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DEEP DISPLACEMENTS MEASURED WITH A ROBOTIZED INCLINOMETER SYSTEM

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SUMMARY

In the field of landslide monitoring systems, the Geohazard Monitoring Group (GMG) of IRPI-CNR have developed and patented a new instrumentation to measure the deep-seated ground deformations using an inclinometer probe within a robotized system. This instrumentation combines the advantages of the traditional measurements (manual readings) with a robotized approach that improves the results in term of revisit time, repeatability and accuracy. The Automated Inclinometer System (AIS) allows to explore automatically all the length of the borehole with just one inclinometer probe. In this robotized system, an innovative Inclinometer Control Unit (InCU) was implemented and directly connected to the probe that allowed to remove all wired connections between probe and Ground Control Station (GrCU). All the cables (probe signal and power supply) were replaced with a fiber cable (Dyneema®, ϕ2.5mm) just to sustain and movie the probe up/down into the borehole. The InCU device is battery powered and is automatically charged via contactless inductive charging system during the AIS idle time. Measurements are taken during the ascent phase with steps of 0.5m (or 1m). The descent phase (continuous) and the ascent phase (by steps with about 5" break to acquire the inclinometer data) is managed by GrCU through the combined use of a μmotor and a high precision encoder. During measurement into the borehole, the InCU is completely autonomous and analyses the signals received from the probe and stores them into its internal memory. The data analysis system implemented in the InCU, is based on the difference of the inclinometric signal amplitude: in case of probe in motion (between one measuring step and the other) and in case of probe stopped (positioned at the i-th measurement depth). By default, this instrumentation perform automatic double reading (0/180°) for accuracy increasing and errors correction. The system is independent from the length of the borehole (1 to 120 meters for standard model), operates on aluminum or ABS inclinometer casing, is completely remote controlled and is powered by solar panels. The AIS was extensively tested on an inclinometer test tube installed at CNR IRPI in Turin and then in landslide monitoring networks. The analysis of the data (about 500 measurements in the Turin test site and about 600 measurements acquired in El

Portalet landslide) allowed to validate the system both in terms of accuracy and repeatability of the measure.

KEYWORDS: automatic inclinometer, landslides, monitoring systems

1 INTRODUCTION

The monitoring of slope instability phenomena represents a key research sector where innovative technologies development plays an important role. Instruments and techniques now available allow accurate investigation of a series of parameters useful to observe the dynamic of slope stability and its evolutionary scenarios. In the field of deep ground deformation monitoring systems, the Research Institute for Hydrogeological Protection of the National Research Council (IRPI CNR) developed in the early '90s the Automated Inclinometer System (AIS). The aim of this system was to automatically carry out inclinometer measurements with just one inclinometer probe (Lollino, 1992). The first experimental versions of AIS immediately showed the high potential of the system, such as:

- Use of just one probe to measure all the length of the borehole;
- High accuracy and repeatability of measurement;
- Complete and continuous measurement of the inclinometer deformation along the tube (measuring step 0.5 m or 1m);
- Measurement of velocity and acceleration of deformations and of the phenomenon;
- Possibility to change starting point and step of the measurements;
- Reuse of the equipment even after large deformations of the inclinometer tube.

These advantages, combined with complete automation and remote control, pointed out AIS as an integration/alternative to "in-place inclinometer" in all fields of Engineering Geology where precise data on deep movements were needed (landslide phenomena, fronts digging, retaining walls etc.). Despite the high potential, the AIS did not obtain a remarkable diffusion mainly due to the artisanship of the equipment. Despite these limitations, various experimental systems were installed in Alpine and Apennine areas. They have confirmed the potential of the prototype by providing interesting results in the research field of landslides (Lollino et Al, 2001, 2002, 2003, 2006). With the acquired experience and new technologies development, a new version of the AIS was redesigned and patented (Lollino et Al, 2008). It shares the basic principles with the first prototype, but features remarkable technological evolution overcoming limitations of the previous one. This article describes the characteristics and operating principles of the new release by also showing some results obtained both in test sites and in a real case study of landslides monitoring.

