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MONITORING OF LARGE LANDSLIDES USING THE AUTOMATED INCLINOMETER SYSTEM (AIS)

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EXTENDED ABSTRACT

Il monitoraggio inclinometrico è riconosciuto come la tecnica standard per il controllo in profondità dei versanti in frana, permettendo di misurare e tracciare con precisione gli spostamenti orizzontali lungo la verticale ed identificare la presenza le eventuali fasce di snervamento. Tuttavia, l'efficacia di questa metodologia è storicamente limitata dalla natura discreta delle osservazioni. Tradizionalmente, le misurazioni sono eseguite con una sonda dotata di sensori (servo-accelerometrici o MEMS) calata manualmente nel tubo dall'operatore secondo campagne di misura periodiche. Questa procedura, per quanto standardizzata, è intrinsecamente affetta da incertezze sistematiche e casuali. L'errore di posizionamento della sonda (anche di pochi millimetri), le variazioni nella tensione del cavo e la manualità dell'operatore introducono un rumore di fondo che può mascherare i segnali deboli tipici delle fasi di innesco o dei movimenti lenti. Inoltre, la bassa frequenza temporale delle letture manuali impedisce la cattura di cinematismi rapidi indotti da eventi meteorologici estremi o variazioni del livello di falda. La necessità di superare tali limiti ha favorito la transizione verso l'automazione. Una prima risposta è stata l'impiego di sensori inclinometrici fissi in configurazione multipla (*In-Place Inclinometers*). Sebbene questa soluzione garantisce un'acquisizione continua e riduca l'errore umano, essa presenta limiti strutturali importanti. La risoluzione spaziale è limitata al numero di sensori installati e l'intero profilo di deformazione viene ricostruito per interpolazione tra punti discreti, rischiando di omettere zone di taglio localizzate tra due trasduttori. In questo contesto, la soluzione tecnologicamente più avanzata è rappresentata dal Sistema Inclinometrico Automatizzato sviluppato dall'IRPI-CNR. Questo sistema robotizzato supera il compromesso tra continuità temporale e risoluzione spaziale, combinando la precisione della sonda mobile con l'efficienza della gestione remota. Il cuore tecnologico risiede in una *Inclinometer Control Unit* (ICU) che gestisce tutta la movimentazione della sonda tramite un encoder di precisione. L'automazione del processo di calata e risalita garantisce la ripetibilità millimetrica del posizionamento, eliminando l'errore di riposizionamento tipico della misura manuale. I vantaggi di un sistema robotizzato sono molteplici sia perché consente di campionare l'intera lunghezza del foro (anche oltre 250 m) con una singola sonda, sia perché permette un'alta frequenza di misura al giorno, abilitando un monitoraggio quasi in tempo reale. Questa capacità di acquisizione continua è fondamentale per il monitoraggio e per la tempestiva attivazione di sistemi di allerta precoce, specialmente in frane con cinematica veloce o in fase di pre-collasso.

Il sistema robotizzato ha fornito ottimi risultati nel monitoraggio di differenti tipologie di frana. Nel contesto delle frane da crollo, un esempio è il dissesto che affligge il Comune di Borrello (CH). Qui, la situazione litologica vede la presenza di arenarie fortemente fratturate, con strati a inclinazione variabile da circa 10° a 45°, poggiate su di un basamento argillitico, che formano una scarpata strutturale di oltre 140 m di altezza. Il fenomeno è un *lateral spreading* lento e profondo che evolve attivamente in superficie in crolli e ribaltamenti. In questo contesto, il sistema robotizzato permette di monitorare la progressione del rilascio tensionale che può evolvere in crolli e ribaltamenti, fornendo dati fondamentali sulla velocità di deformazione dei settori più profondi, laddove la strumentazione tradizionale risulterebbe troppo lenta e poco precisa per intercettare i precursori di un collasso imminente. Nel caso di frane roto-traslative si riporta il caso in studio nell'area nord del Comune di Chieti, storicamente interessata da intensi fenomeni di scivolamenti. L'area è caratterizzata dalla sovrapposizione di un intervallo Arenaceo-Sabbioso, con spessori di oltre 30 m, sulla formazione Argilloso-Sabbiosa pliocenica di base. All'interno della zona superiore, caratterizzata da consistenze non uniformi, si localizzano le superfici di scorrimento responsabili dell'innesco e della propagazione del dissesto.

In entrambi i contesti, la capacità di acquisire profili continui lungo l'intera verticale con frequenze giornaliere permette di abbattere il rumore di fondo tipico delle letture manuali, rendendo visibili micro-deformazioni precursori di fenomeni di collasso, fondamentali in contesti complessi come i lateral spreading di Borrello o gli scivolamenti di Chieti. Tuttavia, l'operatività di tale tecnologia deve ovviamente confrontarsi con vincoli strutturali dovuti alla vulnerabilità meccanica del sistema in presenza di cinematismi rapidi, dove lo sviluppo di deformazioni eccessive lungo la colonna inclinometrica può causare strozzature o deviazioni tali da compromettere la mobilità della sonda. Inoltre, l'elevata tecnologia dell'unità di controllo richiede costi iniziali di implementazione e di installazione sicuramente superiori rispetto ai sistemi di misurazione manuale, limitandone talvolta l'impiego su larga scala. In sintesi, sebbene il sistema si affermi come uno strumento d'eccellenza per la definizione dei modelli di evoluzione cinematica e per l'implementazione di sistemi di *early warning* basati su soglie di velocità, la ricerca futura dovrà orientarsi verso l'integrazione di questi dati puntuali ad alta precisione con tecniche di telerilevamento areale, al fine di mitigare i costi e ottenere una visione tridimensionale della dinamica dei versanti.

