Pull-out creep lab test for rock bolts embedded in soft rock-like material

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ABSTRACT: This research introduces a laboratory creep test for measuring displacements under constant load for long periods of time in anchors embedded in soft rocks. The preliminary theoretical and experimental ideas that have served for the design of the equipment are detailed, as well as its mechanical and geometrical characteristics, defining the test procedure. A rock-like material composed of bentonite, cement and water has been tested, which has been geotechnically characterized by identification, strength and deformability tests. The specific manufacturing process of the test samples is also defined. Three creep tests are carried out with durations between 46 and 75 days each, observing their reproducibility. Considering scale effect, an adequate contrast results between the instantaneous displacement obtained with the test and the obtained with the analytical solution under the same boundary conditions.

1 INTRODUCTION

Any ground subjected to a constant load will deform over time. The magnitude of the time-dependent strain differs according to the strength properties of the structure. One of the main unknowns associated with the design and computation of retaining structures is the behaviour of anchors along their useful life. The principal cause of strength loss of anchors with time is the creep phenomenon, due to the soil, grout and elements that form the ground anchor. For this reason, by providing a constitutive creep model of the soil-structure interaction problem it can be optimized the design that frequently predicts longer strains rather than the strains that really occurred (Ostermayer, 1975). Larger movements of the system “tendon-structure-anchor” are associated with bonded anchor. In order to study these creep displacements a laboratory creep test and equipment are developed. The experience obtained with these tests and the analysis of their results will provide knowledge on the creep ground in these conditions and will facilitate the prediction of the rheological phenomenon in the ground-structure interaction problems, such as that of tied-back structures.

Creep tests are used to know the deformation of the ground during long periods of time under specific conditions that, in a general way, are constant load, temperature and moisture of the sample. Creep and pull-out tests have been carried out on anchors in concrete. Kränkel et al. (2015) performed three types of tests with adhesive anchors in concrete, to estimate: the non-linear dependence of the viscosity coefficient over time, the non-linear dependence of the deformation modulus with the stress, and the degradation caused by the reduction of the deformation module in relation to the displacement of the anchor. Nilforoush et al. (2016) performed creep tests of adhesive anchors in concrete, both indoors and outdoors, with durations of up to 28 years in collaboration with several laboratories. However, the investigations are more limited in terms of creep tests of anchors in soils and rocks. Gurinsky (2002) measured the displacement of an anchor embedded in sensitive clays for approximately 40 days under different steady-load steps. Zhang et al. (2015) developed a test that allowed them to study the mechanism of soil-nailing interaction. They apply seven consecutive loading steps, for only one hour.

In this research, a large-scale laboratory creep test is presented that enables measuring the displacements under constant load for long periods of time in an anchor embedded in a soft rock. In particular, a rock-like material composed of bentonite, cement and water has been tested, which has been geotechnically characterized by identification, strength and deformability tests. The contrast between the results of instantaneous displacement obtained in the test and the results obtained from an analytical solution for our same boundary conditions enables the validation of the test.

2 APPARATUS DESIGN

2.1 *Preliminary ideas*

It is known that the modes of failure when a pull-out test of adhesive anchor in rock are carried out are: rock break-out, partial adhesive-rock bond failure of the anchor, adhesive-rock bond failure of the anchor, and steel tendon tensile failure. Figure 1 shows the most frequently types of failure obtained experimentally by García-Wolfrum (2005).

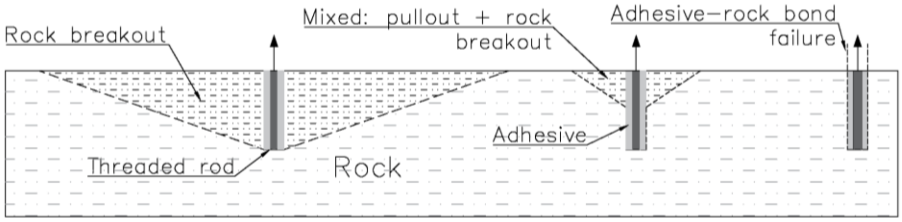

Figure 1. Principal modes of failure of adhesive anchors.

