

Integration of satellite monitoring and 3D modelling approach for multi-scale analysis of existing tunnel infrastructures

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ABSTRACT

Existing tunnel infrastructures are increasingly exposed to external geomorphological processes and progressive structural degradation, highlighting the need for integrated monitoring approaches. This study proposes a multi-scale framework combining satellite-based interferometric data and high-resolution image-based inspections to assess the condition of existing tunnels. Interferometric Synthetic Aperture Radar (InSAR) analysis was used to detect and quantify ground deformation in the surroundings of two tunnel sites in Southern Italy, while three-dimensional (3D) reconstructions of tunnel linings were generated from high-resolution imagery acquired with a mobile system. The integration of both datasets was implemented in a 3D visualization environment, enabling the joint interpretation of external slope deformation and internal defect distribution. Results reveal deformation areas that spatially correspond to tunnel sectors showing defects, e.g., cracked joints and minor water seepages. Although the correlations are qualitative, the integrated analysis provided preliminary evidence of geomorphological control on tunnel degradation, particularly near the portals. The combined use of InSAR and very high-resolution images thus offered complementary perspectives, long-term surface monitoring and detailed internal diagnosis – within a unified georeferenced framework. This study demonstrates the potential of integrating remote sensing and digital inspection tools for preventive maintenance and risk assessment of existing tunnels, enhancing operator safety and minimizing highway closure. The proposed workflow represents a step toward a digital, data-driven approach to tunnel asset management, consistent with national regulations for infrastructure safety evaluation.

1. Introduction

Underground tunnel infrastructures are increasingly exposed to the effects of ageing, environmental degradation, and external geomorphological processes. In recent decades, numerous studies have highlighted that the interaction between infrastructures and landslides, slope deformations, and other large-scale ground instabilities can lead to severe structural damage and pose significant safety concerns (e.g., Chen et al., 2020; Conforti & Ietto, 2019; Zhang et al., 2021). In the Italian framework, some recent literature reports that tunnelling activities can induce or reactivate slope instabilities. As documented in the Val di Sambro tunnel case study in the Northern Apennines (Italy), excavation triggered the reactivation of a pre-existing landslide and produced measurable deformations both at the ground surface and along the tunnel lining (Bandini et al., 2015). Similarly, investigations in the

Central Alps (Italy) revealed the challenges of tunnelling in areas affected by Deep-Seated Gravitational Slope Deformations (DSGSDs), underlining the interaction between slope kinematics and tunnel convergence (Gattinoni et al., 2019). At an international scale, several works from mountainous regions have deepened the understanding of tunnel-landslide interactions, employing *in-situ* monitoring, numerical modelling, and physical modelling approaches to classify failure modes and propose mitigation strategies (Zhou et al., 2025; Zhou et al., 2023; Zhu et al., 2021).

Italy houses the highest number of road tunnels in Europe, most of them belonging to the TEN-T (Trans-European Transport Network), and more than 50% of these structures are over 50 years old. Moreover, tunnels represent approximately 8% of the railway network (~1300 km), and more than a half have been built before 1970s (National Agency for the Safety of Railways and Road & Highway Infrastructures

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in Italy, *Agenzia Nazionale per la Sicurezza delle Ferrovie e delle Infrastrutture Stradali e Autostradali* – [ANSFISA](#)). Recent regulations underlined the need for extensive knowledge of these structures for predictive maintenance and resilient management. Publication of the Italian Guidelines (Italian Ministry for Infrastructures, *Ministero delle Infrastrutture e dei Trasporti* – [MIT, 2022](#)) has introduced a comprehensive regulatory framework for the inspection, monitoring, and maintenance of existing tunnels. The guidelines establish a structured multi-level methodology for safety and risk evaluation, ranging from preliminary data collection and visual inspections to advanced assessments that define an “Attention Class” which in turn guides subsequent monitoring strategies, detailed safety evaluations, and possible interventions ([Salomone et al., 2023](#)). This framework aligns with the broader concept of Structural Health Monitoring ([Brownjohn, 2007](#)), which combines non-destructive testing, periodic surveys, and innovative remote sensing methods to ensure the long-term safety and serviceability of underground infrastructures.

