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AUTOMATIC MEASUREMENT SYSTEM FOR GROUND ANCHOR PROOF TESTING

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Abstract: This paper describes the development of a automatic measurement system used to perform ground anchor proof testing. Among other objectives the new system aims at providing fully automatic data collection, data processing and display. A brief overview of anchor testing, measurable quantities and aspects that governed system design are discussed. The main system components are fully described. System validation through measuring chains calibration and field testing results are presented.

Keywords: ground anchor, automatic, measurement, smart sensor.

1. INTRODUCTION

In the last decades the demographic growth of urban centres and the construction of new road and train networks has lead to a large increase in the number of ground reinforcement works. Ground anchors provide a way to stabilize retaining works, either during construction (temporary ground anchors) or along the entire life span of the retaining structure (permanent ground anchors).

Ground anchors in general are pre-stressed tendons used to induce a compressive force aligned with the anchor axis mobilizing the resistance of the ground mass around the fixed anchor zone.

Integrity and behaviour evaluation of ground anchors is fundamental for the security of the engineering works were they are applied, namely in the case of permanent anchors. It becomes evident the need to develop and to improve methods for anchor characterization in order to foresee eventual anomalous behaviours. This can result from inadequate methods of construction and/or badly executed ones, or other pathologies like the results of changes of water level in the soil.

The anchor behaviour characterization requires the measurement of a large set of quantities, namely: 1) the applied force; 2) the pressure installed inside the hydraulic jack used by the pre-stress equipment; 3) the displacement of a set of notable points (anchor tendons ends, retaining wall, hydraulic jack rod); and 4) the ambient temperature. In Figure 1 a general schematic view of system installation can be observed. The main system components are identified.

This task has been performed by the National Laboratory of Civil Engineering (LNEC) using instrumentation with manual reading and registration. This instrumentation was also found to be of difficult installation for the conditions usually met in the field.

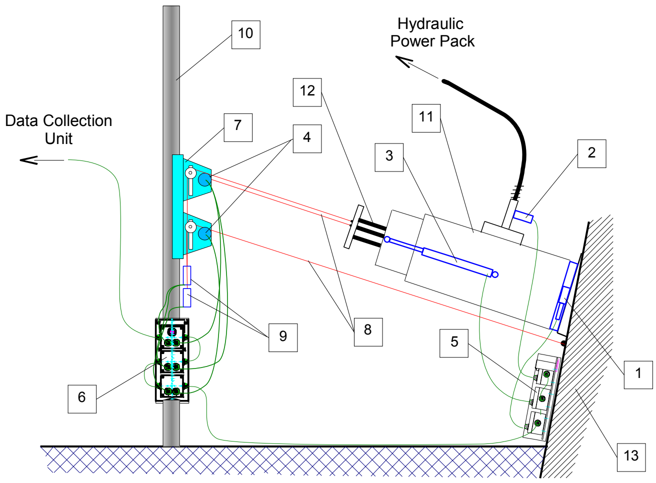

Figure 1 – Simplified scheme of system installation

	Designation	Quantity (Notes)
1 -	Load cell	Force applied by the hydraulic jack to the anchor
2 -	Pressure sensor	Pressure inside the jack chamber
3 -	Displacement sensor	Displacement of jack rod
4 -	'Encoder'	Displacement of tendon (during load and creep) and of retaining wall
5 -	Conditioning device	(Jack group of sensors)
6 -	Conditioning device	(Anchor and wall group of sensors)
7 -	'Encoder' support	(Wire support pulleys, height adjustable)
8 -	'INVAR' wire	(Measurement points transfer to encoders)
9 -	'Active' weight	(Application of constant tension to wires and friction removal)
10 -	Fixed point	(Structure assumed to be fixed in order to measure displacements)
11 -	Hydraulic jack	
12 -	Anchor tendons	
13 -	Retaining wall being anchored	

A multidisciplinary team was formed to perform research work in anchor proof testing, regarding data collection automation in order to optimize measurements and data analysis. The team also aims towards defining improved test procedures that minimize personal intervention during equipment set up and operation, improve reliability and reduce operational costs.

