Design and Evaluation of Two Laboratory Tests for the Meshes of a Flexible Anchored Slope Stabilization System

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ABSTRACT

This paper evaluates two new tests to characterize cable nets used in slope stabilization; a concentrated load test (CLT) and a distributed load test (DLT). These tests enable engineers to obtain the stress vs. displacement graph and the maximum resistance. Both test devices and test methodology have been designed by the Construction Technology Research Group (GITECO) at the University of Cantabria.

These two tests have enabled the certification of two different manufacturers of cable nets, Geobrugg and Malla Talud Cantabria (MTC). The results showed that these tests provide representative results of the net resistance.

To verify the effectiveness of these new tests, they have been performed with various cable nets, from which homogeneous, logical results have been obtained, which are representative of the real working conditions.

When performing the distributed load test, the force was applied to a pyramid of fine gravel sacks that enabled the forces to be distributed throughout the net. With this configuration, the net was deformed, acquiring an elliptical form in the lower free area. In the concentrated load test, the force was applied through a metallic plate of 600mm diameter that deformed the net locally.

The result always showed homogeneous behaviour of the different samples tested. This allowed the test to be repeated in the same conditions several times. With the results of both tests an analysis was carried out relating the net grid, the load applied and the displacement obtained. This enabled the generation of regression functions that provided information about the resistance value and the net displacement according to the chosen grid.

KEYWORDS
Slope stabilisation, cable net, laboratory test, simulation.
1. INTRODUCTION

Recently, the use of cable nets for slope stabilization has greatly increased in the North of Spain, due to the continuous erosion produced by rain, the newly excavated slopes for highway construction and hillside stability problems.

The increase of instabilities has lead to the need to use new solutions, increasing the use of flexible systems for slope stabilization. This system has been used for the last two decades in a simple form but without certification. Recently, the greater demand for these products has also created the need to certify these systems, motivating the University of Cantabria to participate in a project focussed on the design, production and certification of cable nets.

Cable nets anchored to the ground are used over a slope when there is an unstable zone, which must be stabilized, without interfering in traffic flow and with a minimum visual impact. These nets are commonly classified by manufacturers as active or passive systems. The former means the cable net presses the soil from the moment of installation, thus preventing instabilities. Passive systems start to press the ground when the soil movement causes a force on them, so they can be considered as a palliative solution rather than a preventive one.

In active systems, the cable net must be prestressed before fixing it to the ground, and, in addition, it must be positioned over a convex area. These two conditions are strictly necessary to achieve ‘active behaviour’ of the net over the unstable area; otherwise, it is not possible to prevent slope instability, either soil sliding or rock fall. In contrast, in passive systems it is not necessary to prestress the cable net or to choose a convex area. The net performs its function by stopping and retaining material after the sliding has already started.

Cable nets systems consist of three basic elements; anchors, support cables, and nets. The basic configuration of these systems is a net made up of 8mm diameter cable, forming a grid (manufacturers provide different grid spacings: 200, 250, 285mm, etc.) by using staples at each cable intersection. Manufacturers generally supply rolls of this net of different widths: 2, 3, 4m, etc, which will determine the anchors spacing. These rolls are first anchored at the top of the slope, then they are unrolled to cover the slope, and finally vertically ‘sewn’ with 16mm diameter cable to join the strips. Now that the net is a single piece, anchor bolts (throughout the net) and anchor cable (at the perimeter) are installed, with sufficient depth in order to reach the stable substrate [11]. Horizontal cables of 16mm diameter are also installed along anchor rows. The next step is to tighten the perimeter of the vertical and horizontal cables. Finally, the set of cables that converge at each anchor bolt is fixed by means of a plate which is held tight by a nut screwed onto the anchor bolt. Depending on whether it is an active or passive system, the net is tighter (obtaining a net prestress) or less tight.
The first stage of the analysis is to find out the in-situ behaviour of an unstable slope. To represent the forces acting, some hypotheses have been assumed by the authors, based on the bibliography ([2],[4]), field studies ([9],[10],[11],[13],[14]) and experience with thousands of square metres of nets installed by the MTC Company. The general explanation of the whole mechanism is that the net can stabilize an unstable zone in five principal ways (as will be explained later on) and it can be loaded either in a distributed or a concentrated way.

The four cases sketched in Figure 1, represent the passive behaviour of a cable net anchored to the ground, either in rock or soil slopes; meanwhile Figure 2 shows the active behaviour of a net in the particular case of preventing the failure of a rock block, which is the most frequent application of active systems.