2 SYSTEM DESCRIPTION

In the field of measurement instrumentation for deep ground deformations, the AIS represent a robotic system able to carry out inclinometer measurements with the same principles of manual measurement (Dunnicliff, 1993). From the sensor point of view, the system use a standard biaxial inclinometer probe (with force-balanced accelerometers or MEMS). In the manual measurement or in the "in-place inclinometer" the probe is connected with the datalogger (located on the surface), by electrical cable (power supply and signal transmission) (Dunnicliff, 1988). In the AIS, thanks to the implementation of an innovative Inclinometer Control Unit (InCU) connected directly to the probe and powered by an internal battery, the traditional cable (power supply and signals) was eliminated and replaced with a thin and resistant fiber (Dyneema®, ϕ 2.5 mm). The scope of this cable is just the mechanical probe support during the measurement (up/down) and during the idle phase (Fig. 2).

A. 150 m *Dyneema* cable ϕ 2.5 mm
B. µmotor (Up/Down)
C. High precision encoder
D. Ground Control Unit (GrCU)
E. Robotized cable management (wrapper/unwrapper)
F. Contactless induction charger
G. Inclinometer Control Unit (InCU)
H. InCU Battery
I. Inclinometric BiAxial probe (FB-Servo or MEMS)
J. Robotized 180° rotation system
K. Probe safety control
L. Idle probe position
M. GrCU AUX unit (3G/4G Modem router...)
N. Standard fiberglass case

Figure 1. Main components of the AIS system

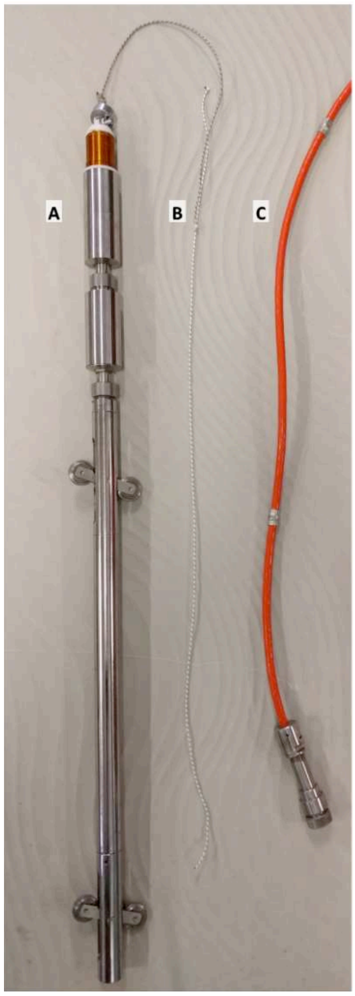

Figure 2. Inclinometric probe (A), Dyneema® cable, ϕ 2.5mm (B) and traditional graduated cable, ϕ 10 mm (C)

The InCU (Fig. 1, G) is directly interfaced with the inclinometer probe (Fig. 1, I) and it is able to manage probe powering and analyze its signals in order to determine if it is in motion (descent or ascent phase) or stopped for the i-th measurement step. The amplitude of the inclinometer signal in these two states (probe stopped/probe in motion), is very different and the InCU is able to recognize them and store or discard the acquired data (Fig. 3).

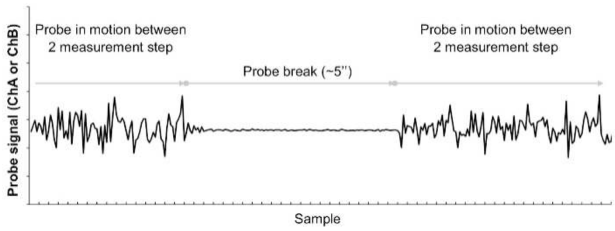

Figure 3. Pattern of inclinometer signal during the motion phases and when the probe is stopped for the i-th measurement step

The system waits in idle state, until starting new measurement (scheduled or on demand) and during this time performs the battery and peripherals check (probe, modem, motors, etc.). At the beginning of the new measurement cycle, the InCU, receives, via wireless, the parameter setup (number of acquisitions, waiting time, number of samples, etc.) and then operates autonomously without communication with the Ground Control Unit (GrCU). Measurements are taken during the ascending phase (toe to top of the borehole) phase with a typical 0.5m (or 1m) step. GrCU manages the descent (continuous) and the ascent (by step) through the combined use of a µmotor and a high precision encoder. This system, joined with the almost inextensibility of the Dyneema® cable provide a high repeatability of probe positioning into the inclinometer casing.
The InCU is powered by a rechargeable battery that allows a continuous measurement of about 6 hours without intermediate charges (12h with MEMS probes). The InCU battery is automatically recharged during the idle state by a contactless induction charging system (Fig. 1, F). This charging scheme guarantees a waterproof system without electrical contacts. Under normal operating conditions, the system runs periodic measuring cycles with stand-by intervals of some hours allowing a complete charge of the InCU battery. The AIS measurement speed are approximately 30" per meter using measuring intervals of 50 cm. Therefore, a 45 m long inclinometer tube is measured in about 1h 5' (with double reading 0/180° approach).

