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MERCURY: MULTI-PLATFORM MONITORING SYSTEM FOR RAILWAY INFRASTRUCTURE SAFETY

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EXTENDED ABSTRACT

In località Scrajo, situata nel comune di Vico Equense (Napoli, Italia), si sviluppa una linea ferroviaria appartenente alla rete della Circumvesuviana, una infrastruttura storica e strategica per la mobilità regionale. Il contesto geologico è caratterizzato da un alto strutturale (horst) di natura carbonatica meso-cenozoica, bordato da faglie ad alto angolo, su cui poggiano depositi di copertura di natura piroclastica (Vitale & Ciarcia, 2018). La morfologia dell'area presenta acclività elevate (30°- 40°), rendendo i versanti suscettibili a fenomeni franosi, come testimoniato dagli eventi storici (frana del 1966 a Scrajo e frana del 1997 a Pozzano) che hanno interessato le coperture piroclastiche mobilizzate lungo i canali di drenaggio e i versanti acclivi (Civita & Lucini, 1968; Santo & Tuccimei, 1997; Fusco *et alii*, 2023). Dall'analisi degli inventari e di studi recenti si conferma la predisposizione dell'area a frane per crollo/ribaltamento e colate detritiche rapide, imponendo la necessità di un monitoraggio specifico della rete ferroviaria, sia per i fenomeni esogeni (versanti) che endogeni (infrastruttura in sotterraneo), utile per studiare e prevenire futuri eventi pericolosi per l'infrastruttura e per la popolazione.

In questo studio vengono presentati i risultati preliminari ottenuti nell'ambito del progetto MERCURIO, che ha come obiettivo quello di sviluppare un sistema innovativo di monitoraggio multipiattaforma a supporto del processo di ispezione e manutenzione delle infrastrutture ferroviarie regionali. Saranno qui presentati i risultati della campagna di monitoraggio (2024-2025) che ha previsto l'installazione di una rete di sensori per correlare le condizioni ambientali (piogge) con la risposta dell'infrastruttura (stato tensionale) e del suolo (contenuto d'acqua). Per il monitoraggio di superficie, sono state installate 12 sonde capacitive a diverse profondità (40 cm e 80 cm) all'interno della coltre piroclastica sovrastante la galleria, affiancate da una stazione termo-igro-pluviometrica (Sepe *et alii*, 2023). Per il monitoraggio strutturale in sotterraneo, all'interno della galleria ferroviaria sono stati installati: un sistema VMS (*Vibration Monitoring System)* per l'analisi delle vibrazioni indotte, un fessurimetro elettrico su una lesione principale in volta, due barrette estensimetriche a corda vibrante e due martinetti piatti ai piedritti per la valutazione dello stato tensionale e deformativo della galleria.

L'analisi dei dati raccolti ha evidenziato dinamiche differenti tra superficie e sottosuolo. Per quanto concerne la coltre piroclastica, il contenuto d'acqua volumetrico ha mostrato una stabilità nei periodi invernali/primaverili e un decremento significativo in estate, interrotto solo da picchi in corrispondenza degli eventi piovosi. È emerso che le variazioni di contenuto d'acqua sono maggiormente influenzate da piogge di lunga durata e moderata intensità (che impattano anche i sensori a 80 cm) rispetto a eventi brevi e intensi, durante i quali le sonde profonde hanno registrato variazioni trascurabili. Relativamente all'infrastruttura ferroviaria, i martinetti piatti hanno indicato una sostanziale stabilità dello stato tensionale dei piedritti. Le misure estensimetriche hanno fatto registrare deformazioni stagionali (aprile-novembre), probabilmente correlate alle fluttuazioni della falda acquifera, rientrate poi a valori di deformazione quasi nulla. Il monitoraggio della lesione in volta tramite fessurimetro ha registrato spostamenti nell'ordine di 0,3 μm, confermando l'assenza di movimenti gravitativi attivi preoccupanti a carico della struttura. Un focus specifico è stato dedicato al monitoraggio continuo delle vibrazioni tramite VMS su un intervallo di 24 ore. Le frequenze registrate si clusterizzano in due tipologie: una frequenza "minore" (0 - 40 Hz), associata a vibrazioni di bassa intensità come il traffico veicolare della galleria sottostante, e una frequenza "maggiore" (> 40 Hz), associata a vibrazioni di media intensità, inclusi i transiti ferroviari. Applicando specifiche tecniche di filtraggio del segnale, è stato possibile eliminare il rumore del passaggio treni e le frequenze del traffico veicolare, isolando così le frequenze residue per studi futuri.

Il progetto MERCURIO ha implementato un approccio modulare per la gestione dell'infrastruttura. La catena di elaborazione del dato, basata sul filtraggio del rumore operativo, ha permesso di verificare l'efficacia e la precisione della strumentazione in sito. I risultati confermano l'assenza di criticità strutturali immediate per la galleria. In definitiva, il sistema contribuisce alla creazione di un gemello digitale dell'opera, trasformando la tratta in una *Smart Rail* (Cruz *et alii*, 2018) resiliente e supportando una manutenzione basata sui dati reali.

