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Technical Note

Field measurements of anchored flexible systems for slope stabilisation: Evidence of passive behaviour.

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Abstract

Flexible systems anchored to the ground constitute a technique for slope surface stabilisation. They are formed by membranes (cable nets, wire mesh, ring net), reinforcement cables and bolts tightly anchored to the ground forming regular patterns. Most manufacturers and independent researchers assume active behaviour of these systems when they propose their design models, which means that the system avoids occurrence of instability. To consider active behaviour, two conditions have to be fulfilled: the membrane has to be initially prestressed and the slope must present a convex shape. Neither of these two conditions has been verified so far, therefore, there are no guarantees that current design methods are adequate. Review of the technical brochures of manufacturers shows that applied prestress force on membranes and reinforcement cables is nonexistent or very low.

In this paper, three field systems in north Spain with cable nets anchored to the ground have been instrumented. Net cables, reinforcement cables and bolt heads have been instrumented by using sensors based on electrical extensometry. Tensile forces on cables and compression forces on bolt heads have been monitored for more than a year from the beginning of installation. Initial tensile forces in net and reinforcement cables induced an average value of 0.7 % and 2.1 %, respectively, of the ultimate strength of each component. In relation to bolts, average compression force on bolt heads was 5.3 % of their ultimate strength.

These measurements demonstrate that prestress force on flexible systems is very low, and nearly negligible. Therefore, flexible systems anchored to the ground cannot be considered as active, but passive, which means that most current design methods are not adequate.

Keywords

Slope stabilisation; cable nets; wire meshes; passive systems; active systems; instrumentation.

1.- Introduction

Flexible systems anchored to the ground constitute a technique for slope surface stabilisation. These systems are formed by membranes, made of cable nets, wire meshes or ring nets, bolts anchored to the ground and reinforcement cables forming regular patterns. This technique has spread extensively due to its low visual impact and its minimal influence on traffic during installation.

Flexible systems may be classified as either low or high resistance systems. A low resistance system is generally formed by a triple torsion wire mesh manufactured with standard steel (ultimate strength ≤ 400 MPa) and anchored to the ground at a few points through bolts, allowing material to slide due to a loose contact between membrane and slope surface. The main application of this system is to work as a curtain, preventing small rock pieces from getting to the road after detachment by steering them along the slope surface till the ditch. As for high resistant flexible systems, these are formed by a cable net, single torsion wire mesh or ring net presenting a relatively more closed and rigid contact with the slope surface, and manufactured with medium to high-resistance steel (ultimate strength ≈ 600-1,700 MPa). The main application of these systems is to avoid soil sliding or rock detachment in slopes by exerting a normal pressure to the ground, p, which prevents occurrence of instability by increasing internal shear resistance in the sliding plane. This pressure p is apparently due to a prestress force applied to the membrane and reinforcement cables during installation, which finally induces the stabilisation effect. Manufacturers and some researchers refer to this behaviour as *'active'* (see Figure 1).

Low-resistance flexible systems were first used in the 50s (Peckover and Kerr 1976), while high-resistance ones appeared in the 80s (Justo et al. 2009). As a rough estimation, around 1,000,000 m^2 of high-resistance flexible systems could be placed yearly throughout the world nowadays. Although the use of flexible high-resistance systems has generalised throughout the world, only one official technical document has been found to guide the design and calculation of these systems (Phear et al. 2005). Moreover, there are few scientific references tackling the topic of design methodology except for those of the manufacturers of cable nets and high-resistance wire meshes themselves, and two PhD theses by independent researchers from the University of Cantabria (Castro Fresno 2000; Da Costa García 2004).

Only two field monitoring studies have been found in the bibliography, one in the USA (Shu et al. 2005; Muhunthan et al. 2005) and another in Italy (Bertolo et al. 2009). In none of these studies was initial prestress force on the membrane measured, so there are no references on the prestress force applied in the membrane systems themselves.

In the USA, vertical slings on top of the slope were fitted with strain gauges. The research was promoted by the Washington State Transportation Centre. The aim was to try to find some correlation between data recorded (voltage output in strain gauges) and snow events, rainfalls, and temperature. Gauges were placed on slings some years after installation, so there are no records of initial pretension of the flexible system. The membrane itself and bolt heads were not instrumented.

The second study was carried out in Italy by the University of Turin and the manufacturer Maccaferri. An in situ test device to apply a point load was installed in field with a cable net anchored into a rock slope. The test device consists of a jack embedded in the rock matrix that was able to exert a point load on the midpoint of a panel. Forces on reinforcement cables, bolt heads and displacements at the midpoint panel of the wire mesh were measured, for different loads applied. However, forces on net cables were not measured. The initial tensile force on reinforcement cables was 3 kN approximately.

Most manufacturers and independent researchers assume active behaviour of these systems when they propose their models. Most models found in the bibliography are analytical, except for two attempts at performing a numerical simulation (Da Costa García 2004; Luis Fonseca 2010) but without realistic solutions. In most existing models limit equilibrium analysis is considered with a particular failure mechanism, either wedge shaped or infinite slope. A uniform pressure p normal to the ground is calculated so that it increases the normal effective stress on the slope surface and therefore the shear resistance between potential sliding surfaces. However, the hypothesis of active behaviour has not been demonstrated by any company, designer or independent researcher. Two main conditions must necessarily be satisfied by a flexible system in order to be considered as active:

- The membrane has to be initially prestressed with a known tensile force T, which depends on stabilisation pressure p and slope curvature.
- The membrane (and therefore slope surface) should present a convex shape, either catenary, circumference or parabola.