In Figure 1a, a passive system is represented, with ascending movement of the slope in the case of volume increase due to the presence of expanding clays or the change of volume due to factors that affect the solid matrix of the rock or soil [4].

Figure 1.b corresponds to a slope with surface erosion problems, where the slumped fragments may be from coarse gravel to small rock blocks. It has been observed that when the system is poorly fixed and the erosion is not homogeneous under the net (greater at the top and lesser below), this erosion generates greater bulk of eroded material and the anchors on top become visible leading to the anchors losing resistance later.

The third case of forces (Figure 1.c) represents the interaction between a net and a soil slope instability (it can be several meters deep). The slope soil that slides is stopped and retained thanks to the nets, which deforms into a convex shape.

The fourth case (Figure 1.d) shows a rock slope with instabilities in wedge form. In this case the cable net can be point loaded by the edge of the wedge or loaded in a distributed way by a face.

The active configuration (see Figure 2) is preferable to avoid any movement that generates a high tensile force that could plasticize the anchors or break the net. Additionally, the dimension of nets and anchors when performing as active systems are smaller than passive systems. In this case, the net applies a concentrated load on the rock, since the irregularity of the rock surface does not allow the net to be totally wrapped over it, and so the contact is generally at a few central points.

In some cases the net will be loaded over an extensive area and in other cases this area will be small. Based on these hypotheses, there are two configurations that can be simulated by means of laboratory tests, one being a situation of concentrated load and the second, one of distributed load. The concentrated load test was simulated by means of a steel plate that applied the force directly onto the net. In the case of the distributed load test, the forces were applied and distributed using a fine gravel sack pyramid trying to simulate the effect of distributed load [1].
2. TEST SETUP

Several tests were carried out in the installations of the University of Cantabria and in external partner companies, generating experimental results that derived in the patents of the test. These patents correspond to code P200101067 for the distributed load test and patent P200101069 for the concentrated load test.[2]

The tests presented here were carried out using nets with staples and cables from the same manufacturer, made between 2003 and 2004 [9]. The configurations used in concentrated load and in distributed load correspond to nets of approximately 2x2 m², with grids (spacing between cables) of 200, 250 and 283mm, using four samples for each grid, of which the three most representative were used ([6],[7], [12]).

2.1. Design of the test device.

The first thing to be designed was the metallic frame to which the nets were fixed. It had to resist the applied loads on the net, which were estimated as 20 tonnes over their entire perimeter (5 tonnes per corner or net quarter). However, it should be noted that 5 tonnes applied in the vertical direction can increase or decrease when decomposed in the displacement direction of the net. This occurs because the load on the net centre deforms the net vertically, which produces a vector decomposition in the sine of the angle between the deformed net and its initial plane. For the analyzed cases, this angle had an approximate value of 10°, generating a value of approximately 30 tonnes applied on each support or on each quarter of the net area. This latter value was the most unfavourable, since the 30 tonne load is distributed in each quarter of the area on the net diagonals formed by 8mm cables. These cables resist a failure load of approximately 4 tonnes. Thus, a minimum of 8 diagonals is needed to support the load of 30 tonnes. This is only a reference value, since it has been estimated taking into account factors that can vary slightly in the real situation.

With these data and an initial design, the geometry in three dimensions was introduced in the software Autodesk Inventor®, to enable the visualization of the design in all directions. The design concept consisted in the union of fixed HEB-type beams forming a base of 2-metre edges to which the nets were fixed on the upper side by means of a metallic plate that was attached by fasteners. Then, this design was moved to the ANSYS Finite Element Program Workbench® (Figure 3) to optimize the pieces and to explore the behaviour under test loads. Although the base behaved very well with the initial HEB profiles, a choice was made to externally and internally reinforce it to avoid overloads due to snagging of the cables during the test. Thus, plastic behaviour and excessive loss of resistance due to fatigue would be avoided, given that this base should be available for use in testing cable nets for several years [8].

In the first tests carried out with this new frame in August 2003, the behaviour obtained led to the assumption that the nets were failing locally due to the geometry of the test, and particularly due to
the way of fixing the net to the metallic plate that consisted in pressing the cables on the frame (Figure 4.a). This fixation was later improved by changing the metallic plate for steel cylinders, where the net was made to pass through them. This avoided the cutting of the cables by the plate edge; however, in some tests, the nets continued to fail at the contact surface of the steel cylinders with the cable, which led to the supposition that in those points there was concentration of stresses and that the previous tests had given real results.

