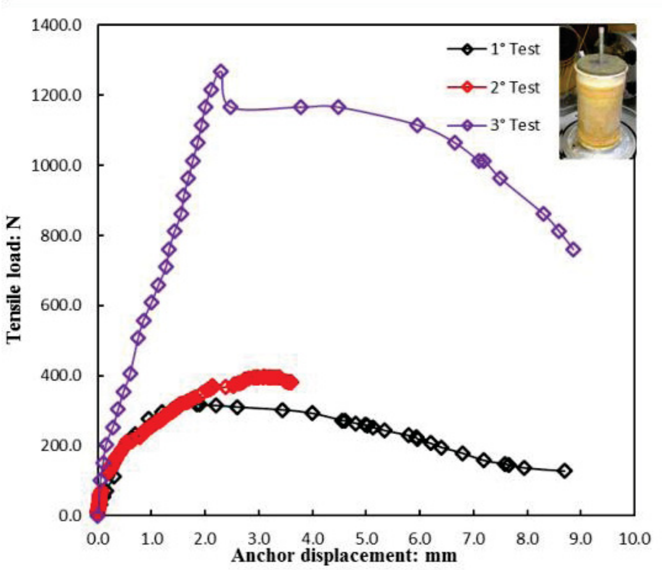

Fig. 4. Results of the pull-out testscarried out in the laboratory on three different samples

The first specimen presented a higher percentage of clay and the absence of any calcareous or marly component. Its ultimate tensile load was about 300 N, corresponding to a skin friction of about 23kPa, that was mobilised for a displacement of about 1.5mm (Figs. 4 and 5).The obtained value was 1/3 of the expected one in drained condition based on the stress acting at the boundary of the sample and on the soil properties. If cohesion is neglected, the obtained value is ½ of the expected value.

The ultimate tensile load of the second sample was about 400 N, mobilised for a displacement of 3.8mm: the skin friction was 40 kPa. This value was 2/3 of the expected value in drained condition; it coincides to the theoretical value if the cohesionis neglected.Figure 6 shows that during the test, a positive excess pore pressure of 60 kPa built up, drastically reducing the skin friction.It is thought that some marly fragmentsdid increase the pull-outvalue.

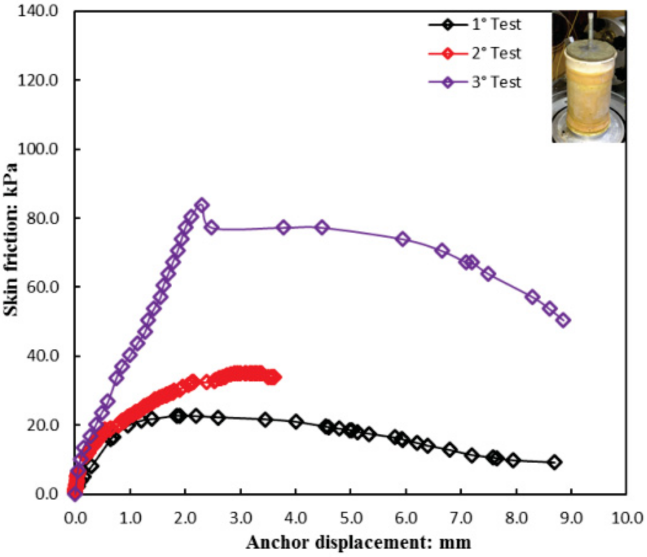

Fig.5. Skin friction measured in the three tests

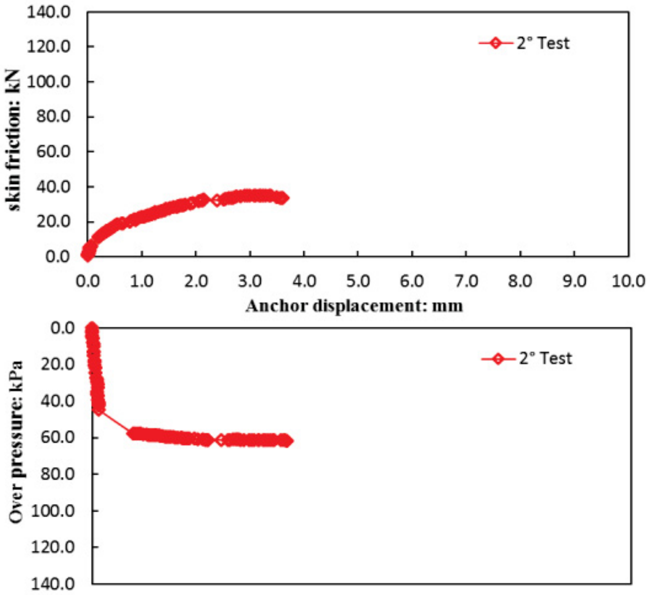

Fig.6. Pull-out test on sample 2: tensile load and excess pore pressures vs anchor displacement

The greater percentage of the calcareous/marlyfragments in the third sample led to a higher tensile load(1250 N, for a displacement of 2.5 mm), corresponding to a skin friction of 85 kPa, higher than the value expected in drained conditions for the clay interface.