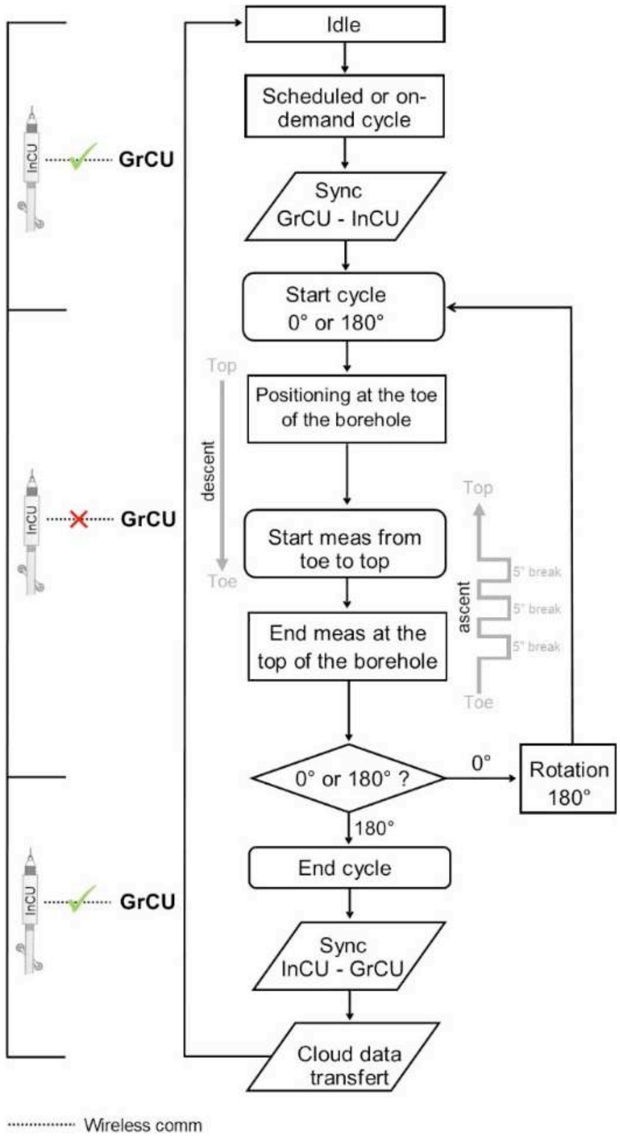

Figure 4. AIS system operational flow chart

In order to avoid potential probe locking issues in deformed inclinometer casing, a load cell system was inserted in to the AIS. This device continuously monitors the weight of the probe (and the unwrapped cable) with the aim of detecting any anomalies during the ascent or descent phase (Fig. 1, K). In case of load cell activation, the GrCU stop immediately the measurements and places the probe in a safe position (Fig. 1, l). The equipment triggers also a signaling procedure awaiting inputs by the instrument manager. This system prevents the probe loss and in case of impossibility to proceed with regular measurements it is possible to move and reuse the system in another site.

3 RESULTS

AIS has been extensively tested on an inclinometer test casing installed in Turin and then in a networks for landslide monitoring. The tests were organized in different phases, according to the progressive development of the hardware/software system. The measurements confirmed the potential of the theorized operating principles, providing excellent results in terms of accuracy and repeatability. After this test, the system was used for the continuous monitoring of landslides in Italy and Europe.