FEM and mathematical analyses were done on the nets (strain-stress relationship under concentrated and distributed loads), however, the results and considerations are presented in other papers by the authors.

**Concentrated load test (CLT).** The concentrated load test calculates the minimal value that causes the failure of a cable net when a perpendicular load is applied to the net, concentrated at the centre, by means of a distribution plate. The failure of the net is considered when any of its elements fail, cables or staples. This load represents the concentrated stresses that the anchored net suffers with an active rocky slope surface or a rock of small equivalent diameter (see Figure 2).

The procedure of the test is to anchor the cable net to the test frame so that the external points remain fixed. The concentrated load is applied on the net using a hydraulic jack through a circular plate of 600 mm. diameter. Simultaneously, the net displacement is measured at the axis of the applied load (see Figure 5). The result of the test is the maximal load supported by the sample and its displacement at the centre of the unit net.

**Distributed load test (DLT).** This test measures the value of the minimal force causing failure of a cable net unit when a perpendicular load is uniformly applied to the net. This load represents the forces that a mass of soil or rock slide causes on the net, (Figure 2). With this test, the uniformly distributed load is obtained thanks to a press with a circular plate of 750 mm. diameter at the edge. This press acts on the sacks of fine gravel placed in a pyramid so that a uniform distribution of the load throughout the net is guaranteed (Figure 6). The result of the test is the maximal applied load supported by the sample and its displacement measured at the axis of the applied load. The initial load induced by the sacks is around 2000kg.

**3. LABORATORY TEST**

**Equipment.**

The test equipment consisted of a frame composed of two pillars and one transverse reinforced beam joining the pillars, where a hydraulic jack was installed in vertical section going down (see Figure 5). To measure the force applied by the hydraulic jack, a load cell that instantly registered the force applied to the net was added. In order to measure the displacement, a continuous distance measurer was set at the net centre using to a steel hook. Both the applied force and the displacement taking place at the centre were continuously registered, so that a relationship between the two could be
established. Both measurement device of the vertical displacement and the load cell were connected to the same equipment, which was used in both tests.

Failure forms.

The two test configurations (CLT and DLT) represent a worse-case scenario in relation to the in-situ situation. In laboratory tests the net has less possibility of displacement since the whole perimeter is fixed, while in situ, the four sides can move (the only fixed points are the bolts, but ‘sewing cables’ can move). For this reason, the maximum strength of the net in laboratory tests will be lower than in the field, therefore erring on the side of safety.

Other test variations, such as changing the application point of the concentrated load, or changing the application area of distributed loads were not considered, at this stage, for cost reasons. Nevertheless, simulations of these two tests were carried out with FEM software, in order to compare results. Once the configuration settings of the simulations give the same results as in the laboratory tests, the software provides a suitable tool for predicting the behaviour of other net configurations or other load cases, avoiding the need for numerous tests.

Once the nets were set up, they were loaded. In the concentrated load test, a great displacement occurred at the point of load application. The shape of net displacement was horizontal under the metallic plate. Also, in the net area that was free around the plate, the net took up the adopted the shape of a potential function (Figure 7). On the other hand, with reference to the distributed load test, the net under the load point took a more or less elliptic form, because the forces were distributed better through the fine gravel sacks. In Figure 7, the forms obtained by the net can be compared for both tests.

In the distributed load test, before reaching the current form, several mechanisms of strength distribution were considered, such as: big spheres, membranes with water, pyramids of balls, concrete parallelograms, etc.

The forces cannot be homogeneously distributed over the whole net, because if the net is loaded with the same force both at the perimeter and the centre, it will tend to break down. The reason is that the cables of the grids in the perimeter would not have capacity for displacement. Thus, a big concrete piece cannot be used in this test (Figure 8.a). This also happens in the nets set on the ground, which slacken the net centre area so as not to stress the perimeter area.