Parallely, innovative tunnel inspection methodologies, especially for existing tunnel infrastructures, have evolved significantly. Recent advances in 3D image-based reconstruction rely on high-resolution photographic surveys to document the tunnel lining and enable automated or semi-automated detection of defects such as cracks, seepages, and surface deterioration ([Attard et al., 2018](#); [Chaiyasarn et al., 2016](#)). These systems provide detailed surface information that complements traditional LiDAR surveys and mobile laser scanning technologies, which primarily capture geometric data ([Ma et al., 2018](#)). In parallel, Digital Twin modelling ([Machado et al., 2025](#)) opens new perspectives for detailed internal inspections, integrating geometric, structural, and monitoring data into a unified environment. Within this framework, the reconstructed 3D models obtained from tunnel image scanning can be continuously updated with new observations or sensor data supporting condition assessment, predictive maintenance, and long-term performance analysis. The use of digital modelling can offer significant advantages for tunnel management. A three-dimensional representation would enable reliable and immersive visualization of the tunnel interior, enhancing inspection activities through innovative scanning systems and advanced data handling procedures. Beyond supporting current inspections, such digitalization also could provide a long-term archive of historical tunnel conditions.

From a civil and geotechnical perspective, several recurrent degradation processes control the evolution of lining anomalies in existing tunnels ([CETU, 2015b](#)). Water ingress and seepage commonly trigger lining deterioration. These processes are frequently associated with drainage issues and ageing, and can lead to efflorescence, local material decay, and the development or enlargement of cracks. Portal sections are commonly more vulnerable due to shallow cover, stress redistribution, and higher sensitivity to active slope deformations, which may favour localised cracking and joint opening (e.g., [Wang, 2010](#)). These observations provide the physical basis for interpreting defect patterns such as seepage, joint deterioration, and cracking, in relation to the behaviour of the surrounding ground.

However, a persistent gap remains; very few studies have attempted to link internal tunnel defects with external geomorphological processes using a unified monitoring framework ([Fan et al., 2022](#)), and almost none address existing tunnel infrastructure. Most of the available research focuses on newly built or under-construction tunnels, where monitoring systems are incorporated during construction. In contrast, existing tunnels – often old structures, in poor condition, and lack instrumentation – have received far less attention in this regard. This gap is critical since internal deterioration is often assessed without a spatially reliable representation of the surrounding ground deformation. Digital tools allow for a more consistent and measurable evaluation of tunnel conditions, but they are still rarely used together with geomorphological monitoring. A joint, georeferenced analysis can provide practical benefits: it can support large-scale screening, highlight sectors where external deformation and internal anomalies co-exist, and help

prioritise targeted inspections or *in-situ* investigations in a cost-effective way.

Interferometric Synthetic Aperture Radar (InSAR) is a well-established tool able to detect and quantify ground and slope deformations with millimetric accuracy. Techniques such as Multi-Temporal InSAR (MT-InSAR) ([Berardino et al., 2002](#)), e.g., Permanent Scatterer InSAR (PSInSAR) ([Colesanti et al., 2003](#); [Ferretti et al., 2001](#)), and SqueeSAR ([Ferretti et al., 2011](#)), have been widely applied in civil and geotechnical engineering for deformation mapping and monitoring in time. For instance, [Barla et al. \(2016\)](#) applied PSInSAR and SqueeSAR to monitor ground movements induced by tunnel excavations in Northern Italy, demonstrating the direct link between excavation activities and surface deformation. In Naples, [Della Ragione et al. \(2023\)](#) used MT-InSAR to monitor settlement profiles during metro tunnel excavation, achieving millimetric detection and validating their displacement models. Furthermore, different studies underscore the utility of SqueeSAR for remote monitoring in urban tunnelling environments, enabling high-density deformation coverage ([TRE ALTAMIRA, 2018](#)). A key advantage of InSAR is the ability to reconstruct long-term deformation trends, allowing for back-analysis of ground motion of wide areas. This historical perspective is particularly valuable in identifying pre-existing or slowly evolving instabilities. Finally, integrated monitoring frameworks combining MT-InSAR and structural assessment (e.g., [Macchiarulo et al. 2021](#)) indicate the possibility of merging external geodetic data with structural diagnostics.