The results of fifteen pull-out tests in mortar samples (García-Wolfrum, 2005) stablish a maximum dimensions of the failure cones between 70 and 240 mm of radius, for anchor lengths (L_a) between 46 and 114 mm, and hole diameters (D_h) between 15 and 18 mm. The geometric ratio L_a/D_h used by the author ranged from 2.6 to 7.2, testing mortars of uniaxial compressive strengths (σ_c) between 2.3 and 7.3 MPa. According to this preliminary ideas, the proposed apparatus has the following geometrical characteristics:

- Cubic rock samples of 745 x 550 x 310 mm.
- Embedment depth: range from 70 to 80 mm.
- Anchor diameter: drill hole diameter of 12 mm with threaded rod of 10 mm adhered to the sample by epoxy adhesive (Sika AnchorFix-3001, compressive strength = 85 GPa, elastic modulus = 5000 GPa).

Therefore, thinking of a mechanical system in which the load is transmitted to the anchor through the direct placement of weights, it must be possible to guarantee the transmission of sufficiently high bond stress to produce creep strains in the sample. Thus, the pull-out force necessary to extract an anchorage from the ground in which it is embedded (T_f) can be expressed as (Littlejohn, 1980):

$$T_f = \Pi \cdot D_h \cdot L_a \cdot \tau_{ult} \quad (1)$$

where, $\tau_{ult.}$ = ultimate bond stress (adhesive-rock bond).

In particular, the usual values of pull-out average strength (τ_a) for different types of ground can be estimated according to Table 1. Therefore, said equipment can be used to test most of grounds that are usually found in nature and in engineering works. Specifically, soft rocks can be tested, with pull-out strengths of between 300 and 1000 kPa, by placing weights in the mechanical system of 60 kg-200 kg of mass, respectively.

Table 1. Pull-out average strength (ATEP, 1996)

Ground type	1	2	3	4	5	6	7
τ_a (MPa)	1 – 2.5	0.3 – 1.0	0.6 – 1.0	0.3 – 0.6	0.6 – 0.8	0.2 – 0.6	0.05 – 0.2

1: Hard rock; 2: Soft rock; 3: Coarse gravels and sands; 4: Medium and fine sands, silty sands and sandy clay; 5: Clays of stiff consistency (C_u>200 kPa); 6: Clays of firm consistency (100<C_u<200 kPa) y 7: Clays of medium consistency (50<C_u<100 kPa). C_u: undrained shear strength

2.2 *Equipment description*

It is a mechanical equipment, because the transmission of the load is done by placing weights. In this way, very long test times are achieved, maintaining the applied load constant without the need to depend on electrical systems that could be interrupted or with which it is more difficult to generate this condition. The scheme of the developed apparatus can be seen in Figure 2 and its main components are:

- plastic cube that contains the manufactured sample,
- structure formed by metallic profiles of high rigidity with a support base on the sample of 745 x 550 mm. In this structure the wiring is placed (galvanized steel cable of 3 mm diameter and tensile strength of 1770 GPa), supported on two pulleys, which joins the anchor (in the central axis) with the hanging weights bar (on one side) that will perform constant tension over time,
- and nine dial gauges of 0.01 mm of accuracy (located at points 1 to 9, Fig. 2), which measure the displacement over time of the sample and of the anchor (point 6, Fig. 2).

The height of the cube is designed to immerse the sample in water during the test and maintain its saturation moisture, a key factor in the study of soil creep. In addition, the test is carried out in a room with controlled temperature, maintaining the sample temperature (-3 / +3 ºC), and, most important, the water found in its pores, approximately constant. Different measurement points have been established according to the scheme in plan of Figure 2. The selected points are symmetrical with respect to two perpendicular axes that pass through the centre and cover the area of expected movement, to study the evolution with time of the rock cone.