ABSTRACT

The MERCURY project aims to develop an innovative multi-platform monitoring system designed to support the inspection and maintenance of regional railway infrastructures, with the ultimate goal of implementing a Decision Support System (DSS). This objective is achieved through a modular and scalable framework capable of integrating data from different sources. MERCURY addresses the critical need for regional railway operators to have a flexible tool that responds to the specific geological and structural vulnerabilities of the territories they traverse. Optimising maintenance procedures is essential for averting critical conditions that could compromise passenger safety, while simultaneously minimising costs related to line downtime and manual on-site inspections. This study discusses the preliminary results obtained following the in-situ installation of a sensor network (comprising flat jacks, capacitive probes, crack gauges, and strain gauges) in the Scrajo locality, situated within the municipality of Vico Equense (Naples, Italy), along the Circumvesuviana railway network. This site was selected as a strategic testbed for the MERCURY project due to its susceptibility to landslides (triggered by rockfall or topple) and rapid debris flows, as exemplified by the historical landslide event of 1966. The implemented infrastructure is designed to monitor both exogenous phenomena, such as landslides (tracked via capacitive probes and weather stations) that could impact the railway track, and endogenous factors, including structural damage to underground assets (monitored via flat jacks, strain gauges, crack meters, and velocimeters). Consequently, the system enables the comprehensive observation of both potential environmental triggers and their direct effects on railway assets.

Keywords: *monitoring, settlements, landslides, railway, hazard*

INTRODUCTION

The management and monitoring of linear infrastructure, such as railways, roads, and motorways, require substantial economic and human resources, representing a significant portion of operators' annual budgets. To guarantee asset functionality and user safety, it is essential to identify vulnerabilities promptly and to plan both routine and extraordinary maintenance interventions (Kurnaz *et alii*, 2009; Di Benedetto *et alii*, 2019; Santo & Massaro, 2025).

Within organisational frameworks, responsibilities are typically allocated through the delineation of macro-areas and sub-sectors, with each entity entrusted with the maintenance and surveillance of its specifically assigned section. Currently, inspections are conducted using mechanical methods and technical personnel (including maintenance staff, supervisors, and technicians) who perform visual assessments to identify potential instabilities or anomalies (Mahmoodian *et alii*, 2022). However, this approach has several limitations, such as the difficulty of centralising field data, non-negligible transmission times, and the inability to identify instabilities until they become clearly evident, which often occurs only after damage has already been sustained.

To overcome these limitations, real-time monitoring techniques have been increasingly adopted techniques (Proto *et alii*, 2010; Zhu *et alii*, 2022), enabling the surveillance of extensive areas via ground-based installations. These techniques facilitate the continuous monitoring of infrastructure sections susceptible to deformation, providing crucial support for targeted inspections and timely interventions. The significance of these methods is further demonstrated by Ngamkhanong *et alii* (2018), who evaluate the advantages and disadvantages of various wired and wireless sensor technologies, focusing particularly on the design criteria for monitoring networks. Similarly, Santo & Massaro (2025) designed a real-time monitoring system that enabled safe infrastructure management by identifying the opening and closing phases of a road section affected by gravitational phenomena. Consequently, the implementation of real-time monitoring has been shown to reduce the frequency of closures and traffic restrictions (Mohanty *et alii*, 2025). Critically, this approach ensures the ongoing surveillance of identified instabilities through integration with diverse systems that facilitate the control of all relevant parameters (Brdys, 2014).

The MERCURY project is specifically designed to develop an innovative multi-platform monitoring system aimed at supporting the inspection and maintenance of regional railway infrastructures (Abbundo *et alii*, 2025). The Scrajo site, located in the municipality of Vico Equense (Naples, Italy), was selected as the primary testbed due to the area's susceptibility to landslides, specifically those triggered by rockfall, topple, or rapid debris flows, which pose a significant threat to the regional railway line (Civita & Lucini, 1968). The resulting monitoring strategy integrates in-situ geological, geotechnical, and structural data to facilitate the detailed analysis of stability conditions. This comprehensive approach offers robust support for risk mitigation activities. Furthermore, all collected data will be integrated into a web-based platform, providing a synoptic view of asset conditions and their surrounding environmental context. Ultimately, this framework will facilitate the development of a Decision Support System (DSS) tailored for infrastructure management authorities.

GEOLOGICAL AND GEOMORPHOLOGICAL SETTING OF THE STUDY AREA

The study area (Fig. 1) is situated within the municipality of Vico Equense (Naples), specifically focusing on the surroundings of the railway segments of interest. This line forms part of the Circumvesuviana railway network, a historic and vital infrastructure for mobility in the Campania region. Extending for approximately 142 km, the network connects

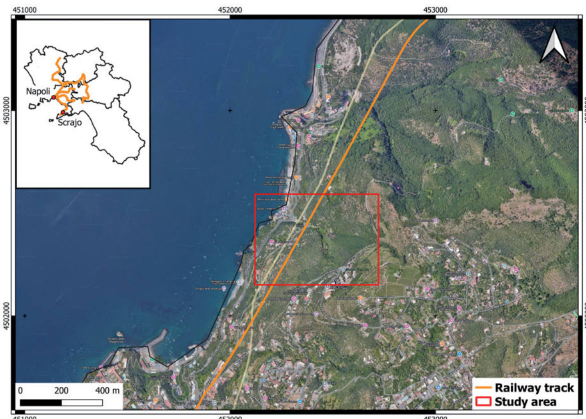

Fig. 1 - Location of the study area in Scrajo, Vico Equense (NA)