2. SYSTEM REQUIREMENTS

Anchor behaviour characterization is performed according to the norm EN1537 [1]. This norm specifies that force measurement should have an accuracy of measurement better than 2% of the maximum force defined in the test programme. In order to measure load loss in anchors during creep stage the measurement system should have a resolution better than 0,5% of test load. According to the same norm the equipment used to measure displacements should have a resolution better than 10 μm and an accuracy better than 50 μm, during creep stages; for all the other stages the accuracy should be better than 500 μm.

The EN1537 defines three anchor test methods; in Portugal type 1 is the most frequently used (fig. 2). Type 1 tests are conducted by applying incremental cycles of load and unloading until the maximum test load (T_e) is reached. For each cycle when the peak load is reached it is maintained for a set period of time. During this period several displacement measurements of anchor tendons ends are performed. At the beginning of the test a residual load (T_0) is applied to the anchor in order to ensure that every element is adjusted and all gaps are closed. Moreover, this initial procedure allows to check relative positioning and general component state. Usually the value of T_0 is circa 10% of maximum load.

The load cycle (T_i , i>0) comprises a crescent load phase, starting at T_0 level until the peak load for the cycle is reached, followed by a set time interval at constant load – creep stage. Afterwards the anchor is unloaded until the T_0 level. During loading and unloading phases measurements are taken at the same levels of peak load reached in previous cycles in order to quantify anchor permanent deformations. The entire process is repeated for each load level until the entire test programme is fulfilled.

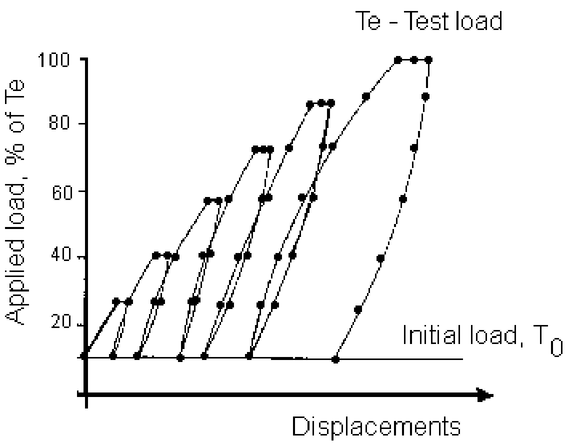

Figure 2 – Load cycling in a load test according to method type 1

Displacement measurement of anchor tendons ends and retaining wall are made relative to a fixed (reference) point. This point is admitted to be sufficiently distant from the wall in order to neglect its influence.

3. SYSTEM DESCRIPTION

Seven smart-sensors, a data collection unit (DCU) and a battery powered portable console with respective battery charger unit, compose the new system. The DCU comprises a power supply unit for the entire system and a dedicated intelligent system. The smart-sensors are connected to the DCU through a digital data network (field-bus) that provide the physical layer for data communication and power supply. In figure 3 the main components can be identified.