Field visits and review of photographic databases show that there is no real control on prestress force applied to membranes. In addition, the slope generally has a flat surface geometry or is even concave, buy rarely convex.

The main problems found regarding all the information collected at the initial stage are:

- The prestress force on membranes (cable net, wire mesh or ring net) has not been measured on site.
- Most existing models assume active behaviour of high-resistance flexible systems, while this main assumption has not been demonstrated so far.
- If high-resistance flexible systems are not active, most existing design methods are incorrect, leading to human risk in some cases or to unnecessary costs in others.

Therefore, the main hypothesis of this research work is:

– High-resistance flexible systems must be considered as passive systems, rather than active ones. Hence, the system only retains the unstable mass after the sliding has already occurred.

Accordingly, the objective of this article is:

– To measure the real forces on flexible systems in different field locations.
– To revise installation procedures from different manufacturers in order to extrapolate conclusions from those field systems instrumented.

2.- Description of the systems

In this section, a complete review has been done of the majority of flexible systems existing on the market. Seven different companies which sell their products all over the world have been included (Iberotalud, Geobrugg, Macaferri, Tubosider, Saggam, Avaroc, Inchalam).

All of them present common elements, such as a non-continuous membrane, reinforcement cables and bolts. The main differences among some systems others are the type of membrane, the connection between rolls or panels, and the pattern formed by reinforcement cables and bolt arrangements (square, rectangular, rhomboidal, only rows, etc). In order to simplify the description of the installation procedure, three main types have been defined and briefly described according to the bibliography reviewed, which are: cable nets, wire meshes and ring nets.

2.1 Cable nets

This type is fabricated by most manufacturers. It includes the following elements:

– Wire mesh: triple torsion fabricated with low resistant steel. Its function is to reduce the net grid spacing to prevent detachment of small fragments of soil or rock. It is not considered to provide any additional resistance to the overall stability. It is the first element installed.
– Cable nets: manufactured with braided 8 to 10 mm galvanised steel cable that forms a weave of grids from 200 to 300 mm. The cables are fixed at the intersection points of the net weave by staples. Cable nets are usually provided by manufacturers in square or rectangular panels of different dimensions, with sides varying from 2 to 6 m.

- Reinforcement/sewing and perimeter cables: employed to join net panels, fit the net to the ground and make the system rigid through connection with the central bolts and anchors of the perimeter cable. The diameter size depends on the manufacturer, but varies from 8 to 20 mm. Reinforcement cables are horizontally and vertically distributed, forming a square or rectangular pattern of 2 to 6 m, knitting the cable net panels. At the intersection points of the horizontal and vertical cables, they are fixed by bolts to the ground along with the membrane by a spike plate and a screw. The perimeter cables enclose the outer area of the zone to be stabilised.
- Bolts: they are placed at the crossing points of the reinforcement cables.
- Cable anchors: they are used at the edge of the zone to be stabilised to brace and tense the perimeter cables.
- Spike plate: to attach the intersection of the net cables and reinforcement cables to the ground by a nut thread in the bolt, which is placed above the plate.

After setting the triple-torsion mesh in place, the net is installed. During the installation process, the cable net panels are laid from the top of the slope to the bottom. The panels are fixed to each other generally by sewing cables, but sometimes also by clamps, depending on the manufacturer. At the corners of the panels, some perforations are made where the intermediate bolts will be placed. A small depression is made around the perforation, so that the reinforcement cables have a slightly convex shape around the bolt. Additionally, tensed reinforcement cables are placed vertically and/or horizontally before tightening the intermediate bolts. When using sewing cables between panels, they also generally work as reinforcement cables, too. The next step is to tense the perimeter reinforcement cables outwards, which helps to prestress the net. This process of tensing is performed both for horizontal and vertical reinforcement cables. Finally, the internal bolts are tightened, attaching the net to the ground in the depression around the bolt, contributing to an additional membrane prestress force.

2.2 Wire mesh

High-resistance wire meshes anchored to the ground are composed of the following elements:

- Wire mesh: generally employed a simple torsion mesh, manufactured with medium (≈600-1000 MPa) to high-resistance steel (>1,600 MPa). They generally form squares or rhombi with variable dimensions and sections. They are provided in rolls instead of panels.
- Clips: certain manufacturers use this element to join rolls of wire mesh and to give continuity to the membrane.

– Sewing cables: it is another alternative for joining rolls, instead of clips. If used, they also work as reinforcements cables.
– Reinforcement cables: depending on manufacturer, they can be placed in horizontal rows or both horizontal and vertical lines.
– Spike plates: they fix the mesh to the ground through a screw thread in the bolt.
– Perimeter cables: the perimeter cables enclose the outer part of the zone to be stabilised, although they are not always used.
– Bolts: bolts (GEWI piles or similar) are arranged in rows and columns with a constant separation, but patterns of square panels are not desired. They are used both for the internal zones of the mesh and the outer perimeter.
– Cable anchors: used on rare occasions on the perimeter.

The system installation process is very similar to the cable net, except that reinforcement cables are not always employed, and when used, they are only placed in horizontal arrangements. Another difference is the attachment between rolls: instead of vertical reinforcement cables, clips are used to attach mesh rolls. For this type of membrane, triple torsion wire mesh is not placed, regarding the small gap of the main membrane.