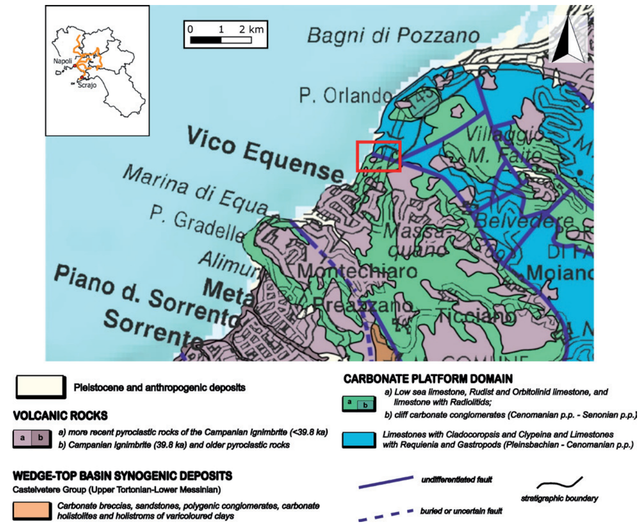

Fig. 2 - Geological map of the Scrajo area (modified from VITALE & CIARCIA, 2018); the study area is shown in red

the city of Naples with the Vesuvian municipalities and several of the region's most prominent tourist destinations, including Herculaneum, Pompeii, and the Sorrento Peninsula. As the sole railway route serving the Sorrento Peninsula, this specific section is estimated to accommodate several thousand daily commuters and over 2 million tourists annually, with a service frequency of approximately 15–20 minutes. The entire network is owned by the Campania Region, while infrastructure management is entrusted to the Ente Autonomo Volturno (EAV), which operates as both the infrastructure manager and the railway undertaking.

The investigated area is known as "Scrajo", a name derived from the historic "Scrajo Terme" thermal spa. Situated in the immediate vicinity of Vico Equense, this zone lies on the north-western coast of the Sorrento Peninsula, within a geomorphological context characterised by medium-to-high slope gradients, typically ranging between 30° and 40° and locally exceeding 45°. The area comprises an assemblage of Meso-Cenozoic carbonate reliefs forming a structural high (horst), bounded by high-angle NE-SW trending faults and dissected by NW-SE trending faults that generate alternating depressions (grabens) and structural highs. Specifically, the Scrajo area (Fig. 2) is located within the Vico Equense graben, which is bordered by the Monte Faito ridge to the north-east and the Meta ridge to the south-west, with two significant normal faults delineating this depression. The basement consists of Meso-Cenozoic carbonates belonging to the Apennine Platform. This entire sedimentary succession is sealed by Pleistocene deposits, which encompass volcanic products from the Campanian Ignimbrite and more recent Somma-Vesuvius activity, alongside alluvial and anthropogenic deposits (VITALE & CIARCIA, 2018).

The area is characterised by carbonate reliefs trending NW–SE along the axial sector of the Apennine ridge. This region encompasses some of the most significant mountainous reliefs in terms of both extent and elevation, often reaching heights of approximately 2,000 metres above sea level (a.s.l.). These reliefs exhibit a polygonal plan geometry, dictated by the fault systems bounding their flanks, and display pronounced slope steepness owing to the low erosional susceptibility of the constituent rock masses. Geomorphological features characteristic of this environment include paleosurfaces, fault scarps, and fault-line scarps, alongside an angular drainage pattern with low drainage density (SANTO & TUCCIMEI, 1997). Slope deposits and alluvial fans are situated at the outlets of drainage channels where they transition into less steep zones. Locally, significant landslide deposits and marine terraces are evident (FUSCO *et alii*, 2023) (Fig. 3). Furthermore, in proximity to the region's volcanic centres, stratified pyroclastic deposits frequently mantle the carbonate reliefs.

Regarding landslide mechanisms, according to the VARNES (1978) classification, these areas are primarily affected by rockfalls and/or topples, debris flows, and complex landslides. Rockfalls and topples are frequently observed on particularly steep slopes where morphology is controlled by tectonic lineaments. Conversely, debris flows typically occur along drainage channels containing mobilisable detrital material or along slopes covered by pyroclastic deposits.

Figure 3 illustrates the historical landslides within the study area included in the Official Inventory of the Basin Authority (FUSCO *et alii*, 2023). Notably, in 1966, the study area was struck by a landslide originating in the valley overlooking the thermal facility; this event resulted in three fatalities and the partial destruction of the railway station (CIVITA & LUCINI, 1968). Within this context, instrumentation was installed to investigate the slopes affected by this most recent landslide activity. This setup aims to monitor the condition of the pyroclastic cover, identified as highly susceptible to future instability, as well as the structural integrity of the railway tunnel housing the station.

