11TH INTERNATIONAL SYMPOSIUM
FIELD MONITORING IN GEOMECHANICS

Inclinometer measurements with robotised and traditional mobile probes in an extremely-slow landslide

Paolo ALLASIA[1], Edgar FERRO[2], Danilo GODONE[1], Anna PASQUATO[3], Lucia SIMEONI[2]

[1] CNR-IRPI, Turin, Italy
[2] Department of Civil Environmental and Mechanical Engineering, University of Trento, Italy
[3] Consulting engineer, Trento, Italy
Corresponding author: Lucia Simeoni (lucia.simeoni@unitn.it)

Abstract

The movements of a large, extremely-slow, deep-seated landslide interacting with a viaduct of the E45 highway (Province of Bolzano, Northern Italy) have been monitored since 2006. The landslide is an active block of a Multiple Rotational Rock Slide (MRRS). It has a planimetric extension of 400 m x 400 m, a maximum depth of the sliding surface of about 50 m, a total estimated volume of 6 Mm^3. Subsurface displacements have been monitored using a traditional, portable, manually-operated probe inclinometer; those of the piers of the viaduct by total station. These measurements have been carried out periodically, 2 to 4 times per year. Redundancy analysis showed that the measurements are reliable, and the mean yearly velocity is less than 10 mm/y. Since December 2019, the Automated Inclinometer System (AIS) was installed in one of the eight inclinometer tubes to robotise manual measurement operations and provide higher-frequency measurements (about one dataset per day). This paper discusses the advantages of the robotised, higher-frequency measurements provided by the AIS compared with the manual, lower-frequency measurements from the traditional manually-operated probe, in terms of: semi-checksum verification, time required to identify the depth of the sliding surface and evaluate the displacement rate for an extremely slow landslide, and ability to recognise its seasonal trend.

Keywords: Extremely-slow landslide, inclinometer, Automated Inclinometer System, checksum, displacement rate.

1. Background

A large, extremely-slow, deep-seated landslide has been recognised to interact with a viaduct of the E45 motorway in the Province of Bolzano, Northern Italy (Figure 1). The landslide represents an active block of a deep-seated, retrogressive, multiple rotational rock slide (MRRS) (Simeoni et al., 2020). The slope movement extends over an area of 0.5 km^2 and its total estimated volume is 6 Mm^3. This landslide has been monitored since 2006 by probe inclinometers and piezometers, and since 2008 the displacements of the piers of the viaduct have been measured by total station. These measurements have been carried out periodically 2 to 4 times per year. Redundancy analysis of inclinometer and total station measurements has demonstrated that surface displacements are caused by sliding over a localised surface, with a maximum depth of about 50 m. The mean yearly displacement rate is less than 10 mm/y. Piezometer measurements have shown that the water table has an average depth of approximately 25 m, with maximum seasonal fluctuations of about $\pm$ 1.5 m, and develops mostly above the sliding surface.

Despite the extremely-small displacement rate of the landslide, the traditional probe inclinometer measurements provided a reliable estimate of the mean yearly velocity. However, the manual operations to collect these data are time-consuming and are carried out 2-4 times per year, not frequent enough to recognise the seasonal changes in velocity that may be associated with the fluctuations of the water table level. In December 2019, the Automated Inclinometer System (AIS) was installed in one inclinometer tube (T5I) located at the toe of the landslide (Figure 1 and Figure 2) to robotise manual measurement operations and provide higher-frequency measurements of about one data set per day (Allasia et al., 2020). In recent years, the AIS has been used successfully to study landslides and the subsurface deformation field caused by large underground works (Herrera et al., 2017; Allasia et al., 2021a; Allasia et al., 2021b). The AIS follows the same conceptual schema typical of traditional measurements with a portable, manually-operated probe (International Organization for Standardization, 2017): use of a single probe regardless of the length of the tube; measurement spatial resolution equal to the probe gauge length (usually 500 mm); and double reading approach (0/180°). Also, the AIS is fully reusable. In December 2021, it was moved to a different site to serve a different geotechnical monitoring campaign.

This paper uses the data collected in inclinometer T5I to discuss the potential advantages of the robotised, higher-frequency measurements provided by the AIS compared with the lower-frequency measurements from the manually-operated probe. The comparison between these measurement systems considers: semi-checksum verification, time required to identify the depths of the sliding surface and evaluate the displacement rate, and ability to recognise seasonal trend.