The tests then fully demonstrated the soil heterogeneity, even at the sample scale, confirming the utility of field tests for the selection of the design load. Also, the data presented in Figure 6 show that excess pore pressures induced during the bar extractioncan be larger than the shear stresses along the bulb. In the fieldthe loading rate then governs the magnitude of the excess pore pressure; as a consequence, an anchor installed in a slow landslide might be more performing than in field tests.

7. Field pull-out tests

The field pull-out testswere performed using a block of reinforced concrete as a contrast(Fig. 7).However, during the test block movementswere measuredin order to obtain the correct displacement of the steel strands.

The tests were performed on two anchors having lengths of 25 and 30m respectively, a bond length of 10m and a nominal diameter of 15 cm.The reinforcement consisted of five harmonic steel strands.The shorter anchor was equipped with an optical fiber glued to the strands. This allowed to determine the strain distribution by the BOTDA technique (Brillouin Optical Time Domain Analysis), then to calculate the skin friction along the bulb.

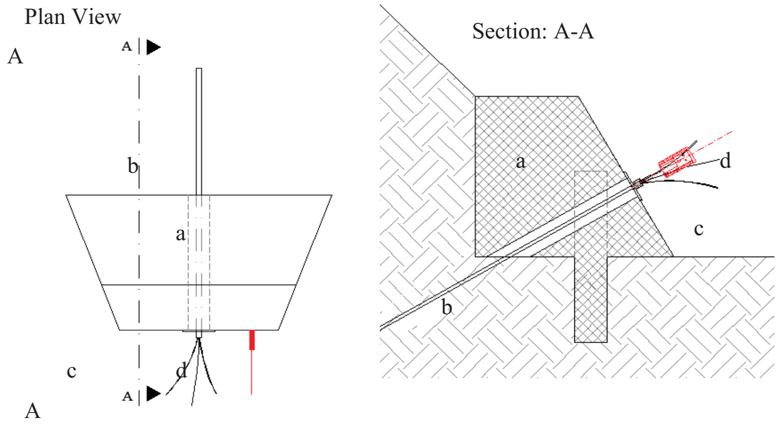

Fig.7. Lay-out of the field pull-out test

The load was applied by means of five hydraulic jacks, each connected to a strand. The test consisted of load steps of 50kN. At each step, the load was kept constant for about five minutes, measuring at the same time the head displacement.

Figure 8 shows the test results. The first anchor (length 30 m) was subjected to two loading cycles. In the first cycle,the maximum applied load was of about 330 kN; the corresponding theoretical skin friction was 70 kPa. The figure (full circles) also shows the calculated strains in the strands in the elastic range, assuming no sliding of the anchor bulb.During the second cycle, the anchor was brought to failure that took place for a load of 470kN, i.e. for a skin friction of about 100 kPa. The second anchor was subjected to a maximum load of 708 kN;the corresponding mobilized shear strengthwhich led the anchor to failure was around 150 kPa.

The plotsin Figures 9 and 10 show the strains measured through the fiber in the second test.Notice thatfor each loading stage, the figure reports the strain measured at the two lateral sides of the same anchor (an unique fiber is in fact glued on the two sides):this clarifies the symmetric strain trend. The plot shows a practically linear axial strain decrease along the strand for any loading stage; this indicates a linear decrease of the axial stress and suggests a rather uniform mobilized shear strength at the bulb-soil interface. In the unloading steps the trend is quite different showing some residual strains[4].

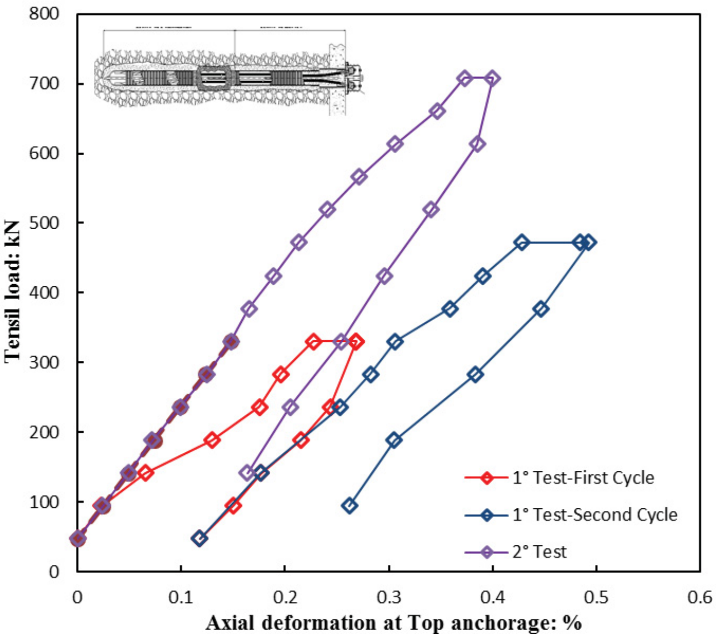

Fig. 8. Results of the pull-out test on the 30 m (test 1) and 25 m long anchor (test 2). The line with full circles represents calculated elastic strains