2.3 Ring nets

Ring nets anchored to the ground are only manufactured by two companies and their applications in field are very rare. However, their description has been considered in this article in order to offer a complete overview of all typologies. They are composed of the following elements:

– Wire mesh: triple torsion fabricated with low-resistance steel. Its function is to reduce the net grid spacing to prevent detachment of small fragments of soil or rock. It is not considered to provide any additional resistance to overall stability. It is the first element installed.
– Ring net: constituted by interconnected rings that form a non-continuous membrane. Each ring is composed by various twirls of one only steel wire of high-resistance steel. The ring wires are finally fixed through clamps or through the wire itself enveloping the whole ring section. Ring net is usually supplied in panels.
– Sewing/reinforcement cables: used to join panels. They can also work as reinforcement cables.

– Spike plates: they fix the mesh to the ground through a screw thread in the bolt.
– Perimeter cables: the perimeter cables enclose the outer part of the zone to be stabilised, although they are not always used.
– Bolts: bolts (GEWI piles or similar) are arranged in lines and columns with a constant separation, forming square or rectangular panels. They are used both for the internal zones of the mesh and the outer perimeter.
– Cable anchors: used on rare occasions on the perimeter.

The system installation process is very similar to the cable net.

2.4 Common aspects

All systems include a flexible membrane, bolts and reinforcement cables. In any case, the flexible membrane does not resist bending moments, only tensile forces. Tightening force on bolts is generally applied with a torque wrench by an operator. Reinforcement cables are always placed in horizontal rows, and are sometimes set up with vertical reinforcement cables too.

In none of the systems is the prestress force applied on either membrane or reinforcement cable calculated or controlled during installation. Only one of the manufacturers established in their technical brochure that the force applied on the bolt head is around 50 kN (Geobrugg Ibérica 2008); however, this is more an approximate value rather than an exact one, since the torque force is not systematically controlled on site.

3.- Methodology employed

Forces on the membrane (cable net typology), reinforcement cables and bolts have been measured. The sensors used are based on electrical extensometry technology.

To measure the forces on cables, special sensors have been found on the market to fit in cables without cutting them. These sensors are generally used as a load capacity alarm in lift cables. Figure 2 and Figure 3 show sensors used for net cables (8 mm diameter) and for reinforcement cables (16 mm diameter) respectively. When a sensor is set up in the cable without any initial force, the cable adopts a triangular shape, since its supports and removable flange are not aligned. When a tensile force is applied to the sensors, the cable becomes aligned so it forces the sensor beam to bend. Internal strain gauges on the top and bottom internal faces measure the deformation. Each sensor is calibrated in order to obtain an individual curve relating tensile force on the cable versus electrical signal of strain gauges.

For the measurement of the tightening force on bolts, special load cells have been specifically designed and fabricated by the corresponding author and installed in Carmona. These load cells consist of a hollowed cylinder with strain gauges in four generatrixes. Strain gauges are connected in a Wheatstone Bridge circuit in order to cancel out bending moments and temperature changes, and also summing up axial deformation to increase the signal (see Figure 4). Therefore, the load cell is able to measure axial loads applied in the axis direction of the bolt. Individual calibrations had been performed in order to obtain the relationship between axial load and electrical signal output from strain gauges (mV/V). In Torazo, commercial load cells were acquired from the same provider as the cable sensors, in order to save time.

The sensors are connected in commercial data acquisition equipment (model DEWE 801, from Dewetron) that includes an amplifier, signal filter, a digital card and an integrated computer.

Periodic measurements have been recorded on site, bringing the data acquisition equipment to site each time and recording the data. Performance of continuous measurement by leaving the equipment in each place was ruled out because of the prohibitively high cost this would involve. In order to take into account possible drift errors, a portable sensor with no load was connected at the beginning of each data collection campaign in order to record initial drift data.

Accuracy errors in sensors were approximately 1 kN for the type 5000 sensor (Figure 2), 3.2 kN for the type 16000 sensor (Figure 3) and 5 kN for the load cells (Figure 4). Therefore, some of the recordings were occasionally negative, which means that the real load on that component was very low or null. Figure 5 shows a typical arrangement of sensors on a cable net anchored to the ground.

4.- Data records

Three different cable nets installed in field have been instrumented in order to measure the forces on flexible systems from the beginning of the installation. The three instrumented systems were located in the north of Spain: Puente El Arrudo (Cantabria), Carmona (Cantabria) and Torazo (Asturias).

Three main reasons motivated the decision to select cable nets instead of wire meshes for instrumentation. Firstly, cable nets are much more widely used systems than high-resistance wire meshes or ring nets. Secondly, the installation procedure of the different systems (cables nets, wire meshes, ring nets) does not differ substantially. Lastly, specific economical and reliable sensors for measuring base lengths of 200 mm were available on the market.

4.1 Puente El Arrudo

Puente El Arrudo is a 5 m high rock outcrop formed by limestone strata and clay filled joints (see Figure 6). Only net and reinforcement cables were fitted with sensors in this specific place.

Table 1 shows the records from the beginning of the installation of the system and for more than one year. Some irregular values taken on 15/06/2007 were detected due to a mistake in the zero setting; therefore, those values were not considered. The recording taken on 17/04/2008 was considered to be representative of the initial prestress force (1^{st} recording) on the system, regarding the anomaly in the previous recording. The 1^{st} recording (17/04/2008) shows that the maximum tensile force on net cables (type 5000 sensor) reached 1.7 kN, while in the reinforcement cable (type 16000 sensor) this force was 4.8 kN. Subsequent recordings did not show a significant difference in relation to the first one. Negative values are related with the accuracy error on sensors, therefore, a very low or null value should be considered in those particular cases.