3.1 Turin Test site

The first series of measurements were carried out on an inclinometer tube about 10m long located in the CNR IRPI Institute in Turin. The system was configured for an almost continuous measurement (1 measure per hour) and powered by solar panels and backup battery. The aims of the tests were: i) the evaluation of the measurement accuracy and repeatability ii) the efficiency check of the cable wrapping/unwrapping system iii) the optimization of the energy management policies for the various devices powering. Regarding accuracy and repeatability, approximately 500 measurement cycles were analyzed and mean and standard deviation, over the entire tube length, were calculated. The results show an average “horizontal local displacements” of -0.005 mm for channel A and -0.006 for B (Fig. 5, 6 and tab.1). These differences, characterized by a very low dispersion, fall within the tolerances commonly adopted for inclinometer measurements (Mikkelsen, 2003). By analyzing time series of channel A and channel B at depths of -5 m and -8.5 m, we observed a very low data dispersion (Fig. 7 and tab. 1). The huge availability of data also allowed carrying out analysis regarding the single and double reading measurement approach in Figs 5,6 a),b) the distribution of the measurements analyzing the single reading A0, A180 (or B0, B180) while in Figs. 5, 6 c) the measurement in double reading are showed. The measurements in single reading, widely described in the literature (Pincent et.Al, 1983; Tommasi, 1986; Sappa et al., 1995), are characterized by a lower accuracy, with values about 15 times than the double reading. From the dispersion point of view, the single reading approach are approximately 3 times higher then double method. This behavior may be negligible in case of large displacements but becomes relevant in case of small deformations. Furthermore, the variability observed for single readings must be taken into account for cumulative movements processing as they are affected by the propagation of measurement uncertainty.

Table 1. Main results obtained by about 500 cycle measurement in 10 meters borehole for a Single Reading (SR) and Double Reading (DR)

	SR 0°		SR 180°		DR 0/180°	
	mean [mm]	**rsm**	**mean** [mm]	**rsm**	**mean** [mm]	**rsm**
ChA	-0.085	0.094	-0.074	0.079	-0.005	0.025
ChB	-0.082	0.102	-0.068	0.090	-0.006	0.024

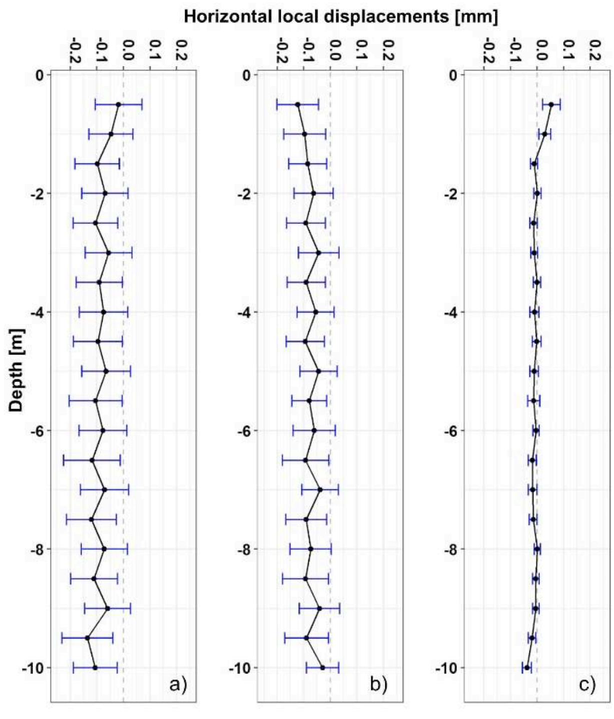

Figure 5. Horizontal displacements in situ test (Turin) for the A channel. a) Single Reading (A0); b) Single Reading (A180); c) Double Reading (A0/A180)

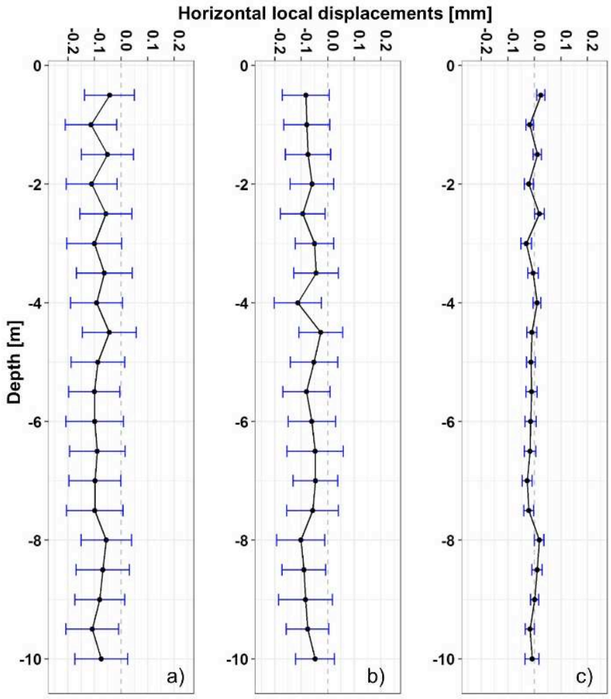

Figure 6. Horizontal displacements in situ test (Turin) for the B channel. Single reading (B0); b) Single reading (B180); c) Double reading (B0/B180)