ABSTRACT

The inclinometer monitoring is a standard method of identifying sliding surfaces on landslide slopes. However, traditional manual techniques are subject to systematic errors relating to operator and probe repositioning and only provide periodic data. To overcome these limitations and gain a better understanding of the complex kinematics of landslide movements, the Automated Inclinometer System (IRPI-CNR) was developed. This robotic solution integrates a single, high-precision probe with an automatic control unit, which allows the entire vertical surface to be sampled at a high temporal frequency. In high-risk systems, eliminating human error and ensuring data continuity can activate real-time early warning systems. The system's performance was demonstrated in various case studies, ranging from the analysis of deep lateral spreading in fractured sandstones in Borrello, Italy, to the study of roto-translational landslides in clayey-sandy soils in Chieti, Italy. In both cases, automation has proved essential for accurately reconstructing the deep deformation profile and providing an important tool for assessing instability and managing hydrogeological risk.

Keywords: *monitoring, automated inclinometer system, lateral spreading, roto-translational sliding, hydrogeological risk*

INTRODUCTION

A full understanding of, and the ability to predict, movements in areas prone to landslides is essential for safeguarding lives and infrastructure. In this context, inclinometric measurements are the most effective geotechnical method for analysing and monitoring horizontal movements in depth (Vassallo *et alii*, 2020; Sombathy *et alii*, 2021; Stark *et alii*, 2008). Not only does the inclinometer indicate that movement is taking place, but it also provides precise information on the extent and direction of the displacement. Landslide movements are often complex phenomena involving unstable masses of soil or rock resting on a stable substrate. Deformations occur along slip surfaces, which can be found at depths that vary greatly, from a few metres to tens of metres. While surface monitoring systems such as GPS/GNSS (Hamza *et alii*, 2023; Caldera *et alii*, 2022; Šegina *et alii*, 2020), satellite interferometry (Solari *et alii*, 2020; Intrieri *et alii*, 2020) and topographic surveys detect ground surface deformations, inclinometer systems can identify the internal deformation state of landslide masses with extreme precision, even determining areas connected to slip surfaces.

While external techniques are limited to recording the visible effects on the most superficial part of a phenomenon, inclinometric surveys enable the precise kinematic evolution of movement at depth to be identified (Bo *et alii*, 2023). This distinction is fundamental to characterize landslide movements, since only analysing displacement vectors at depth allows us to distinguish between simple superficial settlements and deep slides. By identifying horizontal displacements along the axis of a tube fixed to the ground, this technology can locate fracture zones and identify areas affected by deformation, distinguishing them from stable areas. This information is also important for correctly planning stabilisation works. Furthermore, the continuous monitoring of inclinometer data enables the kinematics of the landslide to be defined (Ruzza *et alii*, 2020), *i.e.* how the body moves over time (translational, rotational or complex), thus enabling accurate geotechnical modelling.

The first inclinometer measurements were taken around 1950 using optical instruments. These tools photographed the position of the pendulum and compass needle, achieving an inclination accuracy of around 2% of the maximum amplitude and an azimuth accuracy of 2° or less. The first such instruments were developed in 1952 by S. D. Wilson at Harvard University and introduced to the global market by the Slope Indicator Company in the late 1950s, as documented by Green *et alii* (1988). Technological advances then led to the development of borehole inclinometers, which could provide highly accurate data. The first borehole inclinometers were used to map the distribution of velocities and deformations in ice masses. The development of current technology (Fig. 1) began with the initial work of Gerrard *et alii* (1952), who focused on directly measuring the vertical distribution of velocity within a glacier in the Bernese Alps

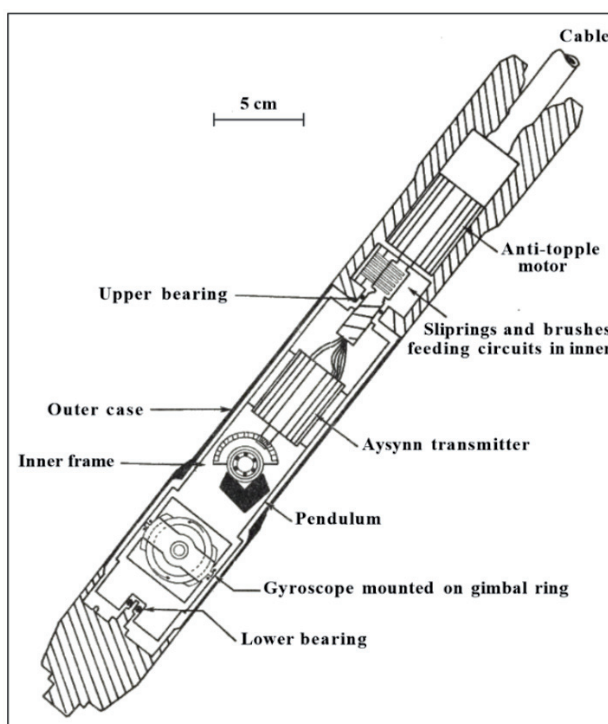

Fig. 1 - Final configuration of the inclinometer proposed by Gerrard et alii (1952) with indication of the main parts

(Switzerland). Their aim was to verify various theories on glacial flow that predicted changes in velocity with depth. The authors describe the drilling of a vertical hole 137 metres deep, extending from the glacier's surface to the bedrock below. This borehole was lined with a 3-inch pipe that tilted and bent according to the movement velocities of the ice mass at different depths.