Apparently, the best idea would be to load the net with one big concrete piece, having a geometry approximately similar to the polygon that the net would acquire when the maximal failure strength was applied; however, this is not essential, because as the net is loaded, it acquires different shapes and different angles with respect to the initial plane (Figure 8.b).
Taking this into account, the sacks are a good solution for distributing the forces, because they do not give the net a specific form; on the contrary, they adapt to the net, varying their distribution in relation to the level of load applied (Figure 8.2): as the load increases, the bulb of load distribution grows too. The test evenly distributed the load towards the net, which it acquired an elliptical shape with a trend to form a small bulb under the application point of the load in the axis of the hydraulic machine. The drawback found in this test is to discover to what extent and in what way the load is distributed, and above all, to verify the area covered by this distribution so as to obtain the pressure values on the net. One calculation may be done through some theories of soil mechanics which propose that when applying a load in a granular, isotropic and infinite soil, load bulbs are produced tangentially to the application point and decreasing in depth, which cancel the surface load as they separate from the application point (Boussinesq’s theory, Geotecnia y Cimientos II, by Jiménez Salas).

Although not all the hypotheses of this theory are fulfilled, it may be seen that the sacks of the load are heterogeneously distributed from the maximum at the net centre, to a minimum found at the test perimeter. It should be pointed out that for the load to observe a controlled distribution, the sacks must be evenly arranged so that tension concentrations are not formed.

Regarding the failure of samples, the criterion to stop the test immediately if one component of the net broke down was adopted. This was done simply using an electronic sensor that reported any decrease in the applied load when an element failed. Moreover, in both tests the nets produced a kind of explosion when a cable broke down, above all in the concentrated load test. To understand this behaviour, it must be taken into account that a net that fails under a load of 120kN produces a force that frequently throws objects through the air from the test frame; for instance, load distribution plates, the failing net itself, cable pieces, measurement equipment, etc. This huge displacement is due to the piston that loads the net that lowers approximately 20cm during the test. When failing, the net goes down and almost instantaneously (less than one second) goes up again to a position similar to the original one. This produces vibrations and oscillations throughout the structure supporting the net. Moreover, the failure point in this test is found in the net centre, just where the plate applies the load, so a hole is opened through which the loading plate passes and impacting on the ground (Figure 9).

In the case of the distributed load test, the initial load applied by the sacks on the perimeter avoids the net going up when one of the cables of the net fails; however, there were sounds like a dry explosion and the sacks were shaken. In some tests some cables cracked before failing, indicating load accommodation. There were no observed sack failures.

The points where the nets failed were diverse and varied but following quite a clear pattern. They always broke from the cable intersection with the grid centre (see Figure 10-right). This could be either because the staple created a point of lower resistance to the shearing of cables when installed, or because the staple fixed the joint in such a way that it caused the concentration of tensions in the staple that the cables could not tolerate. In any case, the staple remained intact and the cable failed.
at the joint. The net failure remained in the grid containing the failure point, and did not spread to the other sides.

In the case of the concentrated load test, the failure points were located, in general, under the load plate perimeter and on the longest diagonal (see Figure 10-left). Some points were outside this circle, but they were equally spaced on the longest diagonal beyond the perimeter. The way in which they failed was immediate, and more than one cable broke at a time (two or three cables broke at the same time, approximately). In the case of the distributed load test, the samples failed at one or two points only, so that comparatively, it failed at fewer points than the concentrated load test. In fact, the cables sometimes did not completely break, but only one fibre of the 8mm cable failed.

In these tests, the net plasticity has not been verified because neither unloading nor measurement was carried out at all the net points. Moreover, after failure, the net does not remain deformed. However, it is possible to observe a small non-recoverable strain, which cannot be attributed to the plasticization of the material but rather to an arrangement of the net in the load situation.

4. RESULTS.

The tests show homogeneous results, which corroborates the test validity since this effectively reports the nets ultimate strength resistance, according to the laboratory conditions. These results can be seen in Table I where it can be observed that the greatest resistances were found in the distributed load tests; nevertheless, the largest displacements were found in the concentrated load tests.

Comparing geometrically, the results between the concentrated load and distributed load tests for different grids (200, 250 and 283 mm), it is observed that the differences are based mainly on the values of ultimate resistance since the results have similar shape and slope (Figure 11). Considering both test (CLT and DLT), it can be also observed that there is a variation of the force vs. vertical displacement graph slope. The slope of the first segment is less inclined in the case of the concentrated load test than in the distributed load test case. This fact is mainly due to the quick stress adaptation thanks to the gravel bags that better distribute the loads over the net, avoiding local displacements. Later, this behaviour changes in the second segment where the behaviour is linear and smoother in both tests. The first and second segment forms a non linear function. In this graph the distributed load test produced a 120mm initial net displacement before starting the test, with an initial load of 1800 kilograms.