This work aims to contribute to this research gap by combining 3D Digital Twin reconstruction of tunnel interiors with MT-InSAR displacement analysis to investigate potential correlations between external slope movements and internal tunnel damage. The main contribution is a multi-scale method, as it integrates image-based 3D models with remote-sensing deformation products within a common spatial framework to support preventive screening and maintenance planning in geomorphologically critical settings. The proposed approach was applied to some assessed tunnels located in areas where geomorphological processes exhibit measurable deformations, offering a suitable context to test the effectiveness of the methodology. In this framework, InSAR data were employed to identify areas where ground deformation velocities may interfere with the infrastructures. Inspection data of tunnel surfaces, i.e. point cloud model and high-resolution pictures, were concurrently analysed. The results are combined in an interoperable 3D environment facilitating critical tunnel assessment. This integrated methodology can significantly improve the safety assessment and maintenance planning of existing tunnels located in geomorphologically critical contexts. Moreover, it can support infrastructure managers in implementing predictive maintenance strategies and in prioritizing interventions based on objective, multi-source data.

2. Study area and Materials

This work focused on highway tunnels located in areas affected by deformation processes, in southern Italy. The case studies include two highway tunnels distributed across two mountain sectors of the Campania and Basilicata Regions. In the first tunnel area in Campania, only the south tube (approximately 629 m long) was analysed, since the north tube is currently closed to traffic and internal data could not be acquired. In the second tunnel in Basilicata, both tubes were investigated: the north tube, extending for about 1,252 m, and the south tube, approximately 1,010 m long. In these tunnels, remote and/or mobile techniques for interior inspection were necessarily adopted because it was prohibited to schedule any traffic interruption. The analysis integrated both remote sensing and *in-situ* inspection data to investigate the relationship between external ground deformations and internal tunnel conditions. The two datasets relied on remote sensing techniques, namely satellite-based InSAR data, obtained from Sentinel-1 imagery, and high-resolution images of the tunnel interior acquired using a mobile system.

2.1. Geological framework of the study area

The analysed area is part of the Southern Apenninic Arc, a geologically complex part of the Apennine chain defined by the presence of a deep-seated carbonate duplex system covered by a stack of rootless nappes originating from both the platform and basin paleogeographic domains (Patacca & Scandone, 2007) (Fig. 1a). This internal structural architecture reflects a compressional tectonic evolution, associated with the subduction and the progressive eastward migration of the Apennine thrust-belt, foredeep and foreland system (Patacca et al., 2007).

The first study area (Area 1, Fig. 1b) is located in a structurally complex region of the Campania Region, on the border with the Basilicata Region. The geological substrate belongs to the Maddalena Unit, consisting of Upper Triassic dolomites, typically light grey to white and often fractured to the point of becoming brecciated or pulverised (Patacca and Scandone, 2007). These are structurally overlaid by the

Alburno-Cervati-Pollino Unit, characterised by dark grey and black radiolarite limestones (calcarenites and calcilutites). The tectonic configuration resulted from compressional dynamics that led to the thrusting and imbrication of major structural units (D'Argenio et al., 1973; Ippolito et al., 1975; Patacca & Scandone, 2007). This area is a prime example of the classic nappe structure of the Campania-Lucania Apennines, where Mesozoic carbonate platform successions have been thrust over the Lagonegro Basin sequences. The latter consist of deep-water cherty limestones and siliceous shales from the Upper Triassic to Tertiary periods (Carbone & Lentini, 2017). The morphology of the area directly reflects its geological structure, which has been shaped by multiple phases of uplift, erosion, and structural deformation.