However, the early models of inclinometers had inadequate azimuth control, which compromised the accuracy of measurements by introducing systematic errors. Improvements to these techniques led to the development of pendulum-based inclinometers, which could initially only measure a single inclination component. Azimuth control via gyroscopes was required to obtain complete data. The introduction of probe inclinometers with electrical sensors subsequently revolutionised data collection, enabling faster and more systematic acquisition of inclination information. This methodology was further improved through contributions such as those of Raymond *et alii* (1971), who perfected the use of inclinometer data in the study of deformations. They emphasised the importance of reliable instruments in detecting glacier deformations (Savage, 1963; Shreve *et alii*, 1970). The aim was to provide a more practical and accurate tool for recording deformation rates by combining remote electrical readings with precise inclination measurements in a single operation. The research shows that the instrument provides greater precision, with an electrical output that enables orientation to be determined with an accuracy of 0.10° in tilt amplitude and 1.00° in tilt azimuth. However, among the critical issues that emerged in Raymond's work, the problem of mechanical friction in the compass bearings is particularly significant. This phenomenon compromises the instrument's accuracy because friction introduces resistance that hinders the free movement of internal components and distorts azimuth readings. Consequently, the data collected is affected by a systematic error that limits the accuracy of the directional measurements taken during the research. These instruments have subsequently been improved, evolving from simple velocity observations to more precise thickness measurements using historical series that analyse the evolution of the phenomenon over time rather than providing a snapshot of it. The most modern, user-friendly and accurate systems have become essential for monitoring the stability of geotechnical works and slow-moving landslides. With advances in technology, more accurate and efficient borehole inclinometer systems have been developed. These include systems incorporating MEMS sensors (Zhu *et alii*, 2020) and automated in situ systems. These systems have significantly reduced probe positioning error (Bordoni *et alii*, 2022). Junior *et alii* (2024) define an inclinometer as any device designed to measure the inclination of a specific point or detect angular variations over time in absolute or differential terms. A recent study by Coimbra *et alii* (2023) provided an updated review of existing knowledge in this area, comparing scientific theories with current operational practices. These studies confirm that inclinometers remain the primary tool for monitoring land safety and detecting ground movements before they can lead to landslides. However, despite significant technological advances leading to modern inclinometer probes, traditional manual monitoring still has limitations relating to acquisition frequency and operator subjectivity. During critical landslide events, the requirement for real-time, high-frequency data collides with the logistical challenges of manual measurements, often exacerbated by adverse weather conditions or site accessibility issues. It is precisely in this context, where there is a need for both accurate depth measurements and automated, continuous data management, that the latest geotechnical research comes into play. To overcome the intermittent reading of manual measurements and minimise systematic errors due to probe positioning (Mikkelsen *et alii*, 2015; Bannikov *et alii*, 2020; Bannikov *et alii*, 2022), research has centred on the development of permanent robotic systems. The Automated Inclinometer System (AIS) is an example of this innovative approach, offering a fully automated measurement procedure inside boreholes. The AIS's development is an evolving research activity, progressing from the prototype phase to scientific validation and finally to real-world applications. Early contributions from Lollino (1992), Lollino *et alii* (2012 and 2016) and Herrera *et alii* (2017) played a pioneering role in demonstrating the validity of the AIS prototype. In Allasia *et alii* (2018), the robotic system was used to monitor deep landslides in Piemonte Region (Italy). This demonstrated that the repeatability and accuracy of the measurements were significantly higher than those obtained using traditional manual probes. This study set the stage for the adoption of AIS as a standard tool in the field. Allasia *et alii* (2020) demonstrate the potential of AIS in highly sensitive urban and archaeological contexts, such as the excavations for Line C of the Rome (Italy) metro close to monumental areas like the Colosseum and the Imperial Forums. The study showcased the automated system's capacity to monitor deep deformations while ensuring the safety of sites of significant historical and cultural importance.

Subsequently, the same authors extended the application of the system to slow and deep landslides, confirming AIS's ability to reduce operator uncertainty and ensure more reliable time series (Allasia *et alii*, 2021). This development represented a significant methodological shift, shifting the focus from technical validation to operational use in complex contexts. In this context, AIS is now considered not only as an automatic tool, but also as part of a broader geotechnical and geomorphological observation system. In fact, the contributions by Dematteis *et alii* (2022) and Godone *et alii* (2023) compared robotic and traditional measurements in an extremely slow landslide. The results confirmed the superiority of AIS in detecting minimal deformations and ensuring measurement continuity, thus further consolidating its position as the reference technology. While the inclinometer of the 1950s enabled us to see inside the body of the landslide for the first time, AIS allows us to observe its evolution in real time today, transforming monitoring from a series of snapshots into true continuous kinematic monitoring. In this context, the objective of this study is to evaluate the effectiveness of the robotic inclinometer by applying it to different case studies, thereby showcasing its remarkable capacity to adapt to diverse geomorphological dynamics. In scenarios involving rigid rock masses on top of ductile formations, where lateral spreading generates slow but inevitable deformations, the AIS has enabled movements along structural discontinuities to be isolated with extreme precision. The continuity of the data has allowed correlations to be established between micro-displacements that would inevitably have been overlooked by discontinuous manual monitoring. Conversely, in landslide contexts involving loose materials, automation has solved the critical problem of reading frequency during acceleration phases. In these cases, the AIS's ability to record the evolution of deformation in real time, particularly around sliding planes, has been fundamental to defining early warning thresholds and offering immediate decision support. Cross-analysis of continuous inclinometer data and rainfall/snowfall data confirmed that the robotic inclinometer is a technological upgrade and a diagnostic tool capable of reading kinematics in real time in different landslide contexts, regardless of their lithological nature. This defines AIS not only as a technological innovation, but also as a significant evolution in the monitoring of deep deformations. This has major implications for scientific research, civil protection and the preservation of cultural heritage.