Concentrated load test (CLT).

All the concentrated load tests are shown in the graph in Figure 12, where the three upper series correspond to the 200mm grids, the three grey series correspond to the 250 mm grids and finally the three lower series correspond to the 283mm grids. As is logical, it is found that the latter have the smallest resistance and the largest displacement due to the bigger grid gap. On the other hand, because the grid hole varies, the resistance is more sensitive than the displacement.
For each grid, three samples have been drawn; however, it is convenient to represent one series and not three. To do this, a new averaged curve was represented for each grid containing the previous three. A regression analysis was applied to this new function. The result is shown in Figure 13. Each of the regressions had an $R^2$ (correlation coefficient of the fitting curve) greater than 0.9, which gave a good fit with the data for each analysis. This correlation factor should be analyzed with more tests, however the equation form and the values were studied numerically by the authors in other publications ([3], [5]).

The regression functions for each grid are infinite, so a maximal limit should be obtained for each. This was done by cutting the series with a curve obtained starting from the maximum resistance values in each test, as can be observed in Figure 13. The equations for each grid given through regression are shown in the Table II.

Once these curves were obtained, a relationship was sought between them. Each test had a curve that fitted a quadratic equation in the form $y = a_1x^2 + bx + c$, which was simplified to a quadratic equation of the type $y = a_2x^2$, varying the slope $a_2$. With these new equations, it was found that they were only differentiated by the coefficient $a_2$. To find a relationship of the $a_2$ variation, these coefficients were drawn to see if there was a relationship with the grid gap. This may be seen in Figure 14.

Once the equations for each grid are obtained, together with the function that relates them, a unique quadratic equation can be found that attempts to relate all the tests, where the $a_2$ rate would be replaced by the equation of regression variation of the coefficients (Figure 14), which is seen in the following equation:

$$L = -0.0000015 \cdot G + 0.00073 \cdot D^2$$  \hspace{1cm} (Eq. 1)

Where:
- $L$ : is the load applied on the net in tonnes.
- $G$ : is the grid of the net in millimetres.
- $D$ : is the central displacement of the net in millimetres.

Nevertheless, it has to be taken into account that this equation is infinite and that a second criterion to limit it was established. This was the criterion of fitting the maximum values of average resistance, as can be appreciated in the graph in Figure 15, from which the following fitting function is obtained and which was drawn without regression in Figure 13.

$$L_{\text{max}}(t) = -0.0594 \cdot G + 25.647$$  \hspace{1cm} (Eq. 2)

Where:
- $R^2$: Correlation coefficient of the fitting curve
These two equations empirically represent the behaviour of the tests and correspond to approximate values, however, the methodology may be used to provide an order of magnitude of possible values of the tests to be performed with grids different to the ones presented here.

**Distributed Load Tests (DLT).**

In the case of distributed load tests, the methodology was the same, except for a change induced by imposed loads. The procedure is presented next:

- Graph of the three tests with four samples each
- Selection of the least representative sample
- Graph of the test with its three most representative samples
- Obtaining the quadratic potential regression curve
- Curve fitting in the form \( y = ax^2 + bx + c \). At this stage, in the concentrated load test the equation was simplified to the form \( y = ax^2 \), but in the distributed load test the curves are more extended, so the equations cannot be simplified.
- Obtaining the three regression functions.
- Adjustment of the coefficients in relation to the grid, obtaining the regression function that fits them.
- Equation composition taking into account the regression functions and the coefficient function.
- Obtaining the regression function that relates the maximal resistance values to the grid.
- Obtaining the error formula when contrasting the values of the tests with those obtained in the calculations.

The results of the distributed load tests without initial displacement (for easier analysis) can be seen in Figure 16. These results are analyzed applying the corresponding regression to each test, obtaining the functions shown in Table III.

These equations could not be simplified from three terms to one, as with the previous regressions in the concentrated load tests, because the distributed load curves are more extended and the second term is essential to draw the graph. Moreover, there is an initial overload, so that the interception on the “y” axis is displaced with the same value as the initial load of 1.8 tonnes (third term in the equation). However, it was observed that the second term had a similar value to the first, divided by 100, so that each equation could be given parameters only in relation to the coefficients of the first term with a fit close to 100%, giving the equations shown in Table IV.