The second area (Area 2, Fig. 1c) is located in the mountainous sector of the Basilicata Region and is part of a major redevelopment project. The tunnel lies in an area where the Campano-Lucano Platform and the Lagonegro Basin define the regional geological setting (Mazzoli et al.,

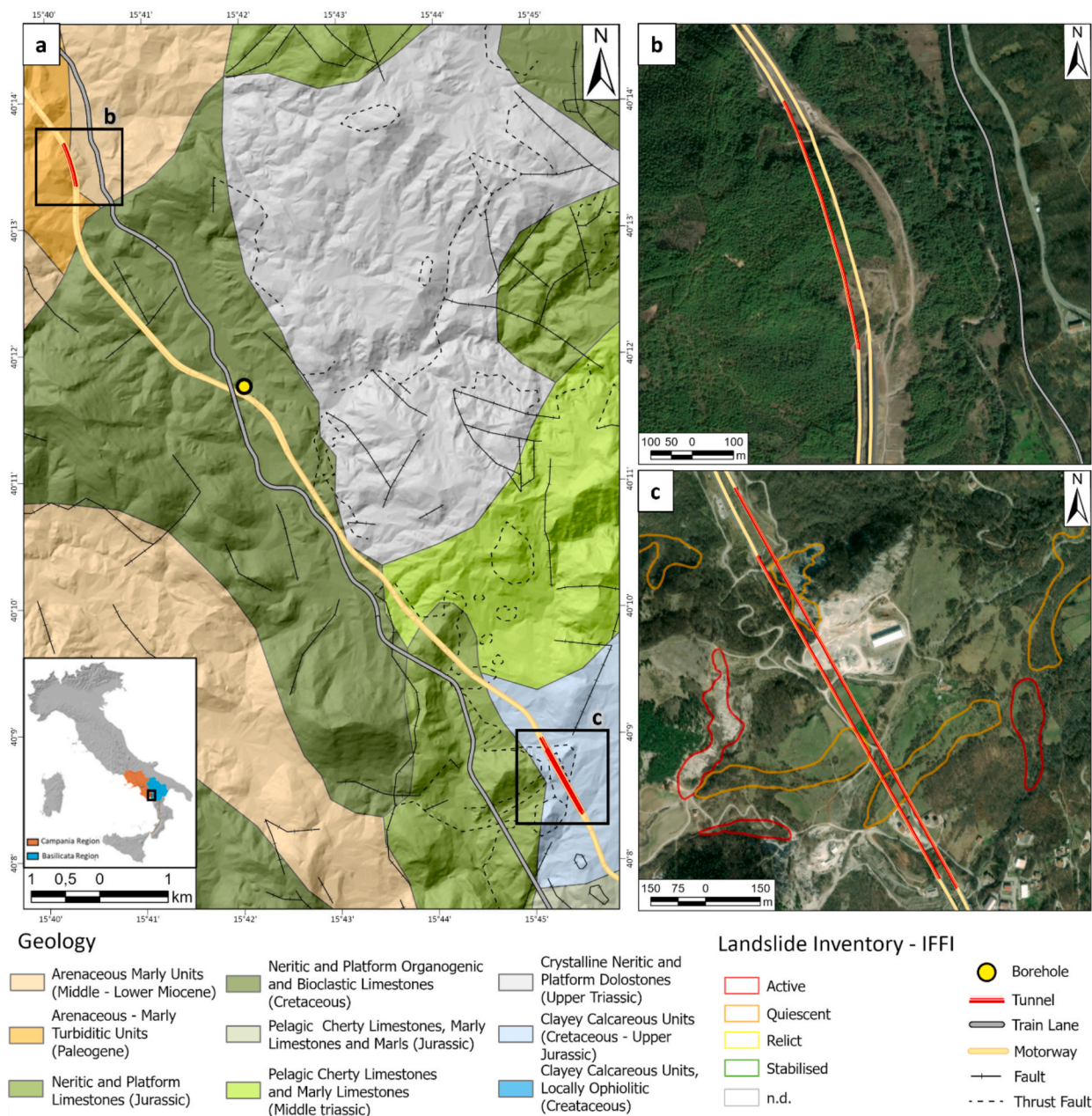


Fig. 1. Geomorphological framework of the study area and geological analysis (a). Focus on the two study areas with the Italian IFFI Landslide Inventory: Area 1 (b) and Area 2 (c).