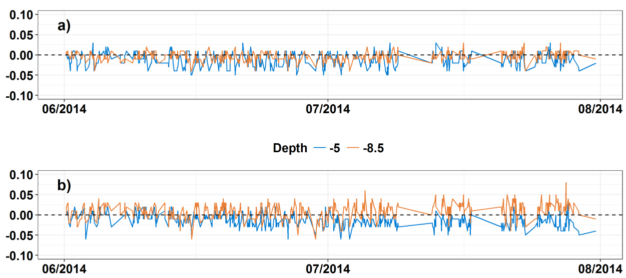

Figure 7. Time series of horizontal displacements [mm] in situ test (Turin) at 2 different depths. a) A channel, b) B channel

3.2 Monitoring El Portalet landslide (Spain)

The AIS was used to monitor several slope instability phenomena in Italy and in Europe. Of particular interest are the results obtained at the El Portalet landslide in Spain (Herrera et Al, 2013). The instrumentation was installed in the framework of the European Lampre FP7 Project with the aim of describing the surface and deep dynamics of the El Portalet landslide (Fig. 9). This landslide is located in the headwaters of the Gállego River watershed (Axial Zone of the Spanish Pyrenees) at 1800 meters asl. This landslide complex is located in the SW-facing slopes of the El Portalet Pass, an old glacial transfluence area at the border between Spain and France. There are three main slope movements, a flow of disintegrated slates and two deep-seated roto- translational slides that smoothly grade into flows in the lower part of the slope (landslides A and B in Fig. 8). The slates in these slides have been largely transformed into a weathered chaotic breccia of gravel-sized angular clasts embedded in a clayey matrix, with a variable sliding surface between 10 and 40 m deep The excavation in the summer of 2004 at the foot of the slides of a parking lot induced the development of a secondary failure in the lower part (landslide C in Fig. 8), probably accelerating the dynamic of the landslide complex (Herrera et Al, 2013).

The AIS, installed on a 46 m long borehole, showed a sliding surface located between 12 and 14 m deep (Herrera et. Al, 2017). An accumulated displacement of 9 cm equally moves the first 12 m below the surface in the period 08/14-07/16 (Fig. 11). A marked seasonal pattern is observed thanks to the high accuracy of the system ranging between 0.05 and 0.1 mm/day, which permits to clearly distinguish 5 to 6 times faster velocities in winter-spring periods after the snow melt (Fig. 10).

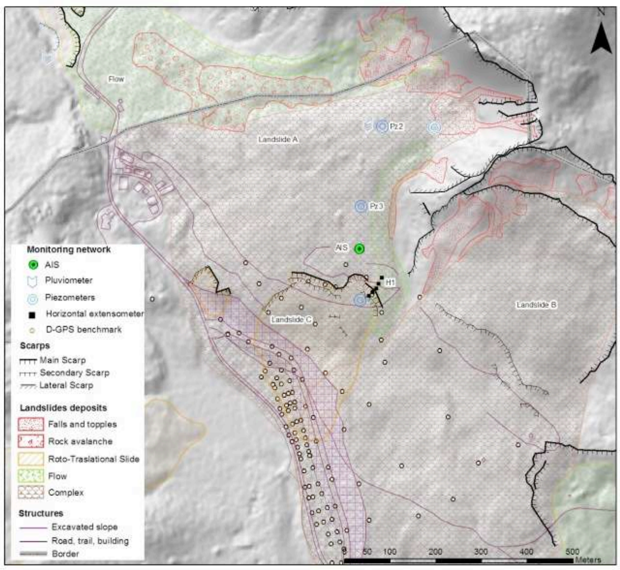

Figure 8. – El Portalet Landslide monitoring network (from Herrera et Al, 2017)

Figure 9. – AIS monitoring system installed on El Portalet Landslide (Spain) at 1800 m asl.