From these equations and performing the relationships corresponding to the same methodology of the concentrated load tests, the following equations could be found:

\[
L = (-0.000003\cdot G + 0.0013) \cdot D^2 + (-0.000003\cdot G + 0.0013) \cdot 100 \cdot D + IL
\]

(Eq. 3)
\[ L_{\text{max}} = -0.0971D + 45.9 \]  

(Eq. 4)

Where:
- \( L \) : Load applied on the net in tonnes.
- \( D \) : Displacement in millimetres.
- \( G \) : Grid size of the net in millimetres.
- \( IL \) : Initial load in tonnes.

It should be mentioned that the limit curve of the load has a correlation coefficient of \( R^2 = 0.9966 \) and that the initial displacement has not been taken into account in any of the samples of the tests. The magnitude of this value was approximately 120mm in all cases generating graphs such as the one shown in Figure 17, where the two types of test are shown. To generate regression curves for this data, new analyses must to be carried out following the previously mentioned methodology.

5. CONCLUSIONS

Both tests simulate the conditions presented in situ with a very versatile and easy-to-use laboratory configuration, given that in the case of the concentrated load test the load plate size can be easily changed and in the case of distributed load test the sacks’ weight and distribution can be adjusted.

The results obtained show homogeneous behaviour that validates the procedure followed; so, the test can be repeated maintaining the initial conditions and load stated in each sample.

The tests have a more homogenous behaviour than those performed before by other authors. For the results to be repeatable from one net to another, the joining staple must be high quality and have homogeneous behaviour. If the staples are poor quality, the net will suffer readjustments as it is loaded, so although the graphs are heterogeneous, the final value of resistance will not be valid.

Of the two tests, the distributed load test is the one that best distributes the forces throughout the net. This can be seen in the way the cables fail and the failure location. The failure was frequently in the central area of the net and there was always a thread from the cable that had unravelled, although the cable itself did not break. However, of the two tests, the concentrated load test is easier to repeat and simulate.

The initial displacement is important in order to know and draw graphs of the results, mainly in the case of the distributed load test as it has an initial displacement due to the initial load, due to the self weight of the sand sacks. When the sacks are installed, due of the overload, there is an initial displacement that is not registered by the test machine, since when beginning the test the machine is configured with the value zero both for load and displacement. The initial load can be obtained by
means of the sacks’ weight; however, the initial displacement should be measured to find the final displacement later.

In the case of the distributed load test, the main problem is that the load distribution applied by the sacks to the net is unknown. This makes it difficult to obtain the nets’ real resistance, so that it is advisable to fit a load cell under the sacks to know the forces at every point. This approximate distribution has been calculated through simulation by finite elements in another report by the same authors.

These tests can be used to certify cable nets employed in slope stabilization and nowadays they are used by the University of Cantabria to certify the production of these systems in the North of Spain. If a more profound analysis is required, the nets should be installed with more instrumentation to obtain the forces within each grid so as to know the local behaviour better.

The relationships found by statistical regressions are simple and easily reproducible and they are useful for analyzing the test variations and knowing the behaviour of untested nets. Once the tests of new nets with different geometries are done, the functions to feedback the regressions should be refitted in order to see if the equations’ behaviour is maintained. The correlations were performed with few samples due to the cost of the test and they should be adjusted with new tests. Nevertheless, the tendency of the curves and the homogeneity in the failure behaviour will be maintained.

The equations obtained by the statistical method were not combined in a single equation because the objective of the work was to verify the real test, and the statistical correlation enables engineers to pre design the test; thus it is better to have one function representing force v/s displacement and another for the maximum load, the former depends on the elastic modulus and the latter on the staple clamping pressure. Besides, the clamping pressure depends on the cable net manufacturer.

The advances pursued in coming years include improving the instrumentation of the distributed load test and changing the method of distributing the load for non-square nets. The discussion of the content of this report and other related topics is relevant for the individuals and organisms related to the field.

Finally, additional tests on real sites are currently being carried out by University of Cantabria researchers. Two of the co-authors of the present paper, Daniel Castro and Elena Blanco are monitoring the forces in cable nets and anchor bolts in two slopes in the province of Cantabria (Northern Spain). The aim of this research project is to increase the knowledge of the ground-cable net interaction, since it is a phenomenon that is not accurately described by either companies or researchers in this field.
6. ACKNOWLEDGEMENTS

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7. REFERENCES.