2001) The area is dominated by Mesozoic sedimentary sequences, mainly carbonate rocks and exhibits significant compressional tectonics, including folding and overthrusting (Pescatore et al., 1999). The tunnel alignment intersects with formations belonging to both the Lagonegrese Basin and the adjacent carbonate platform, particularly the calcarenites and calcilutites (Mazzoli et al., 2001). These are embedded within complex structural geometries. From a tectonic perspective, the area is an example of the NE-verging stack of nappes that was formed during the Apennine orogenesis. The Alburno-Cervati-Pollino Unit lies above the Maddalena Unit carbonates, and both overlie the Lagonegro Units, comprising Triassic-Cretaceous deep-water successions (Patacca & Scandone, 2007). This setting reflects the polyphase tectonic history associated with the Apennine chain formation, marked by the closure of the Tethyan oceanic domain and the progressive eastward emplacement of nappes (Pescatore et al., 1999). The construction of the tunnel, approximately 1,100 m northbound and 1,010 m southbound, presented significant geotechnical challenges due to the heterogeneity and fragmentation of the host rocks, ranging from massive carbonates to highly fractured dolostones. The engineering works were conducted in parallel with environmental recovery and the demolition of obsolete infrastructure.

2.2. Data sources

2.2.1. Satellite data

The InSAR data used in this work were obtained from the European Ground Motion Service (EGMS) of the Copernicus Land Monitoring Service (CLMS) developed under the responsibility of the European Environment Agency (EEA). The data are based on SAR images acquired by the Sentinel-1 mission, launched by the European Space Agency (ESA) in 2014 as part of the Copernicus program (Costantini et al., 2021). The Sentinel-1 constellation was originally composed of two C-band satellites, Sentinel-1A and Sentinel-1B, which operated with a 12-day revisit cycle each and were positioned 180° apart on the same orbit to achieve a combined 6-day repeat interval. However, Sentinel-1B ceased operations in early 2022 due to technical issues. The constellation capability has since been restored with the launch of Sentinel-1C on 5 December 2024 (Klenk et al., 2025), which has re-established the 6-day revisit time.

The dataset provided by EGMS (Table 1) covers the period 2019–2023 and was processed using advanced InSAR algorithms, including PSP-IFSAR (Persistent Scatterer Pair - Interferometric SAR, Costantini et al., 2009), SqueeSAR (Ferretti et al., 2011), and GSAR-GTSl (Prats-Iraola et al., 2012; Sansosti et al., 2006). Data processing was carried out within the OpeRational Ground motion InSAR Alliance (ORIGINAL) consortium, which involves four partners (Ferretti et al., 2023): e-GEOS (Telespazio/Italian Space Agency, Agenzia Spaziale Italiana - ASI), TRE Altamira, NORCE (Norwegian Research Centre), and Geoscientific Analysis and Forecasting (GAF, German Aerospace Center, Deutsches Zentrum für Luft- und Raumfahrt - DLR). Each partner employs its own

Table 1

Main features of the available datasets of Sentinel-1 satellite constellation used in this study.

Satellite	Product	Track Number	Orbit	Temporal span	n. images
SNT	L2a – Basic	44	Ascending	03/01/2019 20/12/2023	240
SNT	L2a – Basic	146	Ascending	04/01/2019 27/12/2023	240
SNT	L2a – Basic	124	Descending	03/01/2019 26/12/2023	235
SNT	L3 – Ortho	Vertical	Vertical component	07/01/2019 18/12/2023	303
SNT	L3 – Ortho	East-West	Horizontal component	07/01/2019 18/12/2023	303

proprietary processing chain, based on Persistent and Distributed Scatterer InSAR methods. The Integrated Wide Area Processor (IWAP) platform (Eineder, 2003; Yagüe-Martínez et al., 2016) ensures the large-scale handling of Sentinel-1 imagery. Before release, all products are harmonized through a standardized validation procedure to guarantee consistent quality and comparable characteristics across Europe.