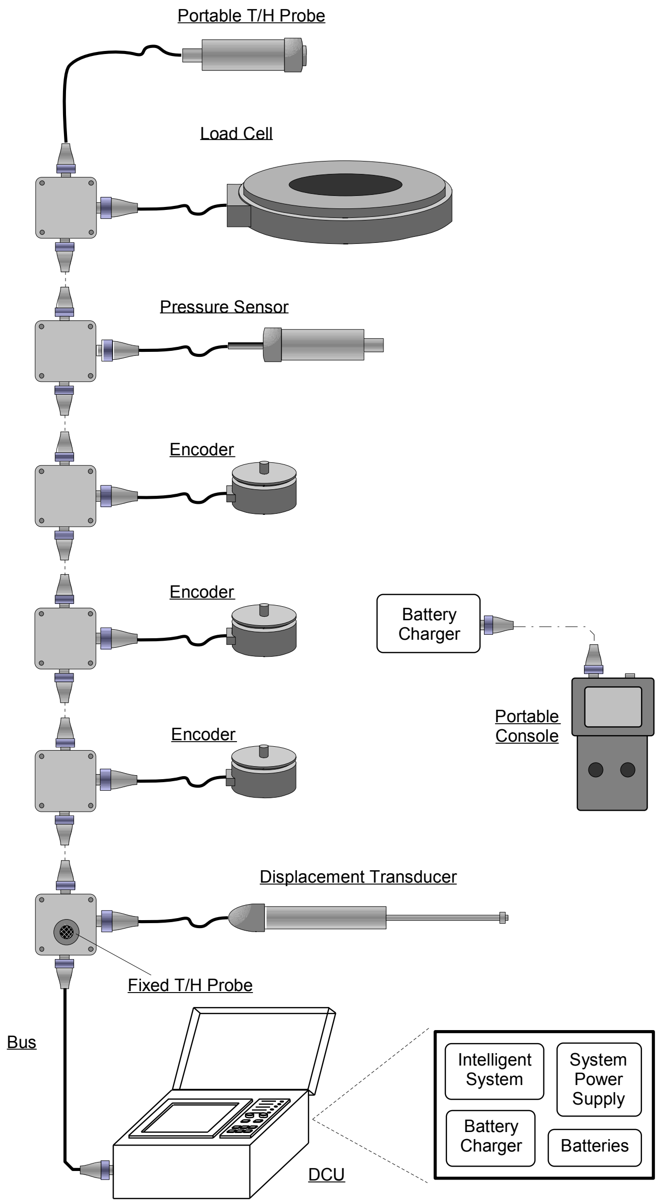

Figure 3 – Main components of the measurement system

3.1. Smart-Sensors

A smart-sensor can be seen as the association of a primary sensor (e.g. load cell) with a custom made electronic device [2]. This device implements a set of functions, namely primary sensor excitation, signal conditioning, analogical to digital (AD) conversion, first stage digital data processing, local data storage, self-test for diagnostic and bidirectional data exchange. The information supplied by this sensor type is already expressed in the units of the measured quantity.

The electronic device is accommodated inside of a watertight box with the dimensions 80x80x45 mm and watertight polarized connectors provide the interface with the exterior. For the temperature/humidity (T/H) smart-sensor it was developed a smaller case, with a cylindrical shape, for portability purposes.

Each smart-sensor can be divided into two parts: the analog part and the digital part. The first one includes the sensor excitation and the signal conditioning, while on the second are the first stage digital data processing, local data storage and bidirectional data exchange. After AD conversion the data flow is almost the same to all smart-sensors, which means that the digital part is almost the same to all sensors; the analog part is different in accordance with the primary sensor type used. The main component of the smart-sensor is a microcontroller with the reference ADuC824BS (supplied by Analog Devices). The presence of this microcontroller allows additional features to the sensor with a minimum of extra components. The analog to digital conversion and all functions previously described are executed or monitored by the microcontroller

Each smart-sensor can measure up to 4 channels, with the main sensor always connected to channel 1. All smart-sensors, but the T/H smart-sensor, has a temperature sensor located inside the box, which can be used for temperature compensation of the electronic device, namely temperature drift, and for monitoring power dissipation. Maxim-Dallas supplies this sensor with the reference DS18S20; the output is a digital signal and the communication with the microcontroller is carried on by a digital interface, One-Wire protocol.

The 640 bytes of data FLASH memory available at the microcontroller are used to store parameters namely, the sensor identification, the sensor configuration and the calibration table. Besides, all smart-sensors have a local non-volatile memory with 32 kBytes for data acquisition storage with roll-over address. With each acquisition data set is also saved the time and the channel identification. This feature along with periodic acquisition can be used, for example, on long term tests, dispensing connection to the DCU, as long as the power supply to the sensor is maintained. The data stored can be read by the DCU at any time using the commands created for that purpose.