Transportation, California Department of Transportation U.S, Department of Transportation, Federal Highway Administration. USA.


TABLES

Table I. Results of the distributed and concentrated load test for each grid.

<table>
<thead>
<tr>
<th>Net grid (mm)</th>
<th>Type of load</th>
<th>Maximum load (kN)</th>
<th>Maximum displacement (mm)</th>
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<tr>
<td>283</td>
<td>Concentrated</td>
<td>95</td>
<td>211</td>
</tr>
<tr>
<td>250</td>
<td>Concentrated</td>
<td>114</td>
<td>175</td>
</tr>
<tr>
<td>200</td>
<td>Concentrated</td>
<td>136</td>
<td>181</td>
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<tr>
<td>283</td>
<td>Distributed</td>
<td>187</td>
<td>147</td>
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<tr>
<td>250</td>
<td>Distributed</td>
<td>209</td>
<td>144</td>
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<tr>
<td>200</td>
<td>Distributed</td>
<td>291</td>
<td>152</td>
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</tbody>
</table>

Table II. Regression functions for the concentrated load tests.

<table>
<thead>
<tr>
<th>Grid</th>
<th>Coefficient</th>
<th>R²</th>
<th>Initial Equation</th>
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<td>0.00042</td>
<td>0.997</td>
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<td>$y = 0.0004x^2 + 0.0067x + 0.0228$ (Eq. 5)</td>
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<td>0.00038</td>
<td>0.999</td>
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<td>$y = 0.00035x^2 + 0.00499x + 0.09984$ (Eq. 6)</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>$y = 0.00033x^2 - 0.0071x + 0.2078$ (Eq. 7)</td>
</tr>
</tbody>
</table>

Table III. Regression functions for the distributed load tests.

<table>
<thead>
<tr>
<th>Grid</th>
<th>Coefficient</th>
<th>R²</th>
<th>Initial Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>0.0007</td>
<td>0.994</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$y = 0.0007x^2 + 0.0715x + 1.9393$ (Eq. 8)</td>
</tr>
<tr>
<td>250</td>
<td>0.0005</td>
<td>0.984</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$y = 0.0005x^2 + 0.0589x + 1.8878$ (Eq. 9)</td>
</tr>
<tr>
<td>283</td>
<td>0.0005</td>
<td>0.971</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$y = 0.0005x^2 + 0.0379x + 2.2255$ (Eq. 10)</td>
</tr>
</tbody>
</table>

Table IV. Edited regression functions for the distributed load tests.

<table>
<thead>
<tr>
<th>Grid</th>
<th>Initial Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>$y = 0.00073x^2 + 0.00073*100x + 1.8$ (Eq. 11)</td>
</tr>
<tr>
<td>250</td>
<td>$y = 0.00055x^2 + 0.00055*100x + 1.8$ (Eq. 12)</td>
</tr>
<tr>
<td>283</td>
<td>$y = 0.00048x^2 + 0.00048*100x + 1.8$ (Eq. 13)</td>
</tr>
</tbody>
</table>
FIGURES

Figure 1. Distinct ways of distributing the load of the slope on the cable net (passive behaviour).

Figure 2. Concentrated load of the rock on the cable net (active behaviour).

Figure 3. Finite element simulation of the metallic frame used for the tests.
Figure 4. Image of the changes made in the frame for attaching the net.

Figure 5. The Laboratory concentrated load test.

Figure 6. (Colour online) Distributed load test.
Figure 7. Net shapes according to the test applied.

Figure 8. Possible geometry after inducing tensions in the net.

Figure 9. Failures of the cable nets in the concentrated load test.

Figure 10. Points of failure in the tests of concentrated and distributed loads on the left and right respectively
Figure 11. Results of the Concentrated Load Test (CLT) and Distributed Load Test (DLT). MTC Net cable of 8 mm diameter.

Figure 12. Results of the 9 Concentrated Load Tests. Net cable of 8 mm diameter. Grid 200-250-283 mm.
Figure 13. Regression curves obtained from the Concentrated Load Tests for different grids. Square grids of 283, 250 and 200 millimetres.

Figure 14. Coefficients of the regression curves of the tests versus the grid.
Figure 15. Relationship between grid and maximum resistance of the concentrated load tests

Figure 16. Results of the distributed load tests. Grid 200, 250, 283 mm. MTC Net cable of 8 mm diameter
Figure 17. Results of test analysis taking into account the initial displacement in the case of the distributed load test.