TECHNOLOGY BACKGROUND

Historically, the monitoring of horizontal ground movements for the characterisation and management of instability phenomena has been conducted using the inclinometric method (Dunnicliff, 1993). The standard procedure involves installing a PVC or ABS guide tube, through which a measuring probe is manoeuvred. Traditional inclinometers, which are based on precision servo-accelerometers, operate by acquiring angular readings at discrete depth intervals along two orthogonal axes, depending on the probe pitch (usually Δ = 0.5 m). These measurements are translated into a series of differential displacements which, when integrated, provide the cumulative deformation profile with respect to the initial reference (Mikkelsen, 2003). The servo-accelerometer (or force balance) is based on an electromagnetic circuit that maintains perfect balance of a mass. This technology guarantees zero-point stability and resistance to thermal variations, enabling the detection of infinitesimal differential displacements with minimal background noise. However, these sensors are expensive and bulky, and they consume a significant amount of energy. This has often limited their use to individual installations, making it difficult to create dense networks or self-powered systems in remote locations. Against this technological background, the servo-accelerometer has been replaced by MEMS (Micro Electro-Mechanical Systems) technology over the last decade, marking a real change of direction. The main advantage of MEMS is their scalability. In fact, miniaturisation and extremely low energy consumption mean these sensors can be integrated in extreme situations (Wu *et alii*, 2025). Numerous studies have demonstrated the adequacy of MEMS performance in monitoring ground deformation, despite their differing characteristics to those of traditional servo-accelerometers (Setiawan *et alii*, 2021). Despite their cost-effectiveness and compact size, the use of MEMS sensors in geotechnical monitoring is subject to balance temporal continuity of readings with the spatial resolution of the monitoring network. Traditionally, fixed inclinometer chains (IPIs - In-Place Inclinometers) have been used to obtain real-time and continuous data over time. While this technology eliminates human error and the costs associated with manual readings, it has inherent limitations relating to the discretisation of measurements. IPIs consist of a series of discrete biaxial sensors that are permanently installed inside the inclinometer tube. This provides continuous monitoring over time, but the monitoring is discontinuous in space (Freddi *et alii*, 2023). Spatial resolution is strictly limited by the sensor installation pitch (typically no less than 1.0-2.0 metres). Covering the entire borehole column with static sensors leads to an exponential increase in costs and wiring complexity, often forcing designers to choose wide measurement pitches. This limitation can be a significant issue because if the sliding plane occurs within the range of two consecutive sensors, its exact location and the extent of the movement cannot be measured directly and must be estimated, which introduces uncertainty into the kinematic analysis.

To overcome these limitations, the AIS (Automatic Inclinometric System) was developed and patented by CNR IRPI. This device uses a single probe with MEMS sensors and a movement mechanism that is controlled by a high-resolution optical encoder to ensure sub-millimetric repeatability of the measurement point. The AIS automatically takes double readings at 0° and 180°, eliminating alignment and drift errors and improving the final accuracy of the deformation profile. The fundamental difference between AIS and IPI systems lies in the spatial resolution of the displacement profile and the resulting diagnostic capability for identifying slip planes. The AIS uses robotic movement and a high-precision encoder to autonomously scan the inclinometer tube with a typical measurement step of 0.5 metres (like manual surveying), covering the entire length to be investigated.

Controlled descent/ascent velocity and precise sensor positioning ensure more consistent and reliable data over time, eliminating operator uncertainty. The AIS can perform measurement cycles autonomously, even daily or more frequently, to ensure continuous, high-density time series. Technological advances in these systems have also led to traditional power and signal cables being replaced by a thin Dyneema cable. This cable is extremely lightweight, and it has minimal stretch that optimises measurement accuracy. Thanks to the control unit being integrated directly onto the probe (Fig. 2), the system takes on a semi-wireless configuration. This not only streamlines the instrumentation but also facilitates installation in remote locations where the entire apparatus can be powered autonomously by photovoltaic panels. The greater density of spatial data generated by the AIS enables more robust identification of the shear zone and more reliable estimation of the thickness of the cut band. These are fundamental parameters for geotechnical modelling and stability checks.

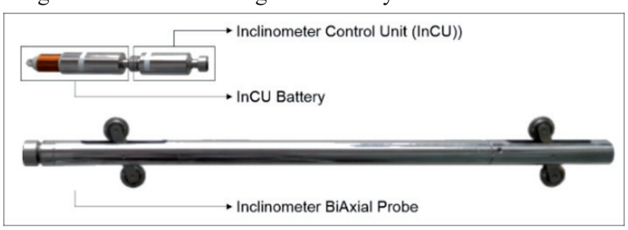

Fig. 2 - Control unit and biaxial probe of the AIS system

Furthermore, this capability for acquiring high-frequency data is essential for active landslides, as it enables the critical acceleration phases induced by piezometric variations to be detected, thus allowing early warning systems to be implemented. In highly critical contexts, AIS also provides the continuous and accurate output necessary for real-time risk control and management (Godone *et alii*, 2025). Consequently, the AIS system is deemed a superior alternative to manual methods and fixed inclinometer chains, offering a comprehensive deformation profile with optimal temporal and spatial resolution, a prerequisite for predictive monitoring in contemporary geotechnical engineering. Table 1 provides a brief comparison of the techniques employed in geotechnical monitoring.