MONITORING SYSTEM SETUP

The monitoring systems at the study area were deployed across two distinct sites within the same river basin during the 2024–25 period, as illustrated in Figure 3. At the pilot site, the monitoring regime quantifies temporal variations in state variables critical to the pyroclastic cover. These parameters include volumetric water content measured at various depths, ranging from the ground surface to the carbonate bedrock, and the environmental boundary conditions that influence the state of the cover (Sepe *et alii*, 2023). Specifically, a weather station situated on the slope provides data on rainfall depth during precipitation events, enabling the correlation of environmental parameters with the physical state of the pyroclastic cover. Furthermore, instrumentation was installed within the railway tunnel traversing the carbonate bedrock to facilitate the real-time monitoring of a specific infrastructure section. This installation was prompted by several site inspections that revealed cracks in the tunnel vault, potentially indicating active gravitational movements affecting the underground structure.

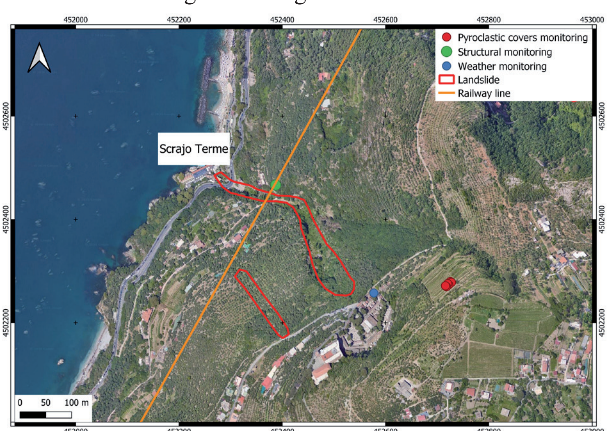

Fig. 3 - Landslide Inventory map (Fusco et alii, 2023) and location of the sensors installed

Specifically, the following instrumentation was deployed for the monitoring of the pyroclastic cover:

- Twelve capacitive probes installed in the soil within the valley affected by the 1966 landslide, overlooking Scrajo Terme and the railway station (see Fig. 3). These probes are positioned within the pyroclastic mantle and distributed at two specific depths: six at 40 cm and six at 80 cm below ground level (Fig. 4a);
- A thermo-hygro-pluviometric weather station situated in close proximity to the capacitive probes (Fig. 4b).
- Regarding structural monitoring, the target section (located approximately 300 m from the Scrajo Terme station) was selected in coordination with the infrastructure manager. The following sensors were installed:
- One Vibration Monitoring System (VMS) unit positioned within the tunnel at the railway station to facilitate continuous vibration monitoring (Fig. 4e).
- One electric crack gauge installed inside the railway tunnel across a lesion affecting the entire span of the vault, at a height of approximately five metres above the rail level (Fig. 4f).
- Two vibrating wire strain gauges mounted on the tunnel vault at a height of approximately four metres above the rail level (Fig. 4c).
- Two flat jacks equipped with pressure transducers installed along the tunnel sidewalls within the same section as the strain gauges, at a height of approximately 1.5 metres above the rail level (Fig. 4d).

Figure 4 provides photographic documentation of the equipment deployed at the two sites illustrated in Figure 3.

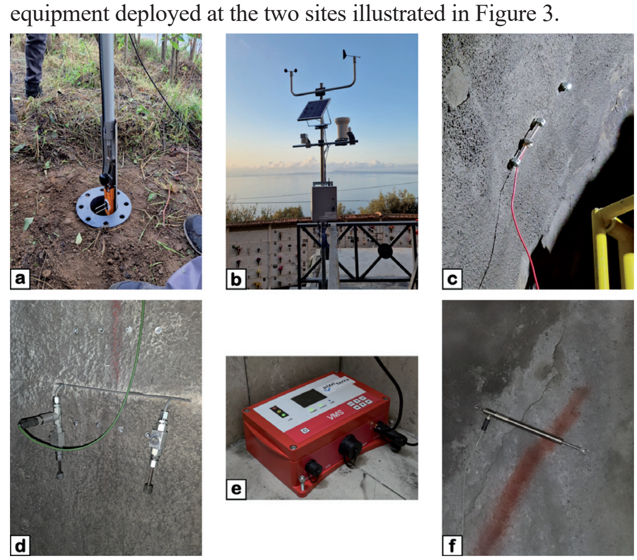

Fig. 4 - (a) capacitive probe; (b) weather station; (c) vibrating wire strain gauge; (d) flat jack; (e) VMS unit; (f) crack gauge

RESULTS AND DISCUSSIONS

As previously established, the surface monitoring regime focused on the pyroclastic cover through the installation of capacitive probes designed to track soil volumetric water content.

Figure 5 presents a comparative analysis of water content and precipitation for sensors positioned at depths of 40 cm (designated 1a–6a) and 80 cm (designated 1b–6b) below ground level. A preliminary analysis of the trends indicates that water content remained relatively stable throughout the winter and spring; subsequently, a significant decrease was recorded until the following autumn, attributable to limited precipitation (as illustrated in Figure 5b, which highlights data from the instrumentation at the 80 cm depth).