The power entry at the smart-sensor is protected against short-circuit, by a resettable fuse, and inverse polarity. Additionally there is a low-pass filter (LC type) to remove power spikes. The transceiver inputs are protected against over-voltage at the data lines.

3.1.1. Applied Force

This smart-sensor is intended to measure the force applied to the anchor. In the tests performed so far the anchor load cell used (ring-shaped stainless steel body) was supplied by SISGEO, with a reference L211V100, with a range of 1000 kN and an accuracy better than 0,5% of full-scale. Sensor excitation is in constant current, which minimise the length effect of the cable; furthermore changing the gain of the programmable gain amplifier (PGA), in-line with the AD converter, other load cells with different sensitivity can be used.

3.1.2. Displacement of Jack Rod

This smart-sensor is dedicated to the measurement of the jack rod displacement. The primary sensor is a displacement transducer with the reference LWG300, supplied by NovoTechnick, with a range of 300 mm and an accuracy of 0,06% of full-scale. In addition, there is a temperature and humidity sensor (in a single package), which can be found on the box cover (called fixed T/H probe) – see T/H smart-sensor. This is the only smart-sensor that makes use of all four acquisition channels. The electronic device is almost the same as the one developed for the previous smart-sensor.

3.1.3. Pressure of Jack Chamber

The smart-sensor dedicated to measure the pressure inside the jack chamber use a transducer with the reference PA-33/1000, supplied by Keller, with a range of 1000 bar, an accuracy of 0,05% of full-scale and an output signal ranging from 4 to 20 mA. Again, the electronic device is very similar to the ones previously described; the current signal is firstly converted to a voltage signal and afterwards is applied to the PGA and AD converter.

3.1.4. Anchor Tendons and Retaining Wall

The wall and anchor displacements are measured relative to a reference point that is aligned with the anchor axis. The displacements are transferred to the sensors installed on the reference point by INVAR wires. The retaining wall displacement is measured by only one sensor while the anchor tendons displacements are measured by two; using this arrangement allows to measure eventual anchor head rotations. Primary sensors used are, one encoder with the reference RI58-O/5000, 5000 steps of resolution, and two with the reference RI36-O/3600 and 3600 steps of resolution, all supplied by Hengstler. The INVAR' wire has a diameter of 0,1 mm. The transmission of wire displacement to the encoders axle-shaft is performed by a pulley with a diameter of 25 mm. Suspended from the wire end is an active weight that is used to vibrate the wire prior to data acquisition in order to remove static friction components from the transmission. The weight has two parts, one of them connected to the wire (fixed part) and the other free to move relatively to the other. The relative motion is created by a solenoid installed inside the mobile part. The frequency and amplitude of vibration is controlled by a micro-controller. Total mass of the vibrating system is around 0,25 kg

Since the encoders used are of the incremental type special measures must be taken in order to avoid loosing any state line transitions; this could happen during wire vibration (many and quick transitions) or when the main microcontroller is busy with other task. To avoid this, another microcontroller (PIC16F818 from Microchip) was used just for this operation. The communication between the two microcontrollers (for transmission of acquisition and configuration data) is carried on by a digital serial interface and a protocol created on purpose.

3.1.5. Temperature/Humidity Portable Probe

This smart-sensor is not a truly portable sensor, since it must be connected by a cable to the bus. However, the helical cable and the case shape allow a reasonable degree of mobility. The primary sensor used has a reference STH15 and was supplied by Sensirion. A single package sensor provides information about temperature and humidity in a digital format. The communication with the microcontroller is carried out by a digital serial interface. The T/H sensor used at the displacement smart-sensor has the same reference. This smart-sensor is the only one that does not have an internal temperature sensor.

3.2. Local Area Network

The system implements a Local Area Network (LAN), field-bus type, based on the RS485 standard. The LAN implements three layers of the Open Systems Interconnected (OSI) reference model: physical, data link and application. At the physical layer, the network satisfies the RS485 specifications. The network topology is of the trunk type with a capacity for connecting up to 254 smart-sensors in an arbitrary order. The network also supports devices of other types, like a driver to command an electric valve.