4.2 Carmona

Carmona is an 80 m high slope with an average inclination of 60º formed by sandy soil (see Figure 7). Net cables, reinforcement cables and bolts were fitted with sensors.

The first recordings in Carmona (Table 2, 04/04/2008) show a maximum tensile force of net cables and reinforcement cables of 1.1 kN and 7.3 kN respectively. Maximum compression force on bolt heads (load cell sensor) was 35 kN. Subsequent recordings did not show a relevant variation.

4.3 Torazo

In Torazo, two independent slopes with a separation of around 100 m were fitted with sensors. The first one (Location 1) is a 6 m high slope with a varying inclination (see Figure 8). The second field (Location 2) has a slope of 15 m high with an increasingly sloping angle from 45º to 90º (Figure 9). In both cases the material is a soft sandy rock. Net cables, reinforcement cables and bolts were fitted with sensors.

During the first recording in Torazo (Table 3, 19/08/2009), maximum tensile force on net cables and reinforcement cables reached 2.1 kN and 6.3 kN, respectively. In the first recording bolt heads reached 23.4 kN (Table 4). In the last recording (14/12/2010) of load cells, there was a substantial increment, reaching 97.9 kN of compression force. This was presumably due to the beginning of sliding that mainly affects bolts rather than the net or reinforcement cables. The first recording in Torazo of load cells and cable sensors did not match because there were some irregular measurements in the load cells, which had to be returned to the manufacturer for repair.

5.- Discussion of results

Ultimate strength in net cables is around 50 kN, while in reinforcement cables this force could reach up to 160 kN. Maximum compression force on bolts is around 270 kN. The first recording, which represents the prestress effect applied to the system during the installation process, shows very low values.

Table 5 shows a summary of the initial prestress force applied to flexible system components, according to the recordings of the in situ instrumentation. Minimum, maximum and average values have been shown. Negative values have been assumed to be equivalent to null forces. The table shows both absolute values (kN) and also relative values in relation to ultimate strength, f_{ult}. Average values for net cables, reinforcement cables and bolts were 0.37 kN, 3.29 kN and 14.35 kN, which represent 0.7 %, 2.1 % and 5.3 % of the ultimate strengths, respectively.

It has to be remarked that sensors installed on either net cables or reinforcement cables are able to detect substantial load increments when the membrane undergoes remarkable deformations. During the earliest stages of a slip circle or a wedge rock, shear displacements on the sliding surface are of only a few millimetres. In this situation, displacements on the slope's external face are nearly negligible, and therefore, the membrane is hardly affected by those displacements.

These findings demonstrate that cable nets anchored to the ground have a very low prestress force.

Regarding the review carried out of technical brochures from different manufacturers, it can be stated that they all essentially employ the same installation procedure. Therefore, these results can be extended to any kind of flexible system, either cable net, wire mesh or ring net.

This confirms that the initial prestress force on system components is very low and nearly negligible, therefore, high-resistance flexible systems cannot be considered as active.

The main consequence to this finding is that current design methods are not suitable, since they assume passive behaviour (Blanco-Fernandez et al. 2011).

6.- On site performance vs. design: pressure comparison

The aim of this section is to compare the designed pressure transmitted to the ground by the flexible system versus the real one applied according to the instrumentation records. To perform this comparison, the real force applied by the system to the ground has been calculated based on the deformed shape adopted by the system and considering the instrumentation records. In relation to the designed pressure, technical manuals of two different manufacturers have been studied to select the pressure that their systems are intended to apply to the ground. Other manufacturers' manuals do not show any data concerning designed pressures of their products.

The real deformed shape of flexible systems has to be considered in order to calculate the real force that they transmit to the ground. The real shape may vary from one slope to another; however, a typical arrangement is shown in Figure 10. It is considered that cable net is generally flat over its whole extension, except around the bolt where it is convex. This convexity is due to the depression around the bolt created during drilling. An average depth of around 10 cm has been assumed for that depression. The convex shape adopted by both net cables and reinforced cables is assumed to be defined by a parabola of base length L and a distance from vertex to parabola base f. Depending on this convexity, the net and reinforcement cables can apply an even force per unit length, p, to the ground. The total force applied can be calculated from the following expression: $F = pL \approx 8T/\sqrt{(L^2/f^2)+16}$. Force T represents the initial tensile force applied to either net cables or reinforced cables. A base length L of 50 cm and a value of 30 mm for the parameter f are assumed.

It has been assumed that around a bolt there are 4 net cables and 4 reinforced cables that can adopt the convex shape, and thus, exert a certain pressure on the ground. According to this deformed shape assumption, a total force per cable around each bolt can be calculated. It is also necessary to determine the angle of application of this force. According to the geometrical assumptions shown in previous paragraphs, the angle that the force F forms with the bolt axis direction is approximately 11º (Figure 10).

There are two different mechanisms to transmit the force from the flexible system to the ground. If the depression around the bolts is not very great (around 10 cm), the torque applied on the bolts will first deform the membrane and the reinforcement cables until the spike plate touches with the ground (Figure 11-Case 1). Then, if the application of torque continues, the spike plate will start exerting an additional pressure on the ground.

The second mechanism takes place when there is a deep depression around the bolts (Figure 11-Case 2), hence the torque on the nut will be transmitted to the spike plate and then mainly to the reinforcement cable by exerting a tensile force T. This force T, considering that the cable has a convex shape, will be transmitted to the ground as a distributed pressure p. In this situation, the spike plate is not in direct contact to the ground.