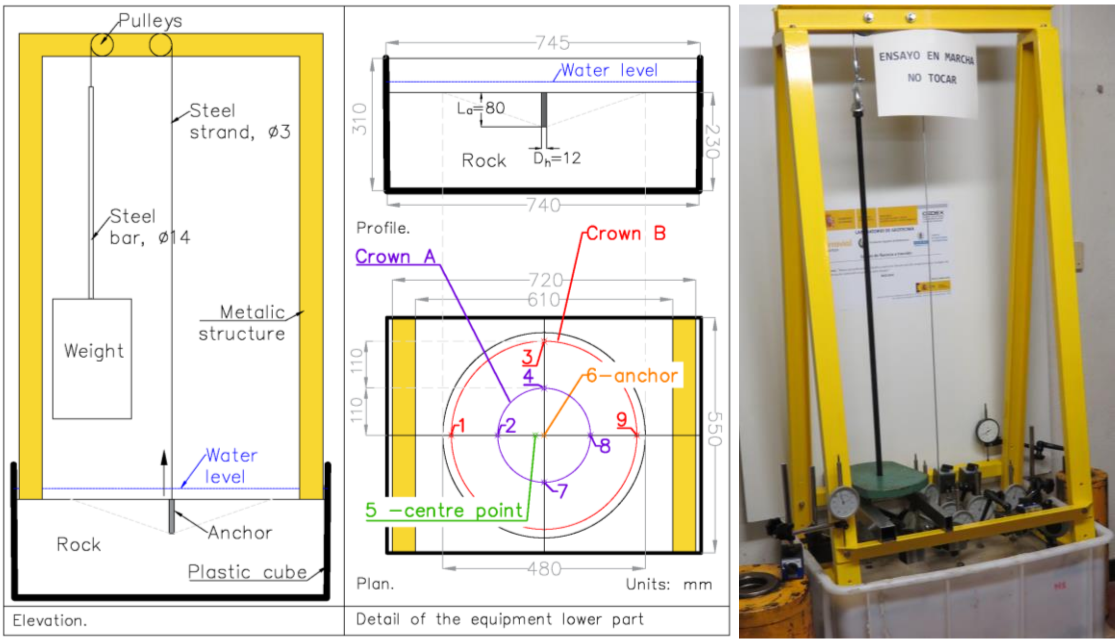

Figure 2. Schemes and photo of the equipment.

3 TEST SAMPLES

3.1 *Selected composition of the rock-like material*

In most natural clays, creep is an inherent property of the interparticle bonding, particularly if they contain bentonite, montmorillonite and organic matter; and, less significantly, chlorite-illites (Mitchell & Soga, 2005). Thus the search was made for artificial mixtures that could present creep, choosing a composition of sodium bentonite, cement and water, which, in turn, were in the range of strength established for soft rocks (Cañizo et al., 1976, Leung & Ko, 1993 and Nishimura, 2016). Cylindrical specimens of 70 mm diameter were made with several dosages and were tested under uniaxial compression at different ages (see Table 2) to know their strength and workability.

Table 2. Uniaxial compressive strength results in samples of rock-like material at different ages

Sample	Age	σ_c	Moisture
	days	MPa	%
B1 / B2	10 /10	0.6 / 0.1	104 / 151
	42 / 41	1.0 / 0.3	64 / 79
	91 / 92	1.3 / 0.3	70 / 109

B1 (bentonite: 20 %, cement: 30 %, water: 50 %), B2 (bentonite: 15 %, cement: 25 %, water: 60 %)

Due to the sodium bentonite content, which induces a delayed evolution on the cement setting, an increase of the strength properties of the blocks with time was foreseen. For this reason, the creep tests begin when the samples have been curing in a humid chamber, needing at least 90 days. It was decided to add sodium bentonite to the mixtures because it is commercial clay with rheological properties and provides good workability when making blocks of large dimensions. After experimentation in small dimensions, the selected dosage for the largest artificial rocks was 50 % water, 30 % cement (CEM II / BL 32.5 N) and 20 % sodium bentonite, due to that with these quantities the desired strengths (around 1 MPa) were reached after their stabilization in time. In order to ensure adherence between the adhesive and the rock-like material created, it was decided to use the dosage of sample B1 foreseeing a less detachment of material during vertical drilling, which would complicate the cleaning tasks of this, as well as a better adhesion with the resin, which, if the B2 dosage of lower consistency had been chosen.

3.2 *Manufacturing process*

Specimens with a diameter of 70 mm and a height of 300 mm have been manufactured simultaneously with the blocks of large dimensions for the geotechnical characterization of the rock-like material. The elaboration process of large dimensions samples (745 x 550 x 310 mm) and of the specimens can be summarized in the following steps:

1) Obtaining the necessary materials: concrete mixer with a maximum capacity of 100 l, plastic cubes, internal electric vibrator (needle), PVC moulds for specimens with a diameter of 70 mm and a height of 300 mm, compacting rod for manual vibration, quantities for the mixture (sodium bentonite, cement and water), weighing containers, mixing blades and support with pouring and weighing.
2) Grease the PVC moulds with oil to facilitate the extraction of the specimens, after curing, without disturbing them.
3) Choice of the thickness of each layer for the manufacture of the block by conditioners of EN 12390-2 Standard. Also, with the aim of achieving the greatest possible homogeneity in the anchored depth.
4) Pouring the solid mixture (bentonite and cement) by depositing it slowly inside the concrete mixer in operation with water (Fig. 3a). This process has been selected after several pour tests in which the result was not the desired in terms of homogeneity.
5) Pour over the cube (Fig. 3b) and continuously vibrate with a needle following the recommendations of EN 12390-2 Standard (Fig. 3c).
6) Four moulds are filled with the final mixture and are manually vibrated using the metal rod.
7) Setting and curing in a humid chamber. Plastic is placed over the first few hours of setting to prevent water from falling from the fogging nozzles of the camera. Next, the plastic is removed, leaving the block uncovered and in a humid chamber for 72 hours (Fig. 3d). After this period, the blocks are very consistent and the surface is completely dry. At that time, the cubes are flooded with water and the specimens are also immersed in water (without extracting from the moulds but removing the lids, by similarity with the curing process of the block).