Notably, a strong correlation is observed between rainfall events and variations in water content at both monitored depths. Indeed, a clear correspondence exists between precipitation peaks and increases in water content, even during the

Fig. 5 - Water content measured by capacitive probes in relation to hourly rainfall accumulation.Sensors placed 40 cm above ground level (a); sensors placed 80 cm above ground level (b). The red box indicates high-intensity but short-duration rainfall events, while the green box indicates moderate-intensity but longer-duration rainfall events

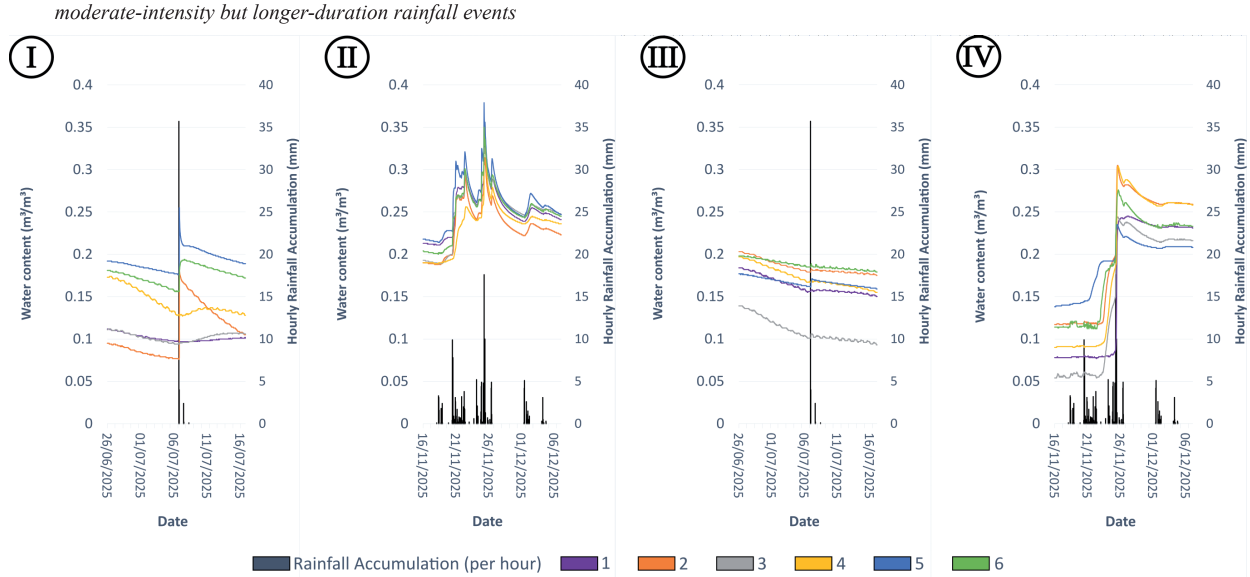

Fig. 6 - Water content measured by capacitive probes in relation to hourly rainfall accumulation. (I) high-intensity and short-duration event, sensors placed 40 cm above ground level; (II) moderate-intensity and long-duration event, sensors placed 40 cm above ground level; (III) high-intensity and short-duration event, sensors placed 80 cm above ground level; (IV) moderate-intensity and long-duration event, sensors placed 80 cm above ground level

summer months. Throughout the monitoring period, the water content within the pyroclastic cover responded directly and proportionally to the cumulative rainfall reaching the ground. Crucially, the data demonstrates that moderate-intensity rainfall sustained over several hours or days induces greater variations in water content compared to high-intensity, short-duration events.

Typical examples of the latter include the events recorded on 7th July 2025 (35.7 mm in one hour) and 23rd September 2025 (28.7 mm in one hour). During these instances (highlighted by a red box in Figure 5), only minimal variations in water content were registered by the shallower sensors (40 cm), while variations in the deeper sensors (80 cm) were negligible. In contrast, long-duration, low-intensity precipitation triggered significant variations across all sensors. Examples of this behaviour occurred during the periods from 3^{rd} to 14^{th} December 2024 (150 mm total rainfall) and from 18^{th} November to 5^{th} December 2025 (163 mm total rainfall), as indicated by the green boxes in Figure 5.

Figure 6 provides a detailed examination of the differing infiltration behaviours within the pyroclastic cover during various rainfall events. As previously noted, during the high-intensity, short-duration event on 7^{th} July 2025, rainwater infiltration was minimal, as surface runoff became the dominant process across the pyroclastic cover due to the precipitation intensity (Figures 6-I and 6-III). Conversely, for events of lower intensity but longer duration, such as the period from 18th November to 5^{th} December 2025, Figures 6-II and 6-IV clearly demonstrate that all sensors respond in direct proportion to water infiltration, which remains constant over time. During such events, surface runoff is minimal, while soil infiltration becomes the prevailing mechanism.

Figure 7 presents the recorded stress states of the tunnel sidewalls via flat jacks (Fig. 7a) and the tunnel vault via strain gauges (Fig. 7b), both installed at upstream and downstream positions; this instrumentation was subject to continuous monitoring throughout the study period.