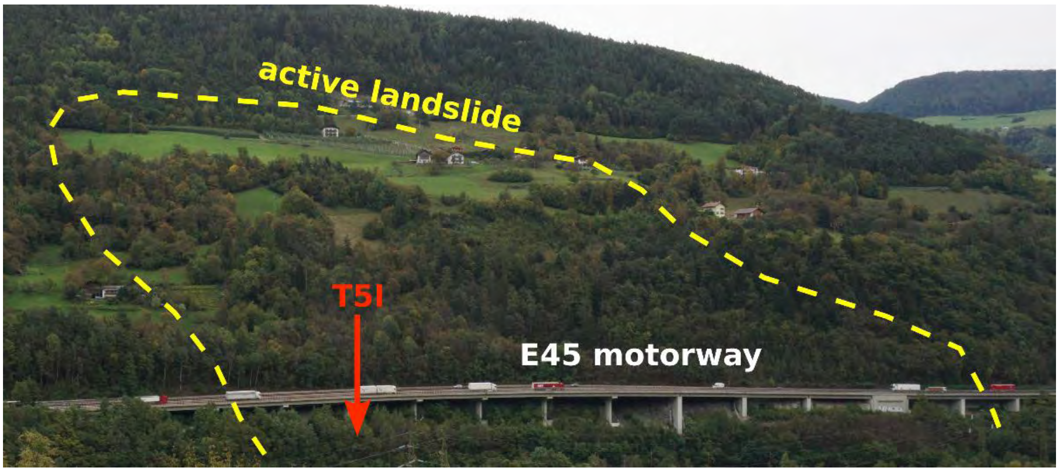

Figure 1: Contour of the active, extremely-slow, deep-seated landslide interacting with a viaduct of the E45 motorway and location of inclinometer tube T5I where AIS and manual measurements have been carried out

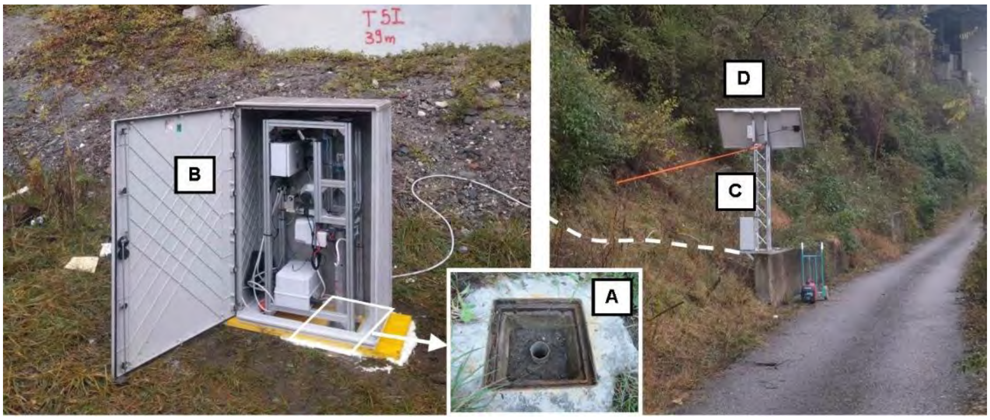

Figure 2: AIS installation on inclinometer tube T5I: (A) inclinometer casing before installation; (B) AIS inclinometer and protective casing; (C) backup battery; (D) solar panel

2. Instruments and measurements

The casing of the inclinometer T5I, made of aluminium and fully grouted, was installed in September 2009 to a depth z = -40 m. Inclinometer measurements have been carried out using a portable, manually-operated probe and the AIS. Manual measurements were taken from November 2009 to December 2017 and, by a different operator, from December 2018 to February 2022. The minimum interval between site visits was 2 months. Manual measurements were carried out from a depth of -39.0 m to the top of the tube with a 0.5 m spacing as the probe gauge length. These measurements have shown that the deformations of the tube are localised within one relatively narrow shear band, located between z = -22.5 m and z = -25.0 m. The AIS was installed in December 2019 and acquired daily measurements (419 data sets) until August 2021. The AIS was programmed so that the depths of the measuring points were approximately the same for the robotised and manual measurements, but its lowest measurement depth was limited to - 32.5 m, well below the shear band. As with the manual measurements, the distance between measurement points was 0.5 m. The AIS was equipped with a traditional probe for inclinometer measurements. The technical characteristics of the probes used for the manual and robotised measurements are listed in Table 1. Only the manual measurements collected since December 2018 (7 datasets) have been considered to allow a comparison with the AIS measurements under similar deformation conditions of the inclinometer tube. On 08/07/2020, both manual and AIS measurements were carried out.