Figure 3. (3a) Optimal mixing process; (3b) pouring of the first layer; (3c) appearance after the vibration of the first layer; and (3d) final appearance after 72 h of setting in a humid chamber.

3.3 *Geotechnical characterization of the samples*

With the aim of identifying and knowing the strength and deformation behaviour of the rock-like materials tested in large dimensions, the following tests have been carried out: uniaxial compression strength (UCS), consolidated undrained triaxial (CU Triaxial) and propagation velocity of compressive waves (V_p). As can be seen in Table 3, the tests are carried out both with specimens manufactured at the same time as the blocks and with cores samples extracted from said blocks, to ensure the representativeness of the samples given their undisturbed condition.

Table 3. Results of geotechnical characterization tests carried out with saturated samples

Block	Type	Nº	Age	$\rho_{sat.}$	w	UCS		CU Triaxial		V_p	
						σ_c	G_u	$\sigma_{1f.}$	G_u	V_p	G_u
			days	Mg/m^3	%	MPa	MPa	kPa	MPa	m/s	MPa
1	S	2	130	1.38-1.51	88-90	1.3-1.8	130-210	-	-	-	-
	C	4	214	-	76-90	0.7-1.6	-	-	-	-	-
2	S	2	145	1.01-1.68	51-75	1.7-2.4	130-243	-	-	1927	2079
	C	2	251	1.50	87-91	1.4-1.8	67-100	-	-	1911	1802
	C*	3	256-468	1.48-1.50	87-88	-	-	1795-2063	33-57	-	-
3	S	1	244	1.55	92	2.0	233	-	-	1966	1949
	C	5	244	1.53-1.54	91-92	1.4-2.1	77-103	-	-	1852-2089	1749-2226
	C**	9	256	1.45-1.56	91-93	-	-	1649-2018	33-57	-	-
4	S	4	49-173	1.44-1.54	91-99	1.8-2.9	140-213	-	-	1959-1981	2015-2046
5	S	3	49-263	1.43-1.55	91-92	1.7-2.5	167-420	-	-	1990-2115	2046-2192

S, specimens manufactured at the same time; C, cores samples extracted from blocks (diameter = 53.4 mm and ratio height/diameter > 2); C*, cores samples (diameter = 36.6 mm and height = 76.0 mm); C**, cores samples (diameter = 36.6 mm and height = 81.8 mm).
σ_3, applied confining pressure (ranged from 49 to 294 kPa); σ_{1f}, vertical total stress on failure.
G_u, undrained shear modulus; G_u (CU Triaxial): considering a 10% of $\sigma_{1f.}$ at failure curve of the test; G_u (V_p): for very small strains, dynamic modulus.

4 TEST PROCCEDURE

The steps of the test procedure can be summed as following:

1) Remove the water until approximately the depth of the anchor, during at least 48 h, to facilitate the curing process of the adhesive that will be injected later. Place the structure on the sample fixing the sides with a layer of cement and sand of approximately 2 cm thick. A plumb line is used to verify the approximate centre of the sample and the structure is levelled on the X and Y axis (Fig. 4a).
2) Drill 12 mm diameter with a rotary drill to the desired depth. Afterwards, the drill hole is dried and cleaned with air under pressure by means of a nozzle and with a specific cleaning brush. Inject the high strength adhesive allowing it to harden for a minimum time of 48 h. The 10 mm metric stainless steel threaded rod is inserted, rotating it for better adhesion with the resin (Fig. 4b)
3) Add water until the sample is slightly covered without exceeding the metal profiles placed at the displacement registration points. Place the wiring, the bar for the weights and the dial gauges (Fig. 4c) according to the scheme of Figure 2.
4) Creep test. Dial indicator zero reading is taken, before proceeding with the first loading of the anchor. During the tests, three consecutive loading steps have been applied, which constitute a percentage of the uniaxial compression strength (10, 15 and 20 %, known to be related to the pull-out strength), previously estimated with cylindrical specimens. During the steps the constant load is maintained in variable periods of time depending on the evolution of the movements, increasing the load when stabilization of these is observed. Finally, the anchor is loaded until failure. Taking advantage of the mobility characteristics of the equipment and the large dimensions of the tested blocks, ultimate pull-out tests have been carried out, at points spaced from the centre or on the other side of the blocks, after the creep tests. Thus the pull-out force after having subjected the sample to a constant load can be compared with the instantaneous pull-out force.