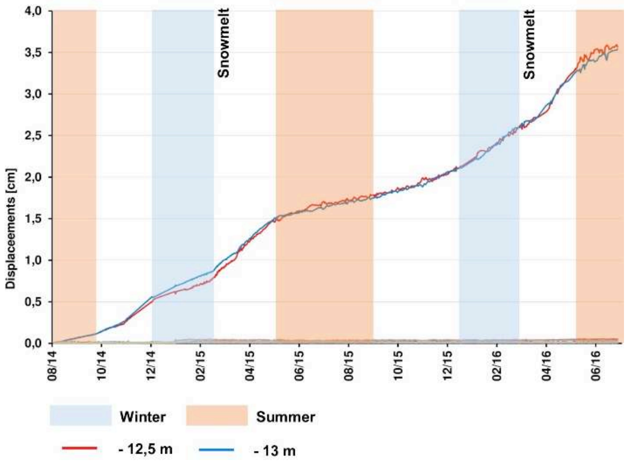

Figure 10. Time series of the local displacements (-12,5m ad 13m). The plot show a clear seasonality of the displacements rate with a maximum velocity during the snowmelt period

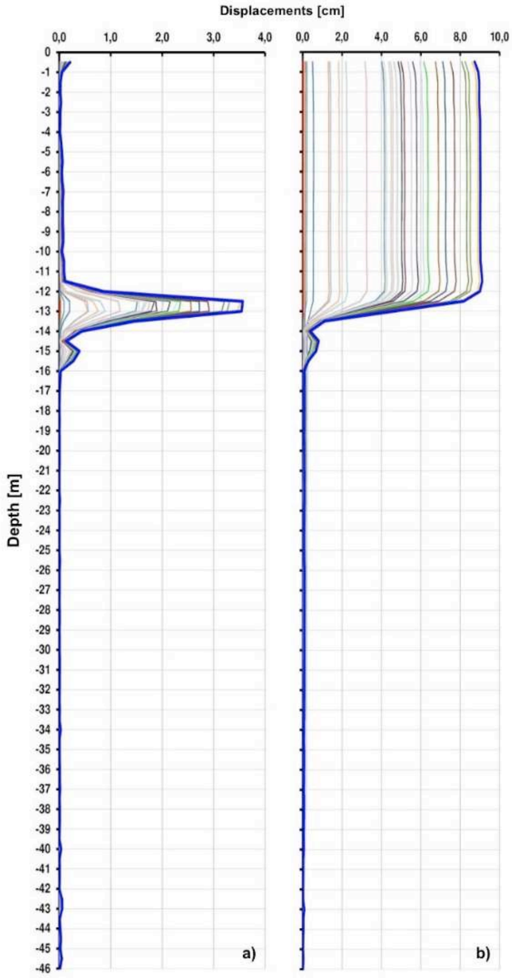

Figure 11. Local displacements a) and Cumulated displacements b) acquired in the El Portalet landslide (700 measurements in about 2 years)

The system was installed in August 2014 and the measures were cautiously interrupted in July 2016 due to the high deformation of the borehole (reported also by load cell safety system). Solar panels and µturbine wind power generator powered the system (Fig. 9). These redundant electrical power sources have guaranteed excellent measurement continuity even during the winter season. The acquired data provided an accurate description of the kinematic of the landslide and they also allowed the evaluation of accuracy the AIS system in a real case study.

In order to evaluate the quality of inclinometer measurement in sectors not affected by landslide deformations, three time series were analyzed below the sliding surface, respectively at -28.5 m, -41 m and -45 m depth. For the timespan 01/2015 - 07/2016, corresponding to approximately 600 measurement cycles, the mean and standard deviation for channel A and channel B were computed and compared with the results obtained at the test site of Turin (Fig. 12 and tab.2). As expected, the accuracy of the measurement is slightly higher in the case of the Turin test site while the dispersion indicator (rsm) is comparable. This result confirms the quality of the system that has maintained also in extreme operating conditions almost the same performances obtained in a controlled test site. The main observed differences could be probably influenced by the different measurement context (test site for 2 months vs real landslide for 1.5 years).