	Manually-operated probe	**AIS probe**
Manufacturer	Sisgeo 0S242DV3000	OTR OG310
Gauge length (L)	500 mm	500 mm
Tilt sensor	biaxial MEMS	biaxial MEMS
Measuring range	± 30°	± 30°
Resolution	0.0013°	0.0015°
Accuracy	± 0.01 % FS (0.003°)	± 0.01 % FS (0.003°)

Table 1: Technical characteristics of the probes used for the manual and AIS measurements

3. Guide tube conditions

In 2018 the inclinometer T5I had already developed significant deformation in the A$^+$ direction (International Organization for Standardization, 2017), approximately parallel to the direction of movement, with a clear shear band between the depths of -22.5 m and -25.0 m.

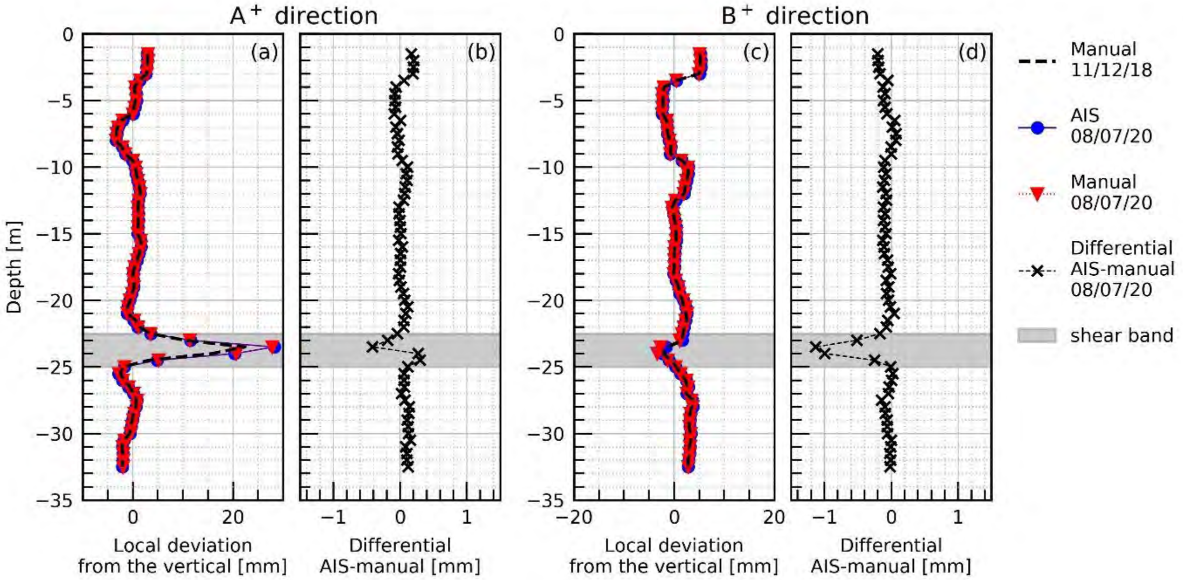

Figure 3: Initial conditions of the inclinometer tube and comparison between manual and AIS measurements; (a) and (c) deviation from vertical for the first manual measurements (dashed line) and the manual and AIS measurements of 08/07/2020 (lines with markers); (b) and (d) difference between AIS and manual measurements of 08/07/2020; the shaded region represents the shear band

Figure 3a and Figure 3c show the local deviations from the vertical in the A$^+$ and B$^+$ directions, respectively, for the first set of manual measurements (11/08/2018 - dashed line) and the manual and AIS measurements of 08/07/2020 (the two lines with markers). On 11/08/2018, the deformation of the tube in the A$^+$ direction (Figure 3a) was already strongly localised between the depths of -22.5 m and -25.0 m (shaded region in Figure 3). On 08/07/2020, the manual and AIS local deviations from the vertical were similar and, within the shear band, greater than those acquired on 11/08/2018. The local deviations from the vertical in the B$^+$ direction (Figure 3c) did not change significantly between 11/08/2018 and 08/07/2020, as B$^+$ direction is approximately perpendicular to the direction of the movement.