However, in any transmission mechanism, the total force recorded in the bolt head will finally be fully transmitted to the ground. Nevertheless, the real situation is better described by the working mechanism shown in Figure 11-Case 1, according to records in sensors and field visual inspections.

Table 6 shows the forces applied by each type of component to the ground (net cable, reinforcement cable, spike plate) and also the total force applied by the whole flexible system. Average values extracted from Table 5 have been considered to compile Table 6. Force T is the average recorded tensile force on each type of cable, p represents the force per unit length (50 cm), F the total force applied by each type of cable, F_n is the total force in the direction of the bolt axis and, finally, $F_{n/bolt}$ is the sum of forces applied by 4 cables of the same type around one bolt. In relation to the forces applied by bolts, according to the instrumentation recordings, these have an average value of 14.35 kN. The force recorded in bolt heads represents the total force applied by the whole system to the ground. The force applied to the ground exclusively by the spike plate can be calculated by subtracting forces applied by cables from the total force recorded in the bolt head.

The most significant factor in the whole system performance is the total normal force applied by the whole system, which reaches an average value of 14.35 kN per bolt, which coincides, as explained in previous paragraphs, with the average load recorded in bolt heads.

In relation to the forces that the system is supposed to apply to the ground, two different manufacturers have been analysed: Geobrugg and Iberotalud.

The Geobrugg technical brochure provides a list of different pressures for different products and arrangements (Luis Fonseca 2010). Table 7 shows a comparison between pressures for different membrane arrangements (p_{DESIGN}) vs. the real ones (p_{REAL}). Typical values of horizontal and vertical separation between bolts, *Sx* and *Sy*, respectively, are listed in order to calculate p_{REAL} as the tightening force applied on bolts, 14.35 kN, divided by bolt spacing ($Sx \cdot Sy$). All values have been calculated with a safety factor of 1.0. In the most favourable case. Real pressure on site was 31.9 % of the designed pressure; while in the worst case, real pressure reached only 3.6 %.

Iberotalud , similarly to Geobrugg, provides a design table for each specific solution in their technical brochure (Iberotalud 2007). This manufacturer provides data expressed in forces, instead of pressures; so, there is no need to divide the tightening force applied on bolts by bolt spacing. Table 8 shows a comparison between design and real forces. All values have been calculated with a safety factor of 1.0. The real force applied on site was 16.5 % of the design pressure in the most favourable case and 5.0 % in the worst case.

The comparison performed in this section is only intended to provide some approximate values of the proportion of the real pressure occurring on site versus the designed pressure that manufacturers attribute to their products. Another important difference between real performance and the theoretical behaviour assumed by manufacturers is the force transmission mechanism. Manufacturers assume that the force transmitted to the ground is an evenly distributed pressure. The real situation is very different, since pressure is only applied in an area close to the bolt by the membrane, reinforced cables and/or spike plate (see Figure 11).

It was not possible to perform more comparisons between designed pressure and real pressure for other manufactures because data were not available. However, installation procedure has been studied from their technical brochures, and it can be stated that it is very similar in all cases. It is important to remark that the torque force applied to the bolt nut is done by an operator using a 0.5 m long torque wrench, which limits the total prestress force applied to the system. That tightening force applied is not generally measured by operators so there are no references about which value is applied. Only one of the manufacturers established in their technical brochure that the force applied on bolts is around 50 kN (Geobrugg Ibérica 2008); however, this is an approximate value rather than a real one, since this torque force is not measured on site.

7.- Conclusions

Three different locations with cable nets anchored to the ground have been instrumented. Sensors based on electrical extensometry, which were placed in net cables, reinforcement cables and bolt heads.

The initial tensile force in the net and reinforcement cables reached an average value of 0.7 % and 2.1 %, respectively, of the ultimate strength of each component. In relation to bolts, average compression force on bolt heads was 5.3 % of its ultimate strength.

Comparison was also made between real pressure, according to instrumentation records, and designed pressure, based on the technical brochures of two manufacturers. In the best case, real designed pressure only reached 31.9 % of the real pressure calculated, while in the worst case, designed pressure only reached 3.6 %.

Most manufactures, despite the type of system employed, recommend very similar installation procedures. The most important input of force used to produce the prestressing of the system is the torque applied on the bolt nut, which is generally very low, since it is applied manually by an operator through a torque wrench. Although instrumentation has been carried out in only one typology of flexible systems (cable net), we can extend these findings to other typologies and manufacturers.

Finally, we can conclude that initially flexible systems are barely prestressed; therefore, they cannot behave as active systems, but as passive ones. This is an important fact, since most manufacturers assume active behaviour to design their solutions (Blanco-Fernandez et al. 2011), which indicates that current design methods of these systems should be modified.