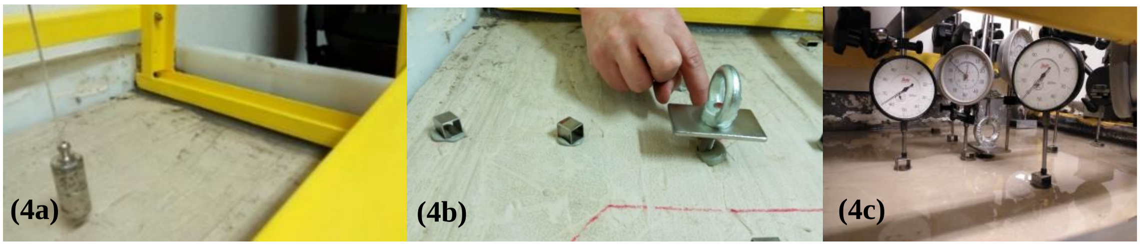

Figure 4. (4a) Detail of the plumb line and levelling layer; (4b) placement of the anchor and profiles; and (4c) detail of dial gauges and water level.

5 TEST RESULTS AND ANALYSES

5.1 *Creep tests*

Following the procedure described in the previous section, the creep tests have been carried out. In order to synthesize the amount of recorded data, blocks 2, 4 and 5 (Table 3) have been represented in Figure 5. The displacements with time of the circular crowns indicated in the scheme of Figure 2 of whose points are expected similar movements, as well as the displacement of points 5 (central) and 6 (anchor) independently are presented. Figure 5 also includes photographs of the two main failures obtained in our experiments.

The initial instantaneous displacement, under a load equivalent to 70 kg of mass, has varied between 0.05 and 0.11 mm for the central point, and between 0.04 and 0.09 for the crown A. The greater creep displacements occur mainly in the crown of points closer to the point of application of the tension. Being said creep displacements, accumulated at the end of the step of 150 kg, variables between 0.01 and 0.12 mm. Deferred movements are observed between the central point and the anchor point in all the tests, which could be due to failures in the adhesive-rock bond.

The pull-out strengths obtained at the end of the tests and in additional pull-out tests have varied between 980 and 1115 kPa, values according to the limits between clay of rigid consistency and soft rock, as shown in Table 1.

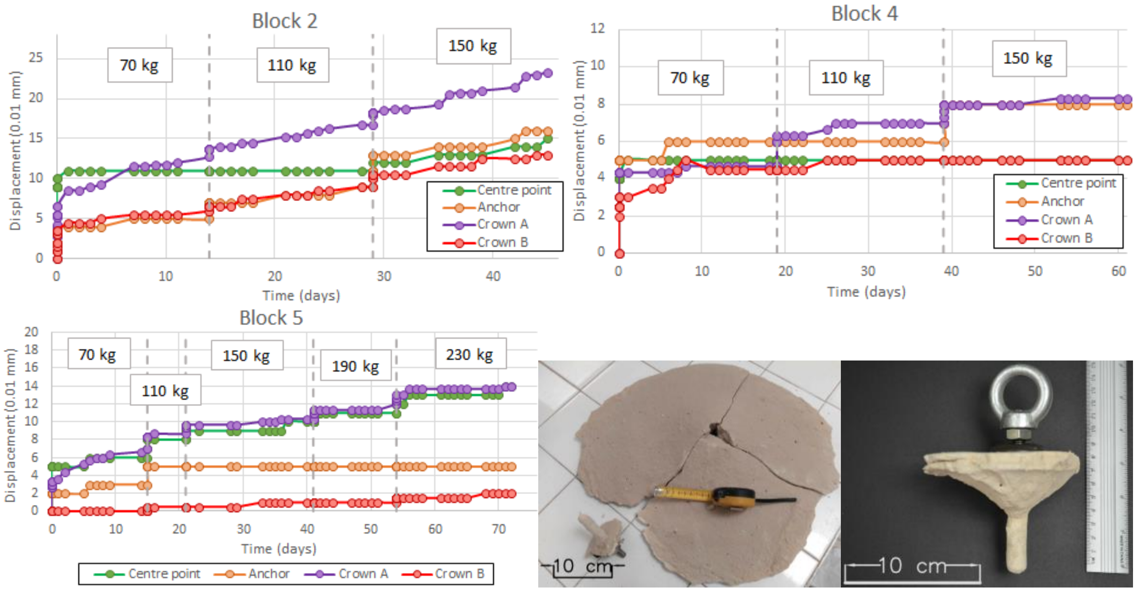

Figure 5. Results of the three creep tests and examples of types of obtained failures.