SYSTEM	MANUAL	IPI	AIS
Probe	Single	Multi	Single
Survey	Periodic	Continuous	Continuous
Interval	Maximum (Full profile)	Limited (Sensor location)	Maximum (Full profile)
Precision	Variable	High	Ultra-high
Costs	Low (operator)	High (num. of sensors)	High (the robot)
Installation	Temporary	Complex (num. of sensors)	Minimal
Footprint	None	Only datalogger	Case for Motor/Winch

Tab. 1 - Comparison between manual, chain (IPI), and robotic (AIS) measurement systems

APPLICATIONS AND CASE STUDIES

The performance of a geotechnical monitoring system is characterised not only by its accuracy, but also by its ability to provide consistent kinematic data in complex, constantly evolving geological contexts. While technological advances have led to increasingly sophisticated sensors, transitioning from manual to automated monitoring is a necessary step in the evolution of modern geo-hydrological risk management. This work aims to demonstrate how high-frequency robotic acquisition overcomes the limitations of traditional instrumentation by offering continuous reconstruction of the deformation profile along the entire vertical. The first scenario relates to instability in the municipality of Borrello (CH), which is characterised by slow and deep lateral spreading. The geological context features imposing, intensely fractured sandstone masses overlying a clayey basement. The geolithological setting is characterised by a structural escarpment that is progressively evolving towards collapse and overturning phenomena. The second scenario focus the landslide on the northern part of the municipality of Chieti (CH), an area that has historically experienced complex roto-translational slides threatening the integrity of the urban centre.

Borrello

The municipality of Borrello is in the south of the province of Chieti, on the border between the regions of Abruzzo and Molise. Situated at an altitude of approximately 804 metres above sea level, the municipality is located on a plateau overlooking the middle Sangro River valley (Fig. 3). Frequent landslides affect the area, mainly in zones adjacent to the urban centre on the west and northwest sides. In this part there is a structural escarpment exceeding 140 m in height. This topographical configuration gives rise to the complex lateral spreading kinematics (Demurtas *et alii*, 2022) affecting the slope, making deep monitoring essential for the town's safety. The upper part of the slope consists of micaceous sandstone formations referred to siliciclastic turbidite deposits, which exhibit significant lithological variability. The lithofacies transition from fine clayey-silty facies to coarse sandy sandstone with local intercalations of conglomeratic lenses as one moves upwards. In contrast, the substrate consists of marly-calcareous units characterised by alternating calcilutites and pulverulent marls, which act as a less permeable base. The structural layout is defined by the position of the discontinuity fractures, which dip towards the southwest. The inclination varies between 10° and 45°, generating a configuration intermediate between crossbedding and bedding parallel to the slope profile. This

Fig. 3 - Large-scale hill shade of the area. (a, b) Location of the survey

geometry, combined with the fracturing of the rock masses, is the main predisposing factor for the deep instability phenomena and lateral expansion movements observed in the northwest part of the hamlet. To identify the kinematics, a geognostic borehole was drilled to 131 metres below ground level.

The upper portion of the succession consists of calcareous lithotypes characterised by a high degree of fracturing, with frequent inclusions of nodular and lenticular flint (Fig. 4). This significantly reduces the mass's mechanical strength and governs its hydrogeological regime, giving it high permeability due to fracturing. At greater depths, however, there is a shift towards clayey deposits intercalated with thin calcarenite layers. This interval, mark the transition to plastic mechanical behaviour.

Fig. 4 - Details of the material extracted from the core drilling performed

The instability perimeter zone was identified using the InSAR technique (Fig. 5). This analysis shows a slow and continuous evolution over time, which poses a significant risk for the long-term integrity of both structures and infrastructures.

Due to the high fracture density and the significant impact of discontinuities on structural weakness, an automatic AIS

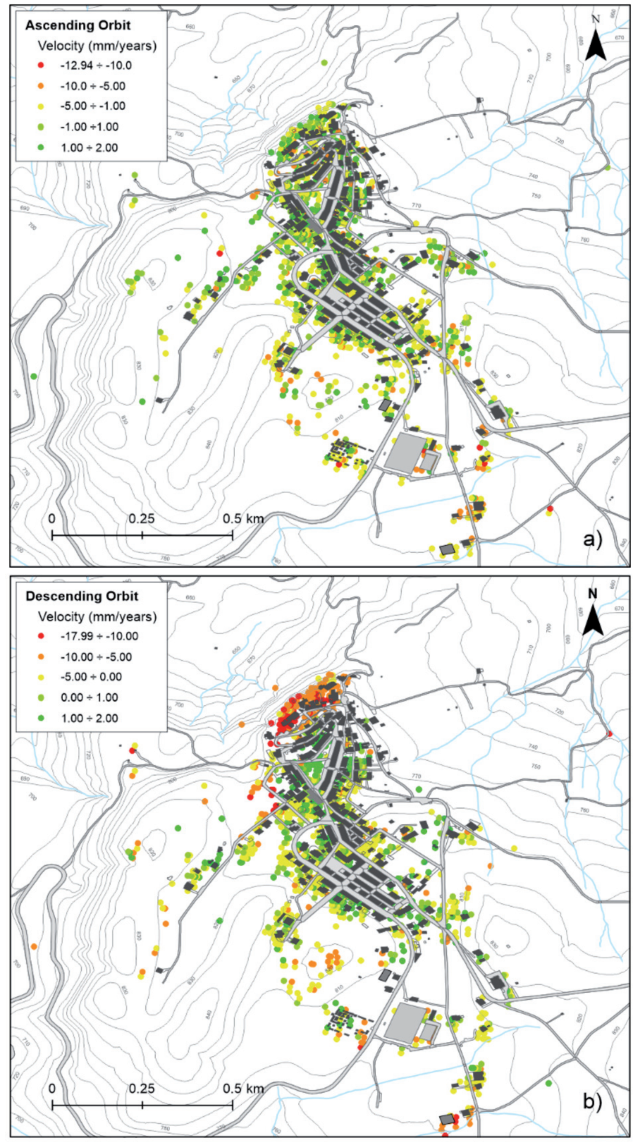

Fig. 5 - Vertical deformation rates for the ascending (a) and descending (b) orbit in the area from InSAR data using Sentinel-1 satellite constellation

monitoring system was installed to study the area's kinematics (Fig. 6). This system uses an inclinometer probe with a measurement pitch of 500 mm and a high-precision, biaxial MEMS sensor, with a resolution of 0.0015° and an accuracy of 0.01% FS.