The differential local deviations from the vertical between the AIS and manual measurements, shown in Figure 3b for A$^+$ direction and in Figure 3d for B$^+$ direction, are less than 0.2 mm outside the shear band but larger within the shear band, i.e. up to 0.5 mm and 1.2 mm in the directions A$^+$ and B$^+$, respectively. These differences may be caused by vertical positioning offset, whose effects are more pronounced in the highly deformed part of the casing, and, in general, the use of two different measurement chains.

4. Semi-checksum analysis

Semi-checksums were calculated to evaluate the quality and precision of the measurements (Mikkelsen, 2003; Simeoni and Mongiovì, 2007). These were calculated as $0.5 \cdot \text{checksum} \cdot L/k$, were L is the distance between the measuring points (500 mm) and k is the instrument constant (20000 $\text{digit}/\sin\alpha$ for the manually-operated probe and 25000 $\text{digit}/\sin\alpha$ for the AIS probe). For each dataset, the average (μ_A and μ_B for directions A and B, respectively) and standard deviation (σ_A and σ_B) of the semi-checksums were computed, with the former representing the bias of the measurements and the latter their precision. Moreover, the gradients (b_A and b_B) of the lines fitting the semi-checksum vs depth (z) data were computed for each dataset to quantify the consistency of the semi-checksums with depth. As an example, the semi-checksums for the manual and AIS measurements of 08/07/2020 are shown in Figure 4, where the averages (μ_A and μ_B), standard deviations (σ_A and σ_B) and fitting line equations (the dashed lines) are shown on top of the graphs. As expected for good quality measurements, the semi-checksums remained approximately constant with depth, with b_A smaller than 0.0006 mm/m and b_B smaller than 0.0013 mm/m. The standard deviation was slightly smaller for the manual measurements, with $\sigma_A = 0.04$ and $\sigma_B = 0.05$ for AIS and $\sigma_A = \sigma_B = 0.03$ for the manually-operated probe.

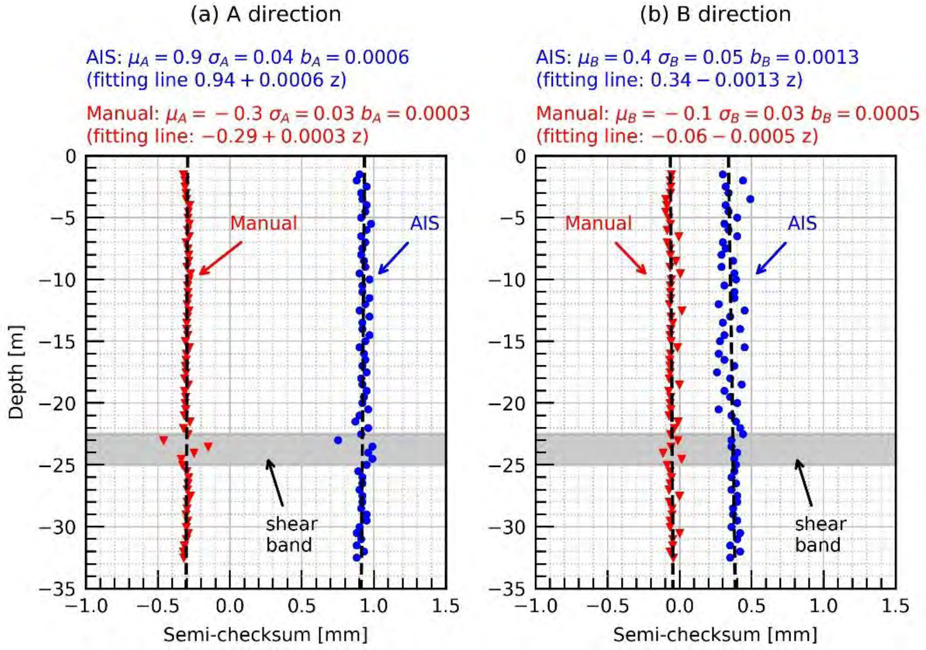

Figure 4: Semi-checksums of datasets collected on 08/07/2020; $\boldsymbol{\mu_A}$ and $\boldsymbol{\mu_B}$ are the averages (mm); $\boldsymbol{\sigma_A}$ and $\boldsymbol{\sigma_B}$ the standard deviations (mm); $\boldsymbol{b_A}$ and $\boldsymbol{b_B}$ the gradients of the fitting lines (mm/m), i.e. the dashed lines