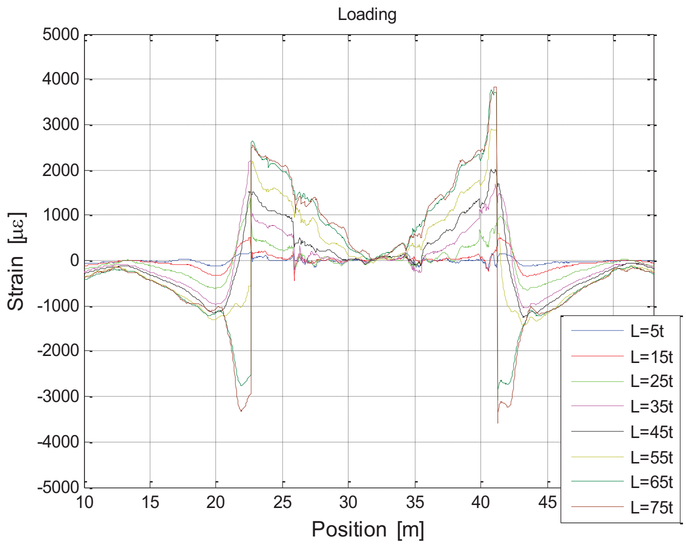

Fig. 9. Results of the test on the 25 long anchor, loading phase

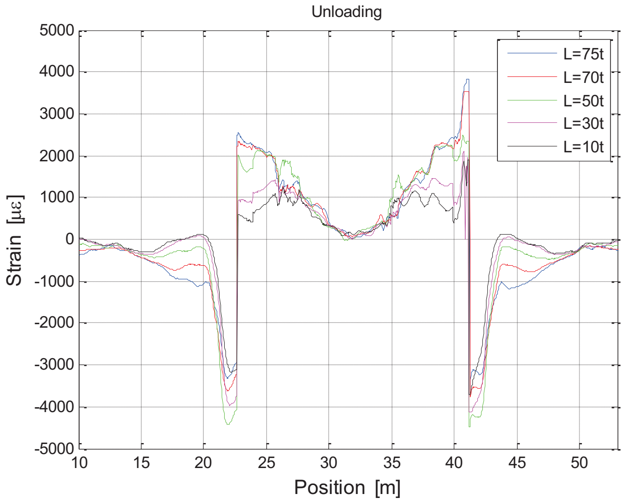

Fig. 10. Results of the test on the 25 long anchor, unloading phase

A careful strain analysis indicates some peaks and some sharp variations, with sections in which the measured values are smaller than those obtained by linear extrapolation. Probably, such sections correspond to layers of marl or limestone constraining bulb deformations.

Figure 11 reports the average skin friction values measured in the two tests. Again, the results highlight the soil heterogeneity. In fact, measured skin friction was quite different in the two cases with values of the mobilised shear strength that cannot be justified only by the different depth of the two anchors. Also,compared to the laboratory tests, the field experiments indicate a significantly higher mobilised soil strength probably due to the role of the lapideous component of the flysch formation.

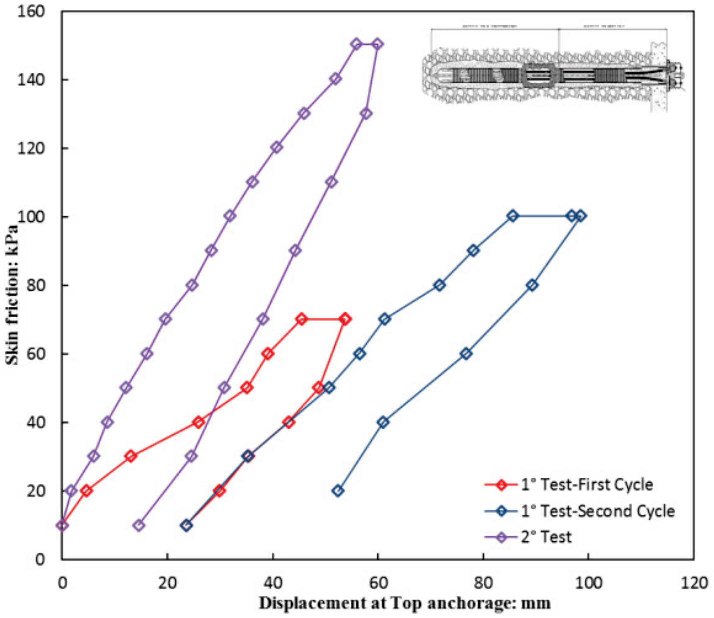

Fig.11. Trend of the average skinfrictionvs. displacement

8. Conclusions

The paper reports the results of pull-out tests carried out in situ and in the laboratory on anchors built in a flysch formation. The measured skin friction in the different tests confirmthe well-known difficulties in the mechanical characterization of these formations due to both the great heterogeneity of the soil andscale effects.

The use of optical fibers in one of the two field tests showed the reliability of this new technique which allowed to measure the skin friction distribution along the bond length.

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