The EGMS provides three levels of InSAR products. The Level-2A product consists of basic deformation maps and displacement time series measured along the Line of Sight (LoS) of the satellite, referenced to local stable points, and available for both ascending and descending acquisition geometries. The Level-2B product is a calibrated version adjusted using a European GNSS reference network. Finally, the Level-3 product, also known as the Ortho product, provides the deformation components decomposed into East-West and Up-Down directions and is mapped onto a uniform grid with a spatial resolution of 100 m (Capes & Passera, 2022). All EGMS products are provided as open-access data. The full EGMS archive became publicly available in 2022, with the first product baseline covering 2015–2021 (Costantini et al., 2021; Crosetto et al., 2020). The service is updated on an annual basis, and at present deformation products can be downloaded for two distinct monitoring periods: 2018–2022 and 2019–2023. These datasets offer spatially dense, time-series deformation measurements at continental scale and were used to identify potential ground instabilities affecting the study area.

In this study, Level-2A (Basic, European Ground Motion Service, 2025a) and Level-3 (Ortho Vertical and Ortho East-West, European Ground Motion Service, 2025b,c) products were acquired through the EGMStream Webapp (Becattini et al., 2025) and used for analysis. L2A-Basic products, which contain LoS velocities and displacement time series referenced to local stable areas within each Sentinel-1 frame, were used as the primary dataset for analysing ground deformation patterns around the tunnels. The L3-Ortho products are obtained by combining ascending and descending LoS measurements of the calibrated Level-2B products. The procedure is performed on a regular grid, where LoS velocities within each cell are averaged and combined from both geometries, resulting in pseudo-targets located at the cell centres (Notti et al., 2014). L3 data were additionally used to support the interpretation of LoS data and to validate the deformation trends obtained from L2a.

2.2.2. Hi-res images

High-resolution grayscale images of the tunnel interior were acquired using the mobile linear imaging system *TunnelEye* (European Commission, 2022). The platform (Fig. 2) consists of two optical line-scan cameras mounted on the roof of a trailer, along with synchronized lighting, positioning sensors, and acquisition hardware. Each camera features a resolution of 6144 pixels per line with a pixel size of 7 µm x 7 µm, and a 35 mm focal length optimized for capturing images in low-light tunnel environments. As a new implementation of the system, a compact LiDAR (Light Detection and Ranging) device was integrated to capture the cross-sectional geometry of the tunnel. The sensor, characterized by a rotating two-dimensional (2D) scan with a range of 0.02–12 m and an angular coverage of 360°, was mounted on the same platform of the cameras and synchronized with the acquisition system. Its purpose was to provide reliable cross-sectional profiles that could support the geometric reconstruction of the images. Acquisition campaigns of the case study tunnels were conducted in September 2024.

The mobile acquisition was performed at a speed of approximately 10 km/h to ensure image sharpness and spatial consistency. Four separate passes were carried out to capture the entire tunnel surface (left and right walls and two for the ceiling) resulting in eight complete images per tunnel. Image acquisition was triggered by a dedicated synchronization unit using OCXO (Oven-Controlled Crystal Oscillator) technology and TTL (Transistor-Transistor Logic) pulses, ensuring microsecond-level temporal alignment across sensors. Each image was stored as 8-bit grayscale (uint8) and labelled according to the camera and acquisition direction.