The consistency of the averages (μ_A and μ_B), standard deviations (σ_A and σ_B) and gradients (b_A and b_B) with time is shown in Figure 5. With regards to the measurements in the A direction, the AIS provided more consistent values of μ_A over time compared with the manual measurements (Figure 5a). Moreover, as shown in Figure 5b and Figure 5c, manual measurements are potentially as good as AIS measurements in terms of standard deviation and consistency of the semi-checksums with depth but are more variable over time. It is worth noting that previous manual measurements (carried out between 2009 and 2017 and not shown in this paper) were characterised by a greater variability of the checksums, e.g. σ_A exceeded 0.3 mm. Therefore, while manual measurements are potentially as good as the AIS measurements, the latter are likely more consistent over time, being operator-independent. In the B direction the AIS semi-checksums are more scattered than those in the A direction (Figure 5, parts d, e, f). Evidently, the AIS was equipped with a probe that provided lower quality measurements in the B direction, even compared with the manually-operated probe. Nevertheless, σ_B remained more stable over time for the AIS measurements, while the first and fourth datasets acquired by the manually-operated probe were characterised by suspiciously large standard deviations and, as it will be shown, provided suspect displacements.

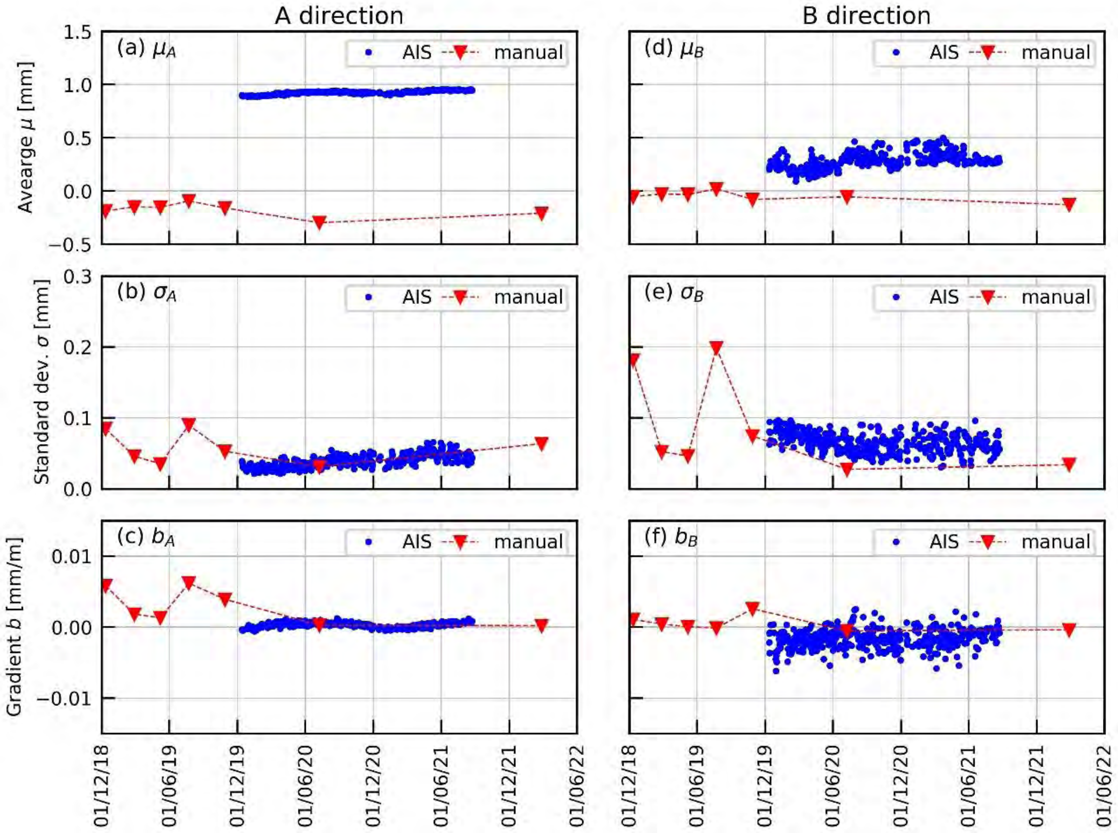

Figure 5: Consistency of the semi-checksums with time; (a) and (d) averages $\boldsymbol{\mu_A}$ and $\boldsymbol{\mu_B}$; (b) and (e) standard deviations $\boldsymbol{\sigma_A}$ and $\boldsymbol{\sigma_B}$; (c) and (f) gradients $\boldsymbol{b_A}$ and $\boldsymbol{b_B}$

5. Displacement rate and seasonal trend

The cumulated displacements were calculated for both the manual and AIS measurements by integrating the local change of deviations from the vertical within the shear band to minimise error propagation (Simeoni and Mongiovì, 2007; Simeoni and Puzzilli, 2017). The cumulated displacements are shown in Figure 6, where u and v are the displacement components in the directions A$^+$ and B$^+$ respectively. All datasets provided by the AIS were considered while two datasets (the first and fourth) from the manually-operated probe were discarded (the