The bus uses a twisted four conductor shielded cable. Two conductors are used for power transmission and two for data transmission. The section of the conductors and the voltage supply was dimensioned to guarantee a voltage between 12VDC and 24VDC at the entry of all smart-sensors connected to the bus.

3.3. Communication Protocol

The communication protocol implemented follows a master/slave model, where the DCU (or the portable console) operate as master and the smart-sensors as slaves. The DCU controls the bus and is the only device that has full access to it. The communication is always started by the master unit by sending a message to a smart-sensor, which is then allowed to send back a response. The messages can be addressed to a single smart-sensor or to all sensors connected to the bus (broadcast message). The broadcast messages are used to synchronise a task with all units and to reduce the data flow in the bus. When a smart-sensor receives a message it must always send a response, except when the message is addressed to all sensors connected to the bus (broadcast message). In this case there is no response to the master unit.

The DCU identifies each smart-sensor by a unique bus address. This address can be any code between 00H and FEH, except the code 26H (“&”) which is reserved for broadcast messages. The code FFH is also reserved for address interrogation.

The message and the response use a similar format. The first two bytes are equal for both: the first is equal to code 80H and is used to synchronise all units with the reception; the second byte is the address of the smart-sensor which serves to identify the recipient of the message and in the response serves to confirm its origin. For the message the next byte is a command, followed by optional data bytes. On the response the next bytes are optional data bytes. The first two bytes must always exist either in the message or in the response. The command byte is also mandatory in the message. All the data bytes are optional.

The exchange of information between DCU and the smart-sensors is supported by a set of 63 commands. Some of them don’t apply to all sensors (ex. vibration frequency for the active weight). This set of commands allows the configuration of general and specific parameters, data acquisition, diagnostic, sensor activation and active weight excitation.

3.4. Data Processing

The data processing can be executed locally in the smart-sensor or centrally in the DCU. In local processing mode the data is converted to the units of the measured quantity. The data can be sent in binary format or in ASCII format, as a string data. In the former case it can be sent in the measuring units or in units of the measured quantity. In the second case it is always sent in the units of the measured quantity.

For each channel, there is one calibration table that can be built or updated at any time. This table is required if data is going to be processed locally. The maximum number of points is respectively 51 for the channel 1 and 11 for the others. Each calibration point at the table uses two bytes for the reference and two bytes for the measured data. At the calibration table it is also saved the date (year and month) and the calibration temperature. The data processing uses the acquired data and the calibration tables to perform the conversion by linear interpolation, into the units of the measured quantity. The mathematical operation is executed in binary format (integer type) and using fixed point arithmetic. The data result is always 16 bits wide.

3.5. Data Collection Unit

As mentioned before the data collection unit comprises a dedicated intelligent system and the power supply unit for the entire system (fig. 4). The intelligent system (IS) is an RLC-ARM-Plus-10.4, 32-Bit Embedded Single Board Computer, supplied by R.L.C. Enterprises, Inc. This computer works under Windows CE system and the application software can be written in Microsoft Visual Basic or Visual C++. Its main hardware features are: StrongARM RISC processor, 32 Mbytes DRAM and 32 Mbytes FLASH memory, real time clock, 10,4 inch VGA LCD colour graphics display, touch screen, two serial ports, two PS/2 ports, two PCMCIA card slots (one of them occupied with Ethernet port), one USB host port and one

USB slave port, four analog inputs, one audio output, and user input/output expansion bus.