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Figures

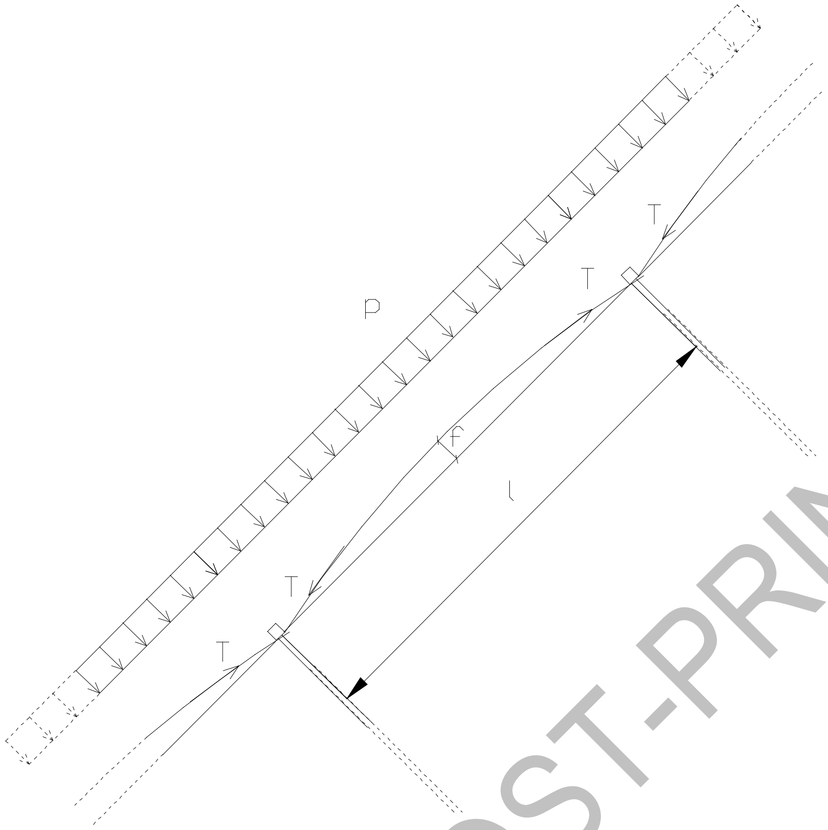
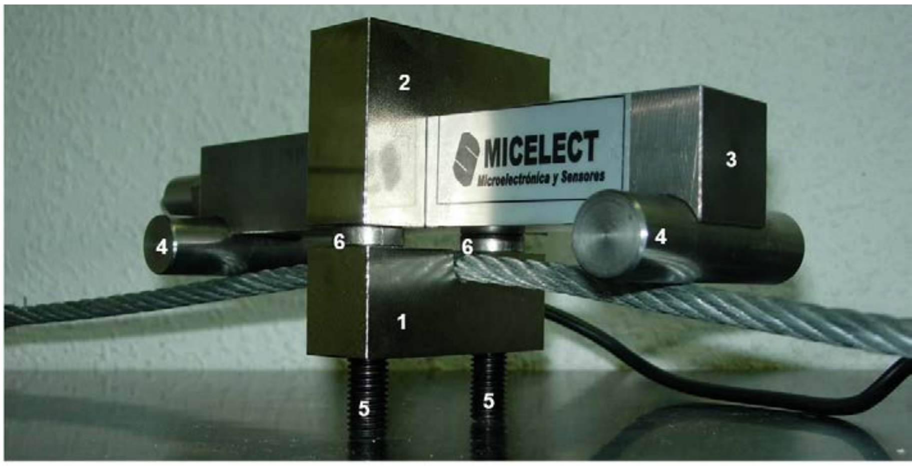
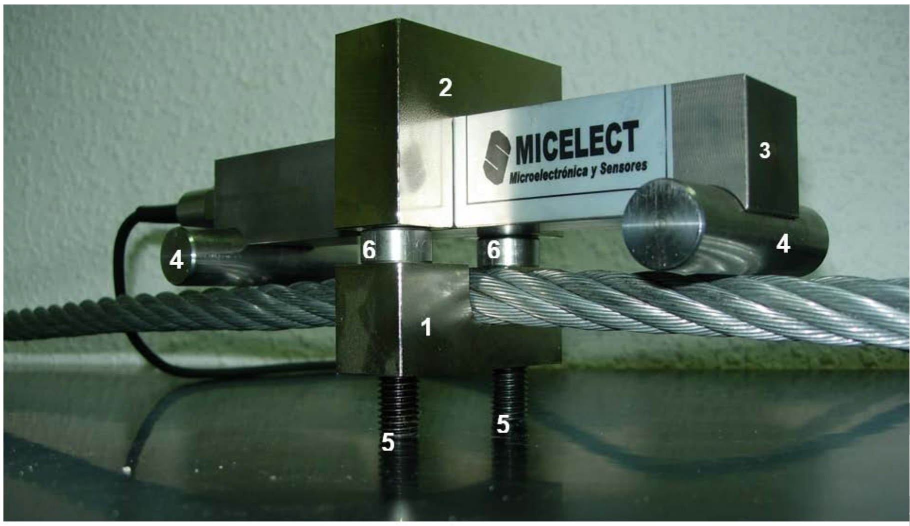


Figure 1.- Active behaviour of flexible systems. Theoretical scheme.



1: REMOVABLE FLANGE
2: BRIDGE
3: BEAM
4: SUPPORTS
5: SCREWS
6: WASHERS (3 mm thickness, for 8 mm diameter cable sensor)

Figure 2.- Sensor type 5000 (8 mm diameter cable sensor). For net cables.



1: REMOVABLE FLANGE
2: BRIDGE
3: BEAM
4: SUPPORTS
5: SCREWS
6: WASHERS (6 mm thickness, for 16 mm diameter cable sensor)

Figure 3.- Sensor type 16000 (16 mm diameter cable sensor). For reinforcement cables.

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Figure 4.- Load cells installed in Carmona. Connection of the Wheatstone bridge of strain gauges.

Figure 5.- Sensors set up in Carmona. Typical arrangement.

Figure 6.- Puente El Arrudo. Installation process of the flexible system.