red crosses in Figure 6). The latter are associated with significantly larger standard deviations σ_B (Figure 5e) and suspect displacements v (Figure 6b). The cumulated displacements from the manual measurements were zeroed with respect to the first reliable dataset (the second one). Those from the AIS measurements were shifted to match those from the manual measurements of 08/07/2020. As shown in Figure 6, the AIS and manual measurements gave coherent displacements, at least if the suspect datasets were disregarded. Figure 6a suggests that the AIS, owing to the higher frequency of the measurements, may be able to recognise seasonal trends.

The ability of the AIS to recognise seasonal trends was investigated for the cumulated displacements in the A$^+$ direction (u). These are represented in Figure 7a, zeroed with respect to the first AIS dataset, with a shaded region representing the error band. The latter was taken as $\pm 3 \cdot \sigma_{u,i}$, where $\sigma_{u,i}$ is the standard deviation of u for dataset i. The standard deviation $\sigma_{u,i}$ was evaluated based on error propagation theory (Simeoni and Mongiovì, 2007): $\sigma_{u,i} = \sqrt{N} \cdot \sqrt{\sigma_{A,i} + \sigma_{A,0}}$, where $\sigma_{A,i}$ is the standard deviation of the semi-checksums for dataset i ($i = 0$ indicates the first dataset) and N is the number of measurements within the integration range

($N = 6$ between $z = -22.5$ m and $z = -25.0$ m). After only two weeks of measurements the u was larger than $3 \cdot \sigma_{u,i}$ (Figure 7a - close-up of the first 30 days of measurements), i.e. the AIS was able to recognise the shear band and provide a meaningful estimate of the displacement rate. To emphasize seasonal trends, the displacement vs time data of Figure 7a were linearly detrended (the fitting line by least squares method was subtracted from the data). As shown in Figure 7b, the amplitude of the detrended displacements is greater than $3 \cdot \sigma_{u,i}$. This suggests that the AIS has the potential to capture seasonal changes in the velocity of this extremely-slow landslide. By smoothing and differentiating the displacement vs time data, it has been estimated that between December 2018 and August 2021 the maximum displacement rate (~14 mm/year) was almost twice the minimum displacement rate (~7 mm/year).