A total of 280 readings were collected at regular intervals between July 2024 and October 2025. The high density of readings confirms both the continuity of the phenomenon and the effectiveness of high-frequency monitoring in capturing the kinematic of the slope.

In detail, the Figure 7 only shows some profiles for the local and the cumulative data processing of both the Channel

Fig. 6 - Final configuration of the Installation of the Automated Inclinometer System (AIS)

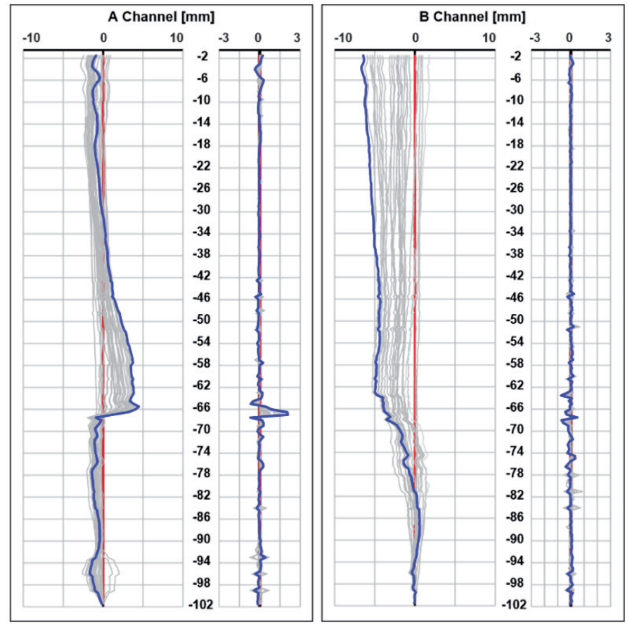

Fig. 7 - Cumulate and local data from 21/07/2024 to 28/10/2025

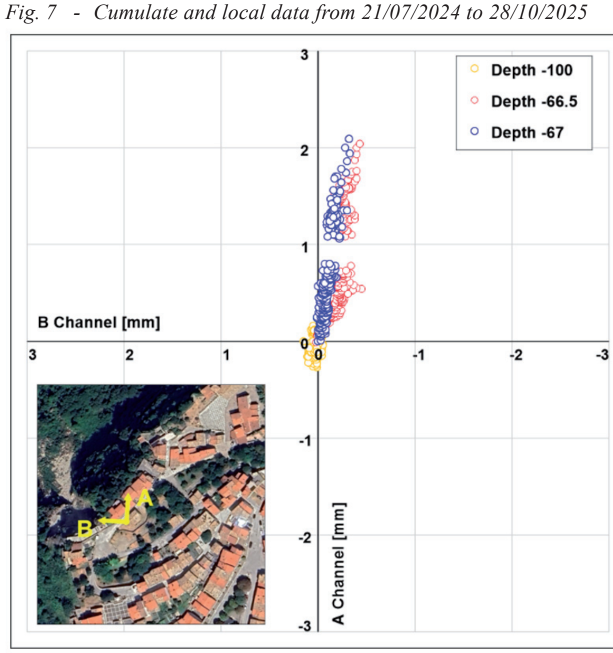

Fig. 8 - Polar graphic of the local displacement results at different level

A and the Channel B. The results highlight a kinematic regime characterised by low, yet constant, displacement velocity. The movement appears to be primarily driven by the component in the direction of Channel A, that shows an extremely localised displacement peak. There is a clear kinematic discontinuity between -65 and -70 metres, with a maximum cumulative displacement of around 5 mm. The unidirectionality of the movement is confirmed by the negligible transverse component recorded in Channel B. The Figure 8 illustrates the local displacement polar results at different level in depth. These data confirm the stability between -76 and -100 m. In contrast, the time series at -66.5 m and -67 m exhibit a progressive and constant displacement trend. The vectors at these depths are strictly concentrated within a single quadrant, indicating well-defined, structurally controlled kinematics. The absence of distributed deformations in the adjacent horizons indicates a rigid planar rupture mechanism.

The analysis of the temporal evolution of movements was conducted by processing data of local displacement at different depths (Fig. 9). This made it possible to isolate the kinematic behaviour of specific sectors of the mass and monitor the velocity of the movement over time. The graphs confirm that the main kinematic activity is concentrated within a narrow depth range of 66.5 - 67.0 metres. This suggests that the mass behaves like an undeformed body translating above a well-defined shear surface. Minor variations at greater depths (*e.g.* -100 m) lack preferential orientation and are attributed to instrumental noise or insignificant micro-settlements.