Regarding the flat jacks, no significant structural concerns were identified; indeed, pressure variations remained limited to less than 10% for both sensors over the entire year. This pressure variation is likely attributable to the thermal expansion of the surrounding rock mass, driven by high solar radiation during the spring and summer months. Given that the rock cover overlying the tunnel is approximately 50 m thick, the seasonal rise in rock temperature accounts for the increased pressure observed in the sidewalls; as the rock enclosing the tunnel undergoes expansion, albeit minimal, it leads to a rise in the tunnel's confining pressure. This process, captured by the flat jacks, resulted in a pressure increment of approximately 1.5 bar across both instruments. With the onset of autumn and the subsequent return to cooler temperatures and reduced solar radiation, a corresponding decline in pressure values is observed.

While the seasonal trends in both datasets indicate overall structural stability, a significant deformation was recorded by the downstream strain gauge beginning on 29/04/2025 (Fig, 7b). These parameters returned to near-zero expansion conditions by 22/11/2025. This specific behaviour will be the subject of further investigation once a subsequent seasonal cycle has been observed and analysed.

Figure 8 illustrates the temporal evolution of displacements recorded by the crack gauge positioned across the primary vault lesion (see Figure 4f). Consistent with the other instrumentation deployed within the tunnel, the crack gauge is subject to continuous monitoring. As indicated in the graph, the maximum movement recorded by the device is approximately 0.3 µm. In line with the trends observed across the broader sensor network, this displacement appears to be influenced by

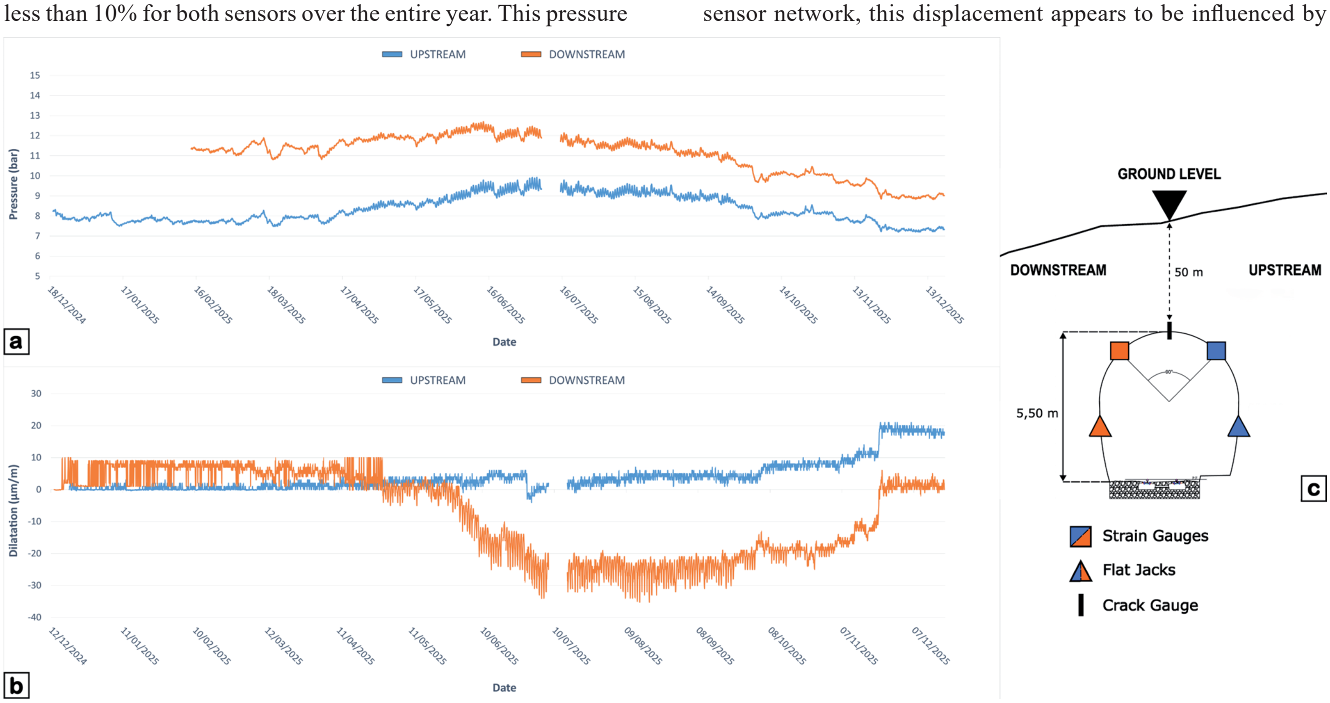

Fig. 7 - Monitoring of the stress state of the tunnel carried out through (a) flat jacks; (b) strain gauges; (c) schematic cross-section of the tunnel showing sensor locations