Figure 7.- Carmona. Flexible system just after being installed.

Figure 8.- Torazo (Location 1). Flexible system with the sensors already installed.


Figure 9.- Torazo (Location 2). Flexible system with the sensors already installed.

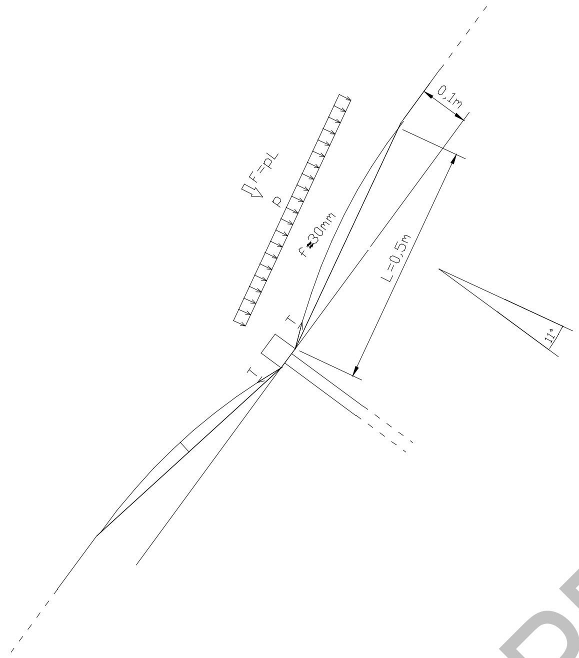

Figure 10.- Typical deformed shape of a membrane. Real situation.

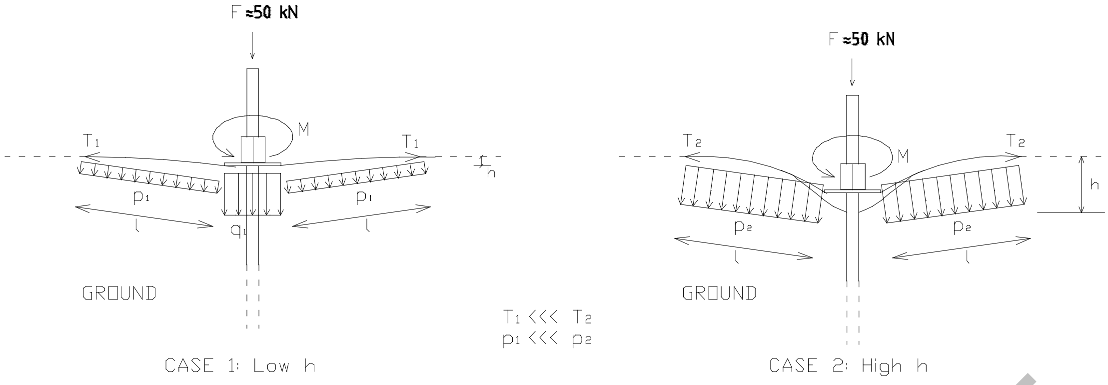

Figure 11.- Force transmission mechanisms: flexible system-ground.

Tables

Table 1.- Puente El Arrudo. Recorded data.

Measurement area	Sensor		Anomalous recording (*) 15/06/2007	1st recording 17/04/2008	2nd recording 03/07/2008	3rd recording 06/11/2008
	Type	**Nº**	**kN**	**kN**	**kN**	**kN**
1	5000	2	2.4	1.7	0.9	1.1
	5000	31	1.6	1.1	-0.4	0
2	16000	39	-0.5	4.4	2.7	-0.3
3	16000	2	1.9	4.8	3.1	1
	16000	50	1.8	2.8	2.1	-0.2
4	5000	51	0.4	0.1	1	1.4
	5000	53	-0.8	0.2	0.3	0.5
	16000	19	-0.6	2.9	1.7	1.8

(*) Anomalous recording. Values not considered.

Table 2.- Carmona. Recorded data.

Measurement area	Sensor		1st recording 04/04/2008	2nd recording 03/07/2008	3rd recording 06/11/2008
	Type	**Nº**	**kN**	**kN**	**kN**
1	CELL	1	30.6	35.3	47.9
	5000	87	0.3	0.5	0.5
	5000	92	0.5	0.2	0.1
	5000	94	0.3	0.5	0.5
	5000	95	-0.5	0.7	-0.3
	16000	40	1.5	1.6	1.3
	16000	42	6.6	6.3	6.7
	16000	46	3.5	2.8	7.6
	16000	48	3.8	4.5	4.7
2	CELL	2	35	41	47
	5000	4	0.4	3	0.3
	5000	28	0	0	0.1
	5000	43	0.1	1	1.6
	5000	60	0.4	-0.1	-0.1
	16000	16	3.7	2.2	1
	16000	21	2.8	1.6	1.4
	16000	37	1.9	2.1	2.4
	16000	38	4.4	-0.9	1.2
3	CELL	3	10.8	16.4	18.6
	5000	48	0.2	-0.2	-0.3
	5000	55	0	-0.6	-0.6
	5000	56	0	-0.9	-0.1
	5000	61	0.6	0	0.1
	16000	1	7.1	6.4	7.8
	16000	2	1.8	3.2	1.6
	16000	10	2.8	3.5	-1.7
	16000	23	7.3	4.5	4.1
4	CELL	4	8.9	10	9.8
	5000	32	0.4	-0.2	0
	5000	36	0.2	1.9	2.5
	5000	42	0	0.2	-0.7
	5000	54	0.5	1.5	1.8
	16000	5	6.3	3.2	-2.6
	16000	22	1.3	2	1.7
	16000	31	1.7	2.4	2.2
	16000	36	2.1	2	1.3
5	CELL	5	13	16.9	21
	5000	5	0.6	0.5	0.5
	5000	29	0.3	0.5	0.7
	5000	67	1.1	2.6	2.9
	5000	68	0.5	0.3	0.3
	16000	3	2.9	2.4	2.2
	16000	8	5.1	3.4	4.3
	16000	17	4.1	2.8	3.1
	16000	24	1.7	1.6	1

Table 3.- Torazo. Recorded data of net and reinforcement cables.