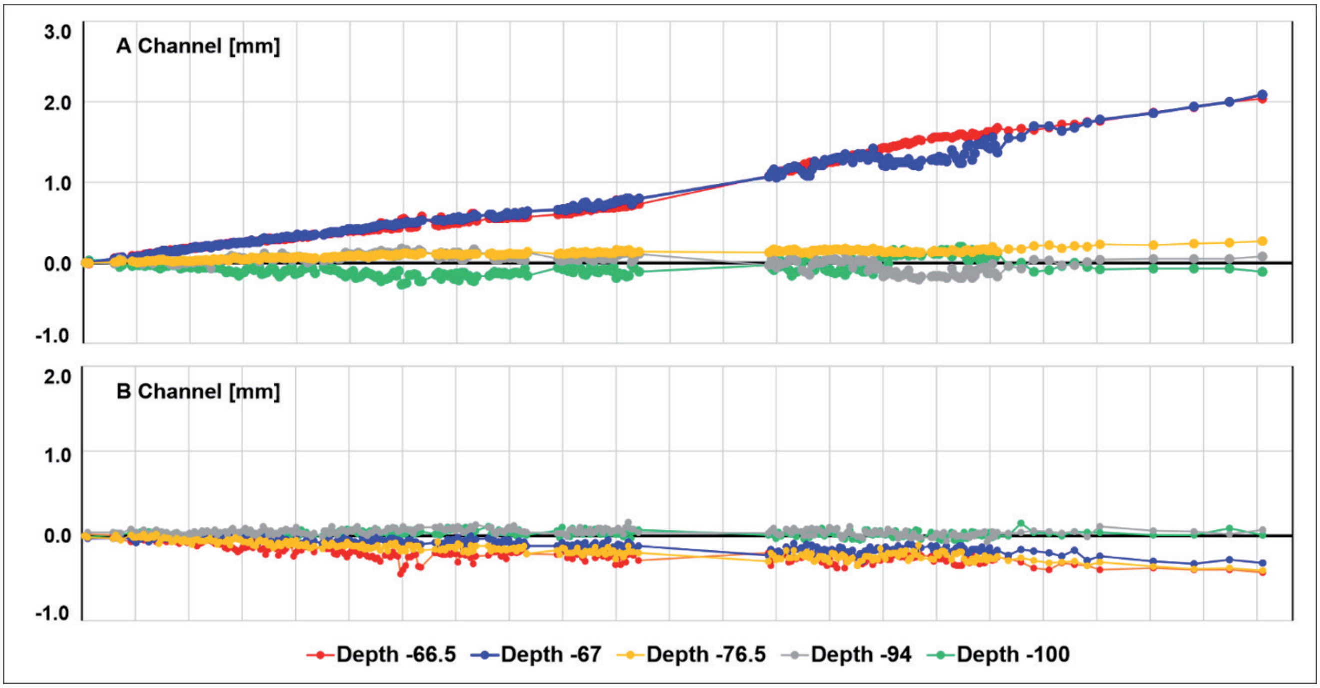

Fig. 9 - Local displacement processing over time at different depths for both Channel A and Channel B. From July 2024 to October 2025

Chieti

Types of landslides such as the one investigated in Chieti represent complex systems that have a significant impact on the vulnerability of infrastructure, land use and settlement safety (Sciarra *et alii*, 2022; Mangifesta *et alii*, 2024). The phenomenon is characterised by its slow and continuous development, which makes assessment and mitigation particularly difficult (Mangifesta *et alii*, 2025). The heavily anthropized northern part of the Chieti hill is one of the most critical and complex hydrogeological risk scenarios in the Abruzzo Apennines. The geological context is characterised by a complex stratigraphic overlap defined by an upper sandy-arenaceous unit (silty sands and sandy silts) of considerable thickness (over 30 metres), which rests on an impermeable substrate of grey-blue marly clays. While the transition between the two units is gradual with no anomalous contacts, the difference in hydraulic conductivity favours the accumulation of suspended aquifers within the sandy-arenaceous body. Flow surfaces are primarily found in the upper levels, where contrasts in permeability and water saturation trigger movements that directly affect the integrity of the urban centre and strategic infrastructure. The spatial distribution of persistent scatterers (PS), obtained from ascending and descending acquisition geometries (Ciampi *et alii*, 2025) and projected onto a 3D digital terrain model, reveals a significant accumulation of negative deformations (lowering) in the northern part of the city. The breakdown of displacement vectors into vertical (up-down) components reveals that kinematics is dominated by differential subsidence rates of up to -8.65 mm/year in areas with steeper slopes. This dynamic is closely related to the local hydrogeological structure. The high density of measurement points in the built-up area has enabled the extent of the landslide to be mapped with millimetric precision and areas of maximum deformation (Fig. 10). The measured displacement rates made it possible to accurately delineate the most active areas, highlighting kinematics that are consistent with the local geomorphological structure. This multi-temporal analysis confirms that the phenomenon does not occur in isolated instances,

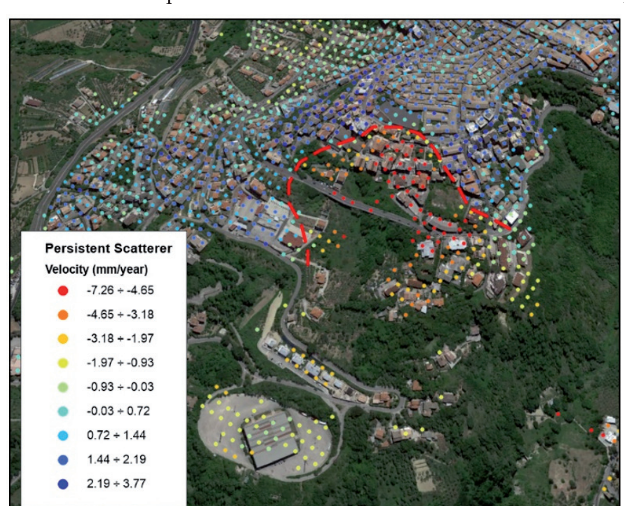

Fig. 10 - Boundaries of area of maximum deformation from InSAR data using Sentinel-1 satellite constellation

but rather in response to continuous stress linked to variations in piezometric levels within the sandy-arenaceous unit.