5.2 *Analytical model for instantaneous displacement*

In order to validate the results of the proposed test, the use of Mindlin analytical formulation (1936) is proposed to find the instantaneous settlement due to a force (T) inside a semi-infinite medium. For the defined boundary conditions, Justo (1993) proposed the analytical solution produced by a constant pressure on a circular area, being able to obtain the instantaneous movement of the anchor (u_a) depending on the diameter of the anchor (D_h), of a coefficient of influence (I_j) and the elastic properties (v, G):

$$u_a = \frac{T}{2\pi D_h^2 G(1-\nu)} I_j \tag{2}$$

Figure 6 shows the results estimated according to the analytical formulation applied to the developed equipment. The undrained shear modulus obtained from the different developed tests (Table 3) are also included in this figure. The observed variability of the shear modulus depending on the test considered is an empirical verification of the scale effect. Thus, it is expected that larger dimensions tested result in a lower values of the deformation modulus, which is confirmed in said figure (13 to 20 cm large specimens have been used for the wave velocity tests while in the proposed test the anchor length is only 7,5 cm).

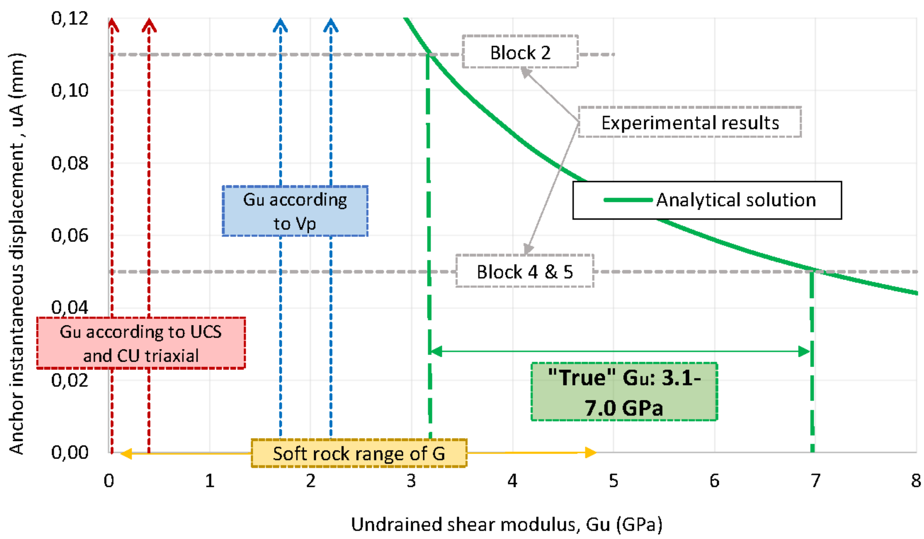

Figure 6. Variation of the instantaneous displacement as a function of the shear modulus.

6 CONCLUSIONS

Based on the experience acquired during the developing of the proposed equipment and the testing of the manufactured samples, the following conclusions can be drawn:

- A loading frame was specifically designed for samples larger than 750 x 550 mm. Simple equipment has been designed, being exclusively mechanical, therefore, very suitable for the study of deformations of adequate precision in the long term under constant load. The equipment allows to immerse the sample in water and maintain its saturation. The mechanical and geometrical characteristics of the equipment are based on previous theoretical and experimental investigations and the test procedure to be followed has been defined, confirming its correct functioning.
- The test enables measuring displacements under constant load during long periods of time (up to 75 days in the presented experiments) both in the rock sample and in the steel bar.
- The results of the tests guarantee its reproducibility. Considering scale effect, an adequate contrast results between the instantaneous displacement obtained with the test and the obtained with the analytical solution under the same boundary conditions.
- The types of failure observed during the pull-out tests agree with experimental and theoretical forms obtained by other authors, in addition to providing values of pull-out strength within the margins established for the type of rock tested.

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