Location	Sensor		1st recording 19/08/2009	2nd recording 26/11/2009	3rd recording 14/12/2010
	Type	Nº	kN	kN	kN
1	5000	7	0.1	3.5	3.6
	5000	62	0.9	-0.4	-0.4
	5000	59	0.2	3.3	3.7
	5000	46	0.1	-0.2	0
	5000	49	0.2	0.3	-0.2
	5000	20	0.4	0.5	-0.5
	16000	29	2.2	2.9	1.6
	16000	15	2.7	3.5	1
	16000	26	3.8	0.3	-0.8
	16000	12	3.6	-0.5	-0.1
	16000	35	4.7	3.1	1.6
	16000	32	5.6	3	2
	16000	9	3.7	3.1	1.3
	16000	33	6.3	5.6	2.7
	16000	4	2.4	3.3	1.3
2	5000	83	-1.1	7.2	7.4
	5000	98	0.5	2.1	1.3
	5000	86	0.6	0	-0.6
	5000	89	-0.2	-0.5	-0.5
	5000	93	0.2	0.8	-0.3
	5000	96	-0.1	-0.6	-0.3
	5000	85	0.1	2.8	3
	5000	81	2.1	-0.1	-0.7
	5000	90	-0.3	0	-0.9
	5000	80	0.3	0.7	-0.7
	5000	97	0.3	0.8	0.7
	5000	91	-0.3	5.1	-0.7
	16000	45	1.7	4.6	-0.5
	16000	44	0.2	6.3	0.6
	16000	49	4	18.7	2.7
	16000	41	3.6	11.8	0.9
	16000	13	-2.3	-1.3	-1.4
	16000	43	1.2	3.4	0.3
	16000	14	1.8	5.9	1.1
	16000	11	2.1	3	-0.3
	16000	7	2.7	4.6	0.7
	16000	25	4.3	12.9	0.8
	16000	47	3	8.6	0.9
	16000	28	1	5	1.1

Table 4.- Torazo. Recorded data of bolt heads.

Location	Sensor		1st recording	2nd recording
			18/12/2009	14/12/2010
	Type	Nº	kN	kN
1	CELL	12	9.7	61.3
	CELL	13	23.4	72.5
	CELL	14	20.4	0.6
	CELL	15	17.8	17.8
2	CELL	1	12	52.3
	CELL	2	15.1	76.4
	CELL	3	6.9	8.3
	CELL	4	3.4	97.9
	CELL	5	2.9	82.3
	CELL	6	11.3	11.4
	CELL	7	11	26.2
	CELL	8	8.2	50.3
	CELL	9	9.4	76.2
	CELL	16	22.8	77.3

Table 5.- Initial prestress force on flexible system. Record summary.

	Min		Max		Average	
	kN	**% f_{ult}**	**kN**	**% f_{ult}**	**kN**	**% f_{ult}**
Net cables	0	0	2.1	4.2	0.37	0.7
Reinforcement cables	0	0	7.3	4.6	3.29	2.1
Bolts	1.1	0	35	13.0	14.35	5.3

Table 6.- Forces applied to ground by flexible system according to records.

Type of component	T (kN)	p (kN/m)	F (kN)	F_n (kN)	$F_{n/bolt}$ (kN)
[1] Net cable	0.37	0.17	0.09	0.08	0.34
[2] Reinforcement cable	3.29	1.54	0.77	0.75	3.01
[3] Spike plate ([4]-[2]-[1])	-	--	-	-	11.00
[4] TOTAL SYSTEM (*)	-	-	-	-	14.35

(*) Total system force applied coincides with the force recorded in bolt head

Table 7.- Geobrugg products. Design pressure vs. real pressure.

Product		**Sy (m)**	**Sx (m)**	**p_{DESIGN} (kN/m^2)**	**p_{REAL} (kN/m^2)**	**p_{REAL}/p_{DESIGN} (%)**
Tecco	S-5	3	3	5	1.59	**31.9**
	S-10	3	5	10	0.96	**9.6**
	S-15	2.5	4	15	1.44	**9.6**
	S-20	2.5	5	20	1.15	**5.7**
	S-30	2.5	5	30	1.15	**3.8**
	S-40	2.5	4	40	1.44	**3.6**

Table 8.- Iberotalud products. Design force vs. real force.

Grid size (mm)	Sy (m)	Sx (m)	F_{DESIGN} (kN)	F_{REAL} (kN)	F_{REAL}/F_{DESIGN} (%)
300	3	3	86.8	14.35	**16.5**
	4	4	116.2	14.35	**12.4**
250	3	3	114.4	14.35	**12.5**
	4	4	150.3	14.35	**9.5**
200	3	3	131.7	14.35	**10.9**
	4	4	185.0	14.35	**7.8**
150	3	3	206.6	14.35	**6.9**
	4	4	285.0	14.35	**5.0**