For consistency and robustness in image reconstruction, a

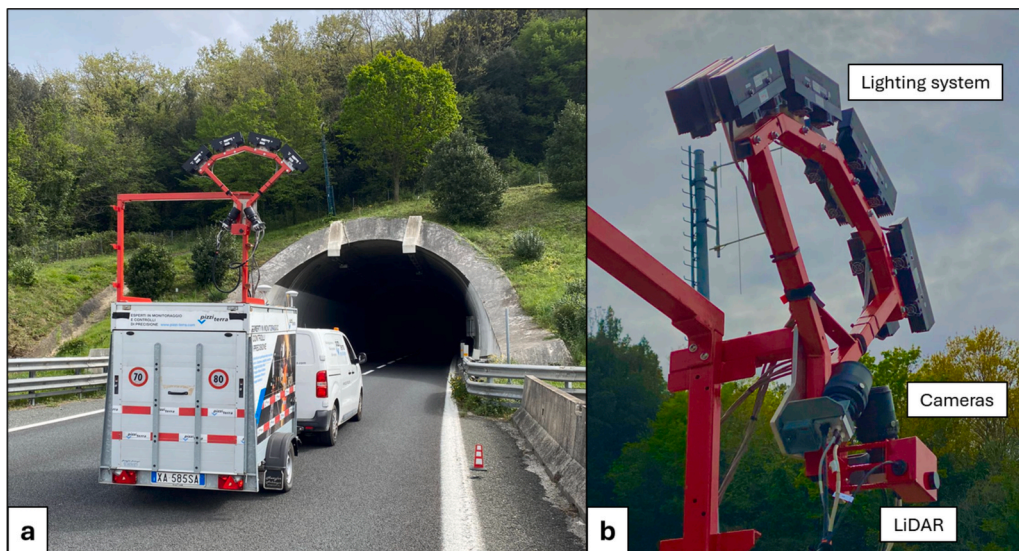


Fig. 2. TunnelEye system during acquisition (a) and zoom to the frame with light lamps, two cameras and LiDAR sensor (b).

conservative resampling of the resolution to 1 mm/pixel was adopted along the tunnel axis. In the vertical direction, the sub-millimetric resolution ($\sim 0.1\text{--}0.2$ mm/pixel) was preserved, depending on the camera-

to-wall distance. The final size of each image was 20000×6144 pixels, covering a 20 m segment of tunnel length. To ensure geometric accuracy, images were corrected for lens distortion using optical parameters.