This context shows a strong correlation with the evidence on the ground. In particular, the area of maximum deformation coincides with the location of buildings displaying severe cracking, some of which have already been evacuated. In this context of historical instability, high-frequency automated monitoring systems are indispensable tool for understanding the kinematic evolution of moving masses and managing risk. The geotechnical investigation and monitoring plan involved the implementation of five multi-parameter stations, which were strategically located within the study area. Two boreholes were taken at a depth of 50 metres below ground level in each station, with the aim of characterising soil kinematics evolution. To reconstruct the hydrogeological model, an open-tube piezometer was installed in each borehole. Each piezometric column will be provided with electric pressure transducers to enable continuous measurement of the hydraulic load. All sensors will be integrated into a data acquisition network based on wireless transmission protocols to capture fluctuations in interstitial pressure and allow the correlation of rainfall patterns, subsoil hydraulic response and deformations in real time. At four of the five stations, displacement data are collected through periodic manual readings using manual inclinometer measurements to ensure spatial coverage of the site. At the most critical sector, which was identified using satellite interferometric analysis (InSAR), an AIS unit has been installed to enable the automated, high-frequency acquisition of displacement profiles (Fig. 11).

The AIS's high sensitivity has enabled deformation signals to be identified that would have been indistinguishable from instrumental background noise in a conventional manual reading. Although the data acquired during the initial monitoring phase show extremely limited movement (Fig. 12), it was possible to identify some kinematic discontinuities of potential geotechnical interest. Analysis of the displacement profiles (channels A and B) reveals three potential critical issues. An initial systematic deviation (millimetric) is observer in the -20.0 m / -23.0 m sector. This could be related to lithological transition horizons, where contrasts in soil stiffness favour a different deformation response. Another point

Fig. 11 - Automated Inclinometer System with power system that include 400w solar panel and storage battery

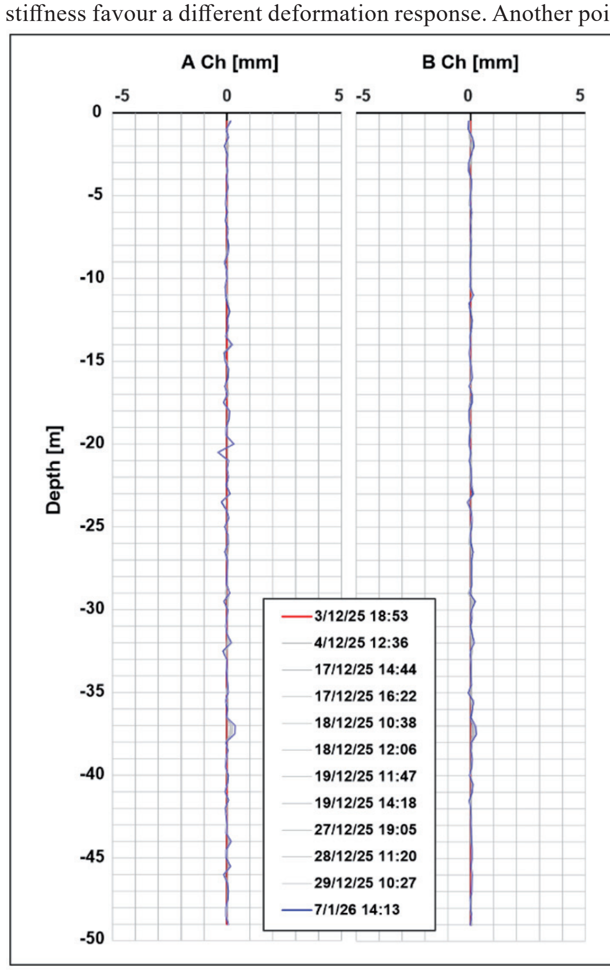

Fig. 12 - Local differential processing from -0 to -50 m (Channel A and Channel B)

anomaly emerges at a depth of -37.0 m. The persistence of this signal in the reading cycles suggests the presence of either a deep slip plane or an incipient viscous process, which requires continuous observation to understand its evolution. While the initial values recorded are currently within the range of 'micro-displacements', the spatial consistency of the readings at -20 m, -23 m and -37 m with the geotechnical information from the surveys suggests that the system is detecting the initial stages of stress variation in the slope. Integrating this data with the variations in interstitial pressures measured by the piezometric mesh will be crucial. The aim is to establish whether these localised deformations accelerate in line with the rise in the water table, thus confirming a causal link between hydraulic variation and the mechanical response of the landslide mass.

CONCLUSION

Evidence emerging from this study confirms the importance of the Automated Inclinometer System (AIS) like a significant technological advancement in conventional geotechnical monitoring. A comparative analysis of manually acquired data and data derived from automation reveals the AIS's ability to detect weak kinematic clues that are often obscured by instrumental background noise and systematic errors associated with manual measurement processes. In the geological context of the Borrello lateral spreading event, the system's high spatial resolution enabled the kinematics of deep deformation to be characterised with extreme precision, locating a primary slip surface approximately 66.5 metres from ground level. The temporal continuity of the readings also enabled the correlation of cumulative micro-displacements of a few millimetres per year with the structural layout of the fractured rock mass. This provided an objective database for validating numerical stability models. At the same time, applying the system in the urban context of Chieti demonstrated the need for high-frequency monitoring for risk management in urban areas. The ability of the AIS to operate in near real time was fundamental in identifying the response of loose soils to hydro-meteorological stresses over time, overcoming the critical issue of discrete measurements, which by their nature cannot guarantee the timeliness required for civil protection. While issues remain regarding the vulnerability of the probe in the presence of high displacement gradients and the need for specialised electromechanical component maintenance, the observed performance makes robotic technology significantly superior to traditional measurements or chain systems. In conclusion, systematically integrating AIS into large landslide monitoring plans optimises the quality of geotechnical data and opens new possibilities for developing early warning algorithms based on artificial intelligence, as well as integrating InSAR satellite remote sensing techniques. The future of hydrogeological instability studies therefore lies in an integrated, multi-platform approach. millimetre-precise deep point measurements are essential for analysing large-scale area deformations and ensuring a comprehensive understanding of the territory's morpho-dynamic evolution.

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