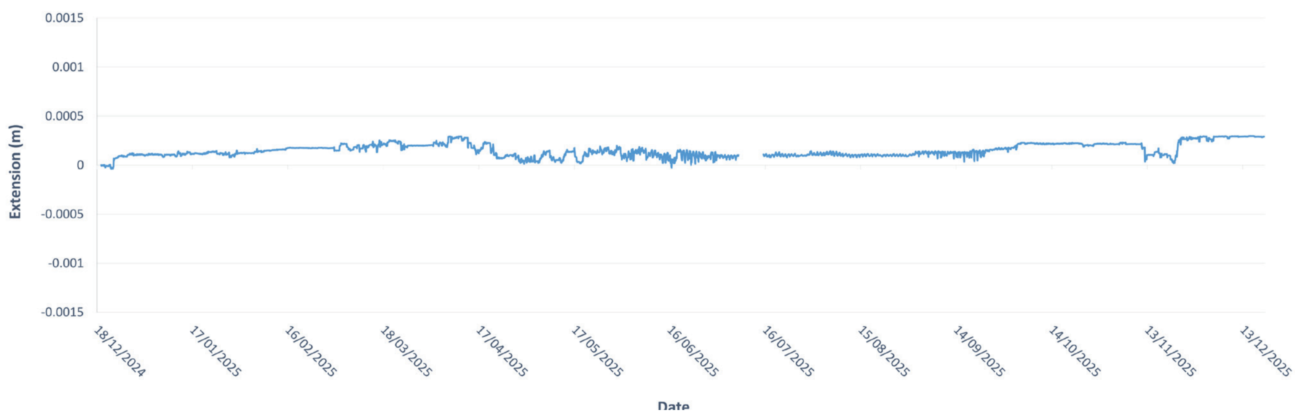

Fig. 8 - Monitoring of the crack affecting the entire tunnel vault tunnel using the crack gauge

Fig. 9 - 24-hour VMS monitoring of induced vibration frequencies recorded along the z-axis. The red diamonds represent the train transit. a) Measurements recorded by the device: "lower" frequencies (green box), "higher" frequencies (red box); b) Measurements filtered from noise caused by train transits and "lower" frequencies

seasonal fluctuations. Specifically, the crack exhibits a positive trend (indicating closure) during the winter and a reduction (indicating opening) during the summer months. While the crack is currently being monitored to assess its long-term evolution, the displacement recorded to date remains minimal.

Figure 9 illustrates the daily measurements of induced vibration frequencies obtained through continuous monitoring, plotted along the vertical component. As demonstrated in Figure 9a, the frequencies recorded by the device cluster into two distinct categories over time:

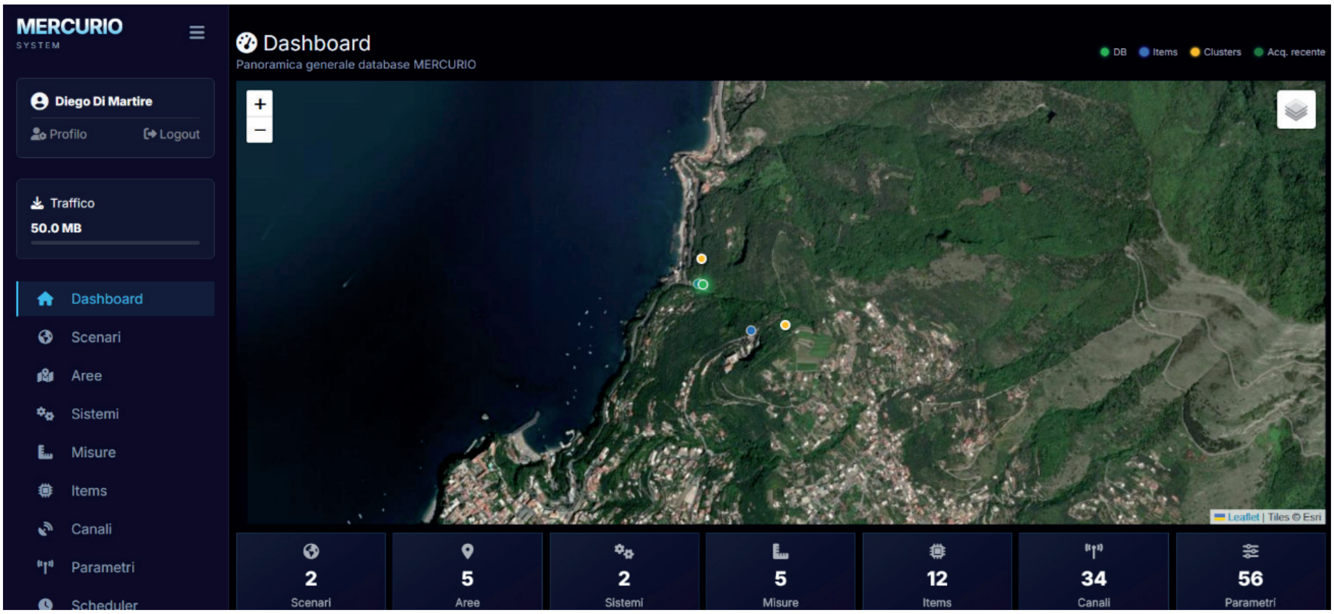

Fig. 10 - Dashboard of the web- based platform

1. A ‘lower’ frequency range (0–40 Hz), associated with low-intensity induced vibrations, such as those generated by vehicular traffic within the tunnel.
2. A ‘higher’ frequency range (exceeding 40 Hz), associated with medium-intensity induced vibrations. This interval encompasses vibrations induced by trains passing through the station, alongside other ancillary frequencies.