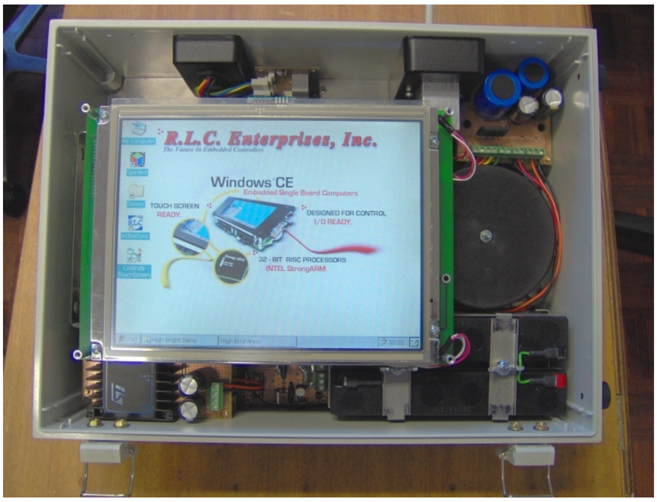

Figure 4 – Internal view of the DCU with the front cover removed

The IS could have been implemented on a portable PC equipped with an RS-485 digital interface. However, the harsh operation conditions usually met in the works advised the usage of another solution. The RLC computer is more reliable by dispensing all components with moving parts, like a hard-disk, a keyboard and a mouse; the LDC display has a high brightness setting compatible with operation under bright sunlight conditions; has a wide range of communication interfaces, is small and can be easily installed in a watertight case, sharing the power supply with all the sensors.

The mains functions of the DCU are: i) information exchange with the smart-sensors, by sending messages and receiving responses according to the developed communication protocol; ii) data processing and presentation of results in a numerical or graphical form; iii) data storage in non-volatile memory; iv) sharing of the data with others systems; and v) establish a user friendly interface with the operator .

The DCU unit can be powered by direct connection to mains 230 VAC/50 Hz or alternatively by battery (24 VDC). The second power source guarantees a non-interrupt power supply to the computer and smart-sensors for 60 to 90 minutes. This feature can be very useful in field tests to prevent data loss and sensor reference points. The DCU has an internal battery charger for battery recharging when it is connected to mains power supply.

3.6. Portable Console

The portable console provides a convenient capability to communicate with the smart-sensors dispensing the usage of the DCU. Only a reduced set of commands is available. Although, they are enough to take measurements, show the acquired data in the built-in display and reading and setting some configuration parameters. The portable console can be connected to the system in two ways, called local connection and bus connection. In the first case the portable console is connected directly to a single smart-sensor by a dedicated interface, being powered through it. This mode can be used to adjust the zero of a primary sensor when the DCU is far from sight. Besides, the DCU can also exchange information with the smart-sensor in concurrent mode. On the second case the connection is made directly to the shared bus. In this case the smart-sensors are powered by the portable console and the DCU cannot be connected to the bus, due to the fact that only one master can be connected to the bus. The communication can be established with any smart-sensor connected to the bus. This mode can be used during the calibration process, were the presence of the complete measurement system is not required, or when performing a survey campaign measuring only the force applied to the anchor.

The portable console has a display with 4 lines by 40 characters for data output and two buttons for data input. One button is reserved to cancel the input data and reset to the root menu; the other is a combined rotary selector and button device allowing navigation in the commands menu and validation of the command selected. The commands are grouped by function in a tree like structure with a maximum of three levels deep. At each level the commands are presented to the operator in a roll-over mode by using the rotary selector. Once found the desired command is sent to the smart-sensor by pressing the embedded button.

The portable console is powered by a small capacity rechargeable battery (200 mA.h, 18 VDC), suitable for short period operations. To charge the battery it was developed a charger, which can also be used as a power supply for the smart-sensors network. However, in this mode the current supplied to the network is limited to 200 mA.

4. MECHANICAL INTERFACES

The system was designed aiming at significantly improving the installation conditions and operation in the works. Several solutions for fixture of the equipment were studied, taking into consideration the materials usually available in the works, the reduced space available at the platform constructed on purpose to perform the tests, the need to reduce the number of cable connections to be performed on site and the environmental conditions. Special care was taken to minimize the number and complexity of the tasks required to place the new system in a operating condition.

Due to physical proximity of the instruments during tests two sets of measurable quantities were grouped. Therefore the force applied to anchor, the pressure installed inside the hydraulic jack and the displacement of the hydraulic jack rod constitute one of the groups while all three encoders form the other one. Minimization of cables dimension and general encumbrance of the working platform was the main criteria used to establish the sensor groupings.