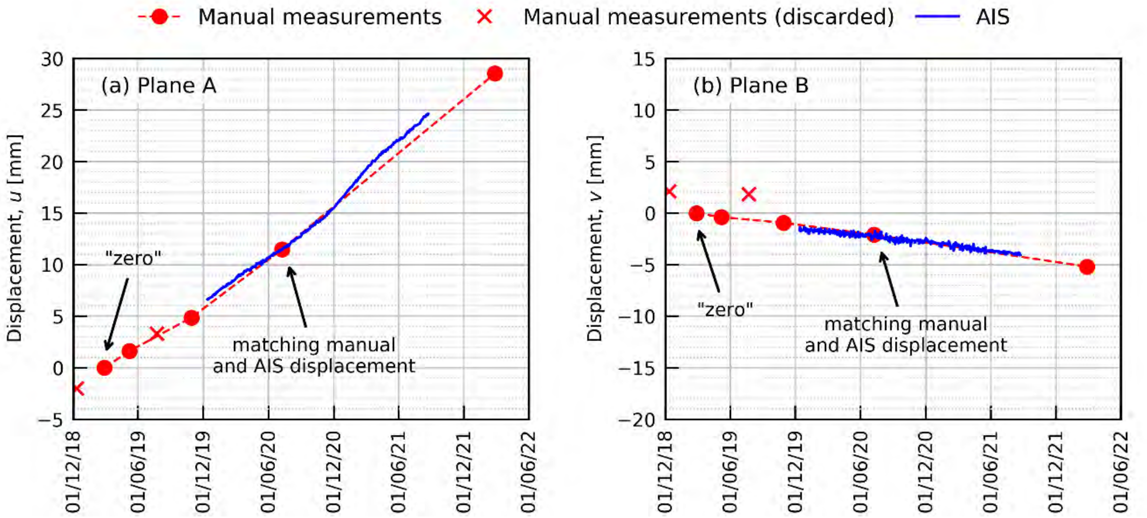

Figure 6: Cumulated displacements in directions A$^+$ and B$^+$, calculated by integration along the shear band (between -22.5 m and -25.0 m)

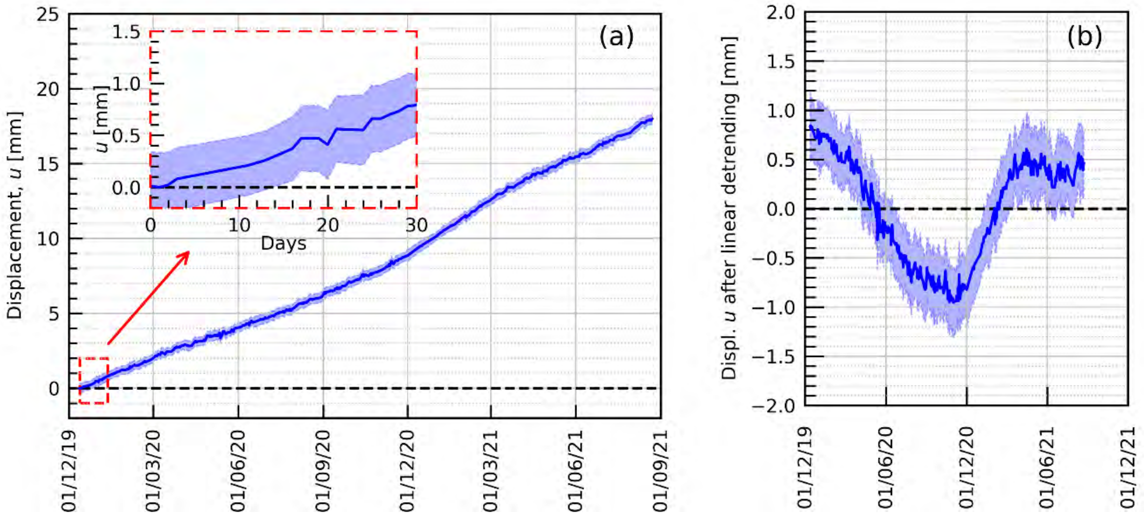

Figure 7: AIS cumulated displacements in A$^+$ direction ($\boldsymbol{u}$); (a) $\boldsymbol{u}$ vs time with error band of size $\pm 3\sigma_u$ and close-up of the first 30 days of measurements; (b) $\boldsymbol{u}$ after linear detrending with error band of size $\pm 3\sigma_u$