To isolate the structural data from the influence of train transits, a filter based on two distinct criteria was applied: (a) the exclusion of all frequencies associated with the arrival, station transit, and departure of trains, based on official timetables provided by the Infrastructure Manager (this resulted in the removal of a substantial number of measurements recorded during train passages); and (b) the filtering of all ‘lower’ frequencies, as previously defined. Figure 9b presents the frequency results following the application of this filter; these outcomes will be the subject of further investigation.

Finally, as previously noted, all acquired monitoring data were integrated into a web-based management platform (Fig. 10) and a dedicated data fusion framework. This architecture enables real-time data visualisation and analysis, empowering the infrastructure management authority with the actionable insights necessary to implement informed and effective risk mitigation strategies.

CONCLUSIONS

To address the diverse challenges inherent to railway infrastructure management, the MERCURY project employs a modular approach. This strategy integrates data from sensors distributed across the network into a unified, open-architecture web platform, ensuring that the monitoring system remains adaptable to both technological advancements and evolving operational requirements. Central to this framework is a sophisticated data management and processing chain designed to filter operational noise from daily measurements; this enables the dynamic identification and classification of risk zones within the infrastructure itself.

As previously discussed, this study outlines the preliminary results of the implemented monitoring system. This framework utilizes *in-situ* instrumentation essential for assessing surface displacements and triggering conditions (via capacitive probes), as well as for monitoring the deformation and stress-strain dynamics of the tunnel (via strain gauges, crack meters, and flat jacks). Analysis of the ongoing monitoring and the data acquired reveals that the system is highly effective in detecting high-precision parameters in real time. At present, no significant criticalities regarding the stress or cracking state of the railway tunnel have been identified.

Ultimately, MERCURY will contribute to the development of a comprehensive “Digital Twin” of the infrastructure, transforming specific railway sections into resilient “Smart Rails” (Cruz *et alii*, 2018). This digital evolution is designed to ensure the continuous management and processing of heterogeneous data streams, supported by the deployment of cutting-edge technologies such as three-dimensional acquisitions via Unmanned Aerial Vehicles (UAVs) in both surface and underground environments. The initial results of the photogrammetric survey conducted using UAVs within the Scrajo tunnel are illustrated in Figure 11.

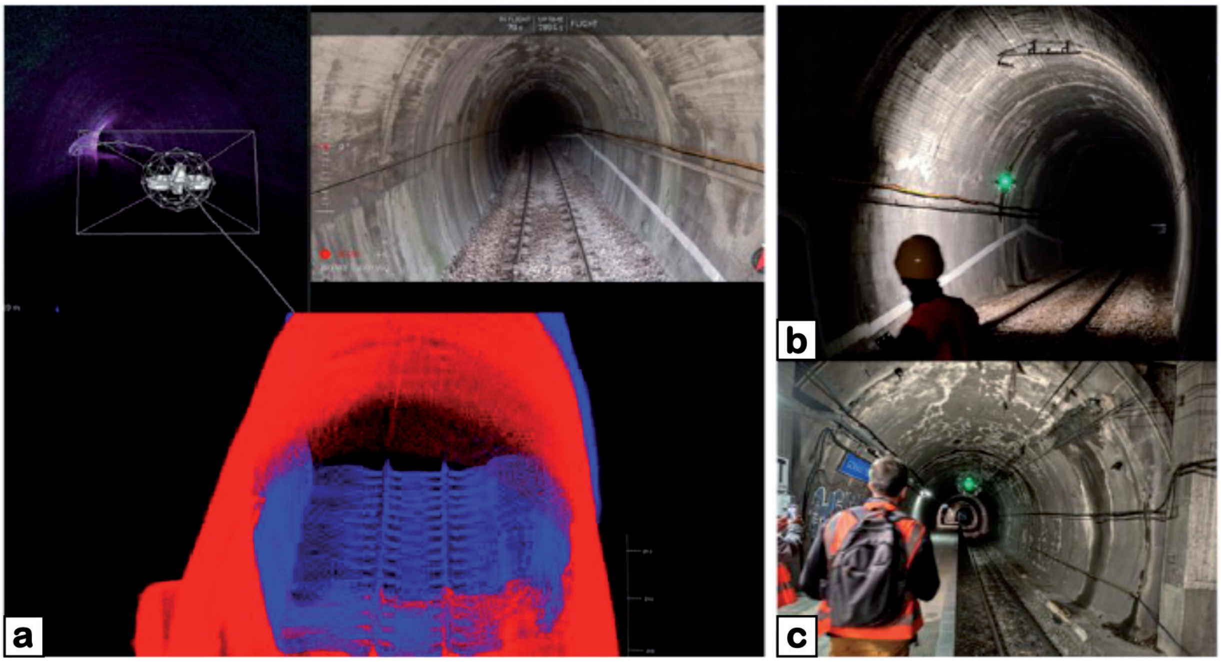

Fig. 11 - (a) Example of drone acquisition; (b) and (c) photographs taken during the drone flight within the tunnel (Abbundo, 2026)

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