The jack rod displacement transducer is applied over the jack body by specially designed support in order to be compatible with a wide range of models. The support is fixed in place by an adjustable strap with integral ratchet. Attachment of the transducer rod end is performed by means of a small magnet. The correct positioning of the magnet along the radial and longitudinal directions of the jack is performed by an adjustable mechanism installed at the rod end of the transducer.

Each smart-sensor group shares the same support for the boxes containing the electronic devices. The support is endowed with several types of mechanical interface compatible with elements usually found on site. It can be simply suspended from a bolt placed in the retaining wall or other suitable structure or braced with a plastic strap to the support structure of the reference point or other tubular elements that form the platform structure or covering (fig. 5).

Figure 5 – Example of fixture of sensor boxes over the covering structure

The three encoders are installed in two independent supports in order to guarantee the best relative positioning among them and in relation to the measuring points for a wide range of anchors elevation. The usage of only two supports allow to minimize the number and complexity of tasks required to install the sensors. The vertical component of the force due to the wire traction is taken from the encoders axle by a pulley equipped with roller bearings. This pulley is adjustable in height relative to the encoder to allow for alignment with the anchor axis.

The pressure sensor is directly installed in the pressure line of the jack by using a device endowed with quick coupling ports compatible with the load system used.

5. RESULTS

All measurement chains were subjected to a former calibration aimed at transfer function evaluation of each smart-sensor, stability assessment and repeatability of measurement results. These results were also required to generate the internal calibration table of each smart-sensor.

The results achieved so far were considered adequate for the application requirements. Table 1 illustrates the results obtained in terms the expanded uncertainty for some of the measurement chains.

All calibrations are traceable to National Standards and were performed by LNEC metrology laboratories.

Field tests were performed in order to validate the complete system. The test was also used to observe the main difficulties with system installation and operation and to collect data for usage procedures establishment.

Table 1 - Summary of smart-sensors calibration results

Smart Sensor	Measuring Range	$U_{95\%}(y)$ or $W_{95\%}(y)$
Applied force [3]	100 kN – 1000 kN	< ± 0,19 %
Temperature [4]	10 ºC – 50 ºC	< ± 0,7 ºC
Humidity [4]	30 %rh – 80 %rh	< ± 4,6 %rh
Encoder (5000) [5]	78,54 mm/turn	± 8 µm *
Encoder (3600) [5]	78,54 mm/turn	± 9 µm *

* indicated value does not account for reversibility effects. The effect can be disregarded due to specific test procedures in use.

The field test was also used to perform a comparative study with the previous system that has been used to perform ground anchor proof tests. The results obtained with the new system were deemed as satisfactory, being observed a close following between the two systems (fig. 6).

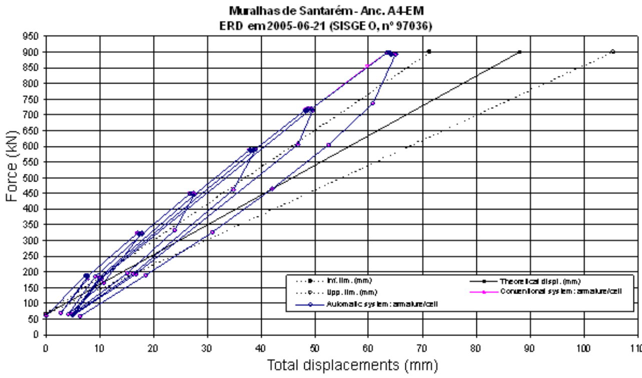

Figure 6 - Detailed test: comparison of total tractions/displacements

6. CONCLUSIONS

The design of a new system for automatic measurement in ground anchor proof testing was described. The system was developed taking into consideration a large set of criteria and special needs regarding anchor proof testing.

The results obtained so far lead us to conclude that all of the initial objectives have been achieved, namely the ones expressed by the norm EN1537 [1].

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