6. Conclusions

The Automated Inclinometer System (AIS) was installed in an existing inclinometer tube located in an active, extremely-slow, deep-seated landslide with a mean yearly velocity of approximately 10 mm/year to investigate the advantages of this robotised system compared with the conventional measurements acquired using a manually-operated probe. The analysis of the semi-checksums indicated that manual measurements are potentially as good as the AIS measurements, as the latter follows the same measurement procedures followed by human operators. However, the quality of the AIS measurements appeared more consistent over time, being operator-independent. While all datasets acquired by the AIS seemed reliable, two (out of seven) datasets from the manually-operated probe provided semi-checksums with larger standard deviations and suspect displacements. In about 2 weeks, the AIS was able to detect the shear band and estimate displacement rate, provided that the displacements are computed by integration only within the shear band to limit error propagation. This time interval is much smaller than that between the site visits to collect manual measurements, which was always greater than 2 months. Although the landslide was extremely-slow, the AIS was able to recognise seasonal trends of the displacements. Hence, if installed in a sufficiently large number of inclinometer tubes, it could provide data to be used for calibrating hydro-mechanical models that relate the displacement rates to the pore water pressures. Usually, for an extremely-slow landslide, first manual measurements are carried out to evaluate the yearly velocity of the landslide and identify the depth of the shear bands. Then, In-Place Inclinometers are installed at the depths of the known or expected shear bands to investigate the seasonal trends. The AIS was found able to perform both these tasks.

Acknowledgements

This research has been supported by MIUR PON R&I 2014-2020 Program (project MITIGO, ARS01_00964) and by Autostrada del Brennero S.p.A (Brenner Autobahn AG).

References

Allasia, P., Godone, D., Giordan, D., Guenzi, D., Lollino, G. (2020). Advances on measuring deep-seated ground deformations using robotized inclinometer system. *Sensors*, 20(13):3769. https://doi.org/10.3390/s20133769

Allasia, P., Baldo, M., Faccini, F., Godone, D., Notti, D., Poggi, F. (2021a). The Role of Measure of Deep-Seated Displacements in the Monitoring Networks on Large-Scale Landslide. In: Casagli, N., Tofani, V., Sassa, K., Bobrowsky, P.T., Takara, K. (eds) *Understanding and Reducing Landslide Disaster Risk*. WLF 2020. ICL Contribution to Landslide Disaster Risk Reduction. Springer, Cham. https://doi.org/10.1007/978-3-030-60311-3_4

Allasia, P., Godone, D., Pezzetti, G., Mammone, I., Romani, E. (2021b). The Use of a Robotized Inclinometer System to Measure Deep-Seated Ground Deformation in a Monumental Area During TBM Tunnel Excavations. The Case of Rome Subway, New Line C. In: Shehata, H., Badr, M. (eds) *Advancements in Geotechnical Engineering. Sustainable Civil Infrastructures*. Springer, Cham. https://doi.org/10.1007/978-3-030-62908-3_4

Herrera, G., López-Davalillo, J.C.G., Fernández-Merodo, J.A., Béjar-Pizarro, M., Allasia, P., Lollino, P., Lollino, G., Guzzetti, F., Álvarez-Fernández, M.I., Manconi, A., Duro, J., Sánchez, C., Iglesias, R. (2017). The Differential Slow Moving Dynamic of a Complex Landslide: Multi-sensor Monitoring. In: Mikos, M., Tiwari, B., Yin, Y., Sassa, K. (eds) *Advancing Culture of Living with Landslides*. WLF 2017. Springer, Cham. https://doi.org/10.1007/978-3-319-53498-5_25

International Organization for Standardization (2017). *Geotechnical investigation and testing - Geotechnical monitoring by field instrumentation - Part 3: Measurement of displacements across a line: Inclinometers*. ISO 18674-3:2017.

Mikkelsen, P. E. (2003). Advances in inclinometer data analysis. *Proc. 6th International Symposium on Field Measurements in Geomechanics*, Oslo, Norway, pp. 555–567.

Simeoni, L., Ronchetti, F., Costa, C., Joris, P., & Corsini, A. (2020). Redundancy and coherence of multi-method displacement monitoring data as key issues for the analysis of extremely slow landslides (Isarco valley, Eastern Alps, Italy). *Engineering Geology, 267*. https://doi.org/10.1016/j.enggeo.2020.105504

Simeoni, L. and Mongiovì, L. (2007). Inclinometer Monitoring of the Castelrotto Landslide in Italy. *Journal of Geotechnical and Geoenvironmental Engineering*, 133(6), pp. 653–666. https://doi.org/10.1061/(ASCE)1090-0241(2007)133:6(653)

Simeoni, L. and Puzzilli, L. M. (2017). Sliding surfaces and displacement rates of extremely-slow landslides: reliability of inclinometer measurements. *Proc. 19th ICSMGE,* Seoul, pp. 3281–3284.