Table 2. Comparison between the inclinometer measurement in the Turin test site and in El Portalet landslide. All the measurements was taken with DR approach

					ChA		ChB	
	N.meas	Timespan	Temp. [°C]	Depth [m]	mean [mm]	rsm	mean [mm]	rsm
Turin Test site	507	01/6/14 01/8/14	13°÷37°	-5	-0.005	0.012	0.010	0.020
				-8,5	-0.011	0.017	-0.013	0.016
El Portalet Landlslide	600	14/1/15 26/6/16	12°÷32°	-28,5	0.038	0.022	0.008	0.021
				-41	0.009	0.019	0.069	0.029
				-45	-0.002	0.024	0.059	0.030

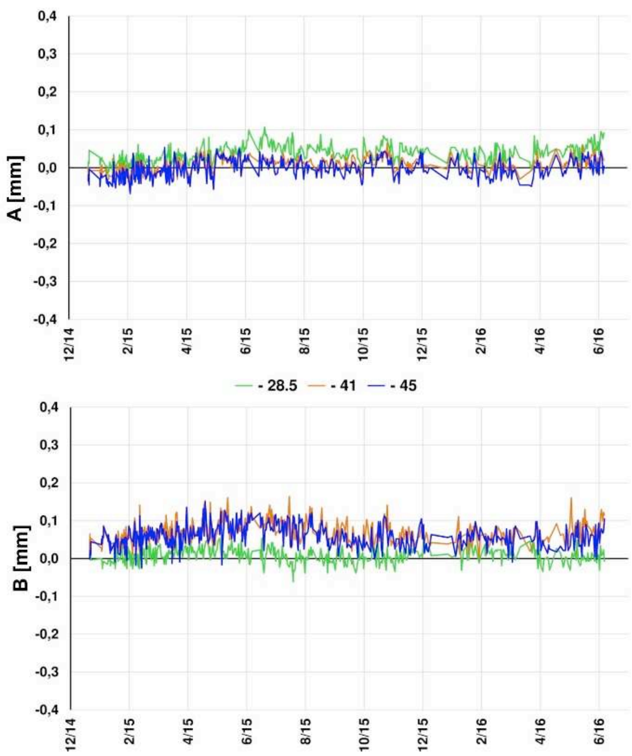

Figure 12. Time series of horizontal displacements (A, B channels) in the El Portalet landslide at 3 different depths. The 3 selected sectors was chosen in a stable area below the sliding surface.

4 DISCUSSION AND CONCLUSION

The availability of accurate and reliable dataset related to the deep deformations can increase the quality of the interpretation of landslides behavior. The Automated Inclinometer System, designed in the '90s and currently completely revisited, is an equipment with a high potential, especially due to the new technologies implemented. The mechanical and electronic improvements allowed replacing all the electrical connections from the probe to the Ground Control Unit leaving only a thin and resistant synthetic fiber just for the mechanical support (up/down into the borehole). The elimination of the graduated cable allowed to noticeably reduce the instrument size and power consumption, but also to reduce the system maintenance and the Total Cost of Ownership (TCO). The tests carried out at the IRPI CNR of Turin and in a series of landslide monitoring cases, showed that the development of an intelligent electronic system connected to the probe, proved to be a valid choice. The versatility of this device, allowed obtaining high quality results with a very intelligent algorithms approach. Regarding the handling system, the electronic wrapping/unwrapping management system has ensured the regular operation of the instrument without remarkable issues and with negligible cable wear. The repeatability of the probe positioning into the borehole, guaranteed by a high precision absolute encoder, constitutes a further benefit of the developed equipment. The large number of the analysed samples obtained in test site and in landslides, allowed the validation of the system in terms of accuracy and repeatability of the measurement. Optionally, this application provides also the management of alert or alarm services (SMS, email, etc.) that can be activated when displacements thresholds are exceeded. The AIS is an instrumentation that allow continuous measurements into the boreholes up to about 120 meters long (with standard configuration) with a single inclinometer probe. Concerning the comparison with the sensor arrays installed on the “in-place inclinometer”, the AIS allows overcoming the limitations of such equipment regarding numbers of sensors, accuracy and duty cycles (Lollino et Al, 2018). For a correct monitoring network design and implementation, the AIS is therefore indicated both as a standalone instrument and as a temporary device for the identification of the sliding surfaces not yet clearly known. In the second case, once the main areas of deformation were identified and the state of activity clearified, the AIS can be integrated or replaced with fixed arrays sensors installed at the specific depths, optimizing both the economic and logistic resources. The AIS is managed (remotely or locally) by a simple web interface usable also by smartphones or tablet. The system has completed the experimental phase and represents a mature and robust system usable in the Engineering Geology monitoring field. Developments are underway for the implementation of an integrated system (with just one probe) for inclinometer measurements, vertical deformations and temperature.

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