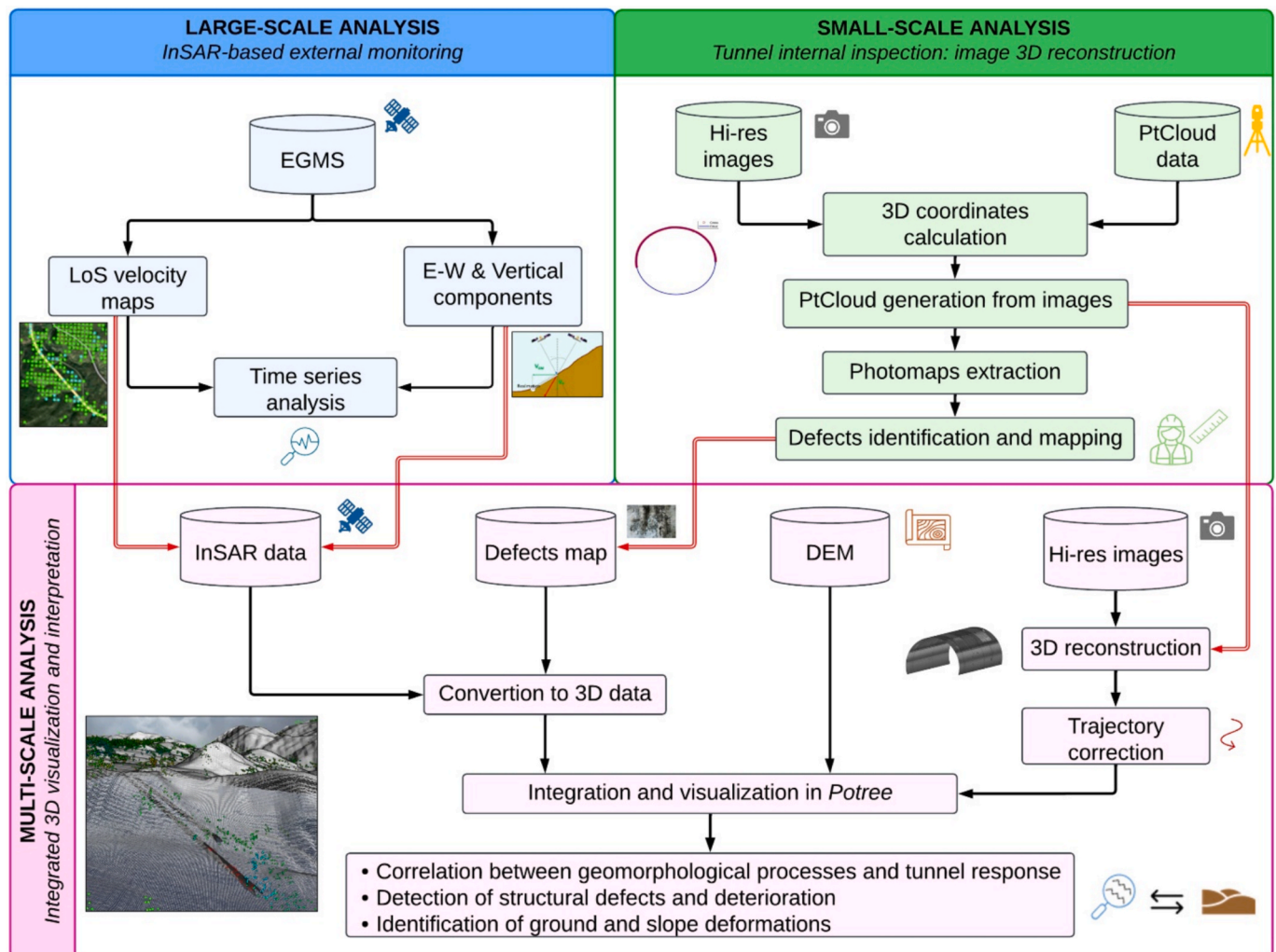


Fig. 3. Methodology workflow.

The resulting dataset provides a detailed and continuous visual representation of the tunnel lining suitable for defect detection and 3D reconstruction applications.

3. Methodology

The adopted methodology integrates remote sensing data and high-resolution imaging to assess both external ground movements and internal tunnel conditions with the aim of identifying any spatial correlation between them in a multi-scale analysis approach (Fig. 3). InSAR deformation maps derived from Sentinel-1 data were analysed to identify areas affected by ongoing displacements, potentially linked to active geomorphological processes in the surroundings of the tunnels. In parallel, the high-resolution images were processed through a 3D reconstruction procedure to correct geometric distortions, resulting in both a high-resolution three-dimensional model of the tunnel and photomaps of the lining. The reconstruction of the 3D model from pictures is described in detail in Dahanayaka et al. (2026). Unrolled 2D photos were then generated and used to detect and classify structural defects, i.e., cracks or surface deterioration, along the tunnel interior. Defect classification was based on Italian tunnel guidelines specifications. Finally, the available data is integrated into a 3D data handling software for interpretation purposes. By comparing the spatial distribution of external ground deformations with the internal defect mapping, potential correlation between geomorphological activity and tunnel damage was investigated.

3.1. InSAR data interpretation

InSAR velocity maps derived from the EGMS dataset provide information on the mean annual velocity of measurement points (MPs) across the study area for the analysed period (2019–2023). Separate maps were first produced for the L2a ascending (Fig. 4a) and descending (Fig. 4b) data of Sentinel-1, allowing the distribution of stable and unstable zones to be visualized along the area where the tunnels are located. The density of ascending MPs was approximately 735 points/km² in the study area, while for descending MPs it was 493 points/km². To further characterize the displacement velocity field, East-West (Fig. 4c) and Vertical (Fig. 4d) velocity components were also considered.

The adopted colour convention highlights ground stability and areas of deformation. MPs displayed in green, with ground motion rates within ± 2 mm/year (corresponding to the standard deviation of the dataset) indicate stable conditions. Negative LoS velocities, which represent movements away from the radar sensor, are shown in warm colours, while positive LoS velocities, indicating movements towards the sensor, are represented in cold colours. The same convention applies to the component maps: negative vertical velocities and westward horizontal displacements are expressed with hot colours, while uplift and eastward motion appear in cold colours.

The combination of ascending and descending data allowed the detection of complex displacement patterns. Within the study area, the interpretation of these maps was used to identify sectors affected by geomorphological processes, e.g., slope instabilities which could potentially interact with the tunnel infrastructure.

3.2. 3D image reconstruction

The images acquired with the mobile inspection system were processed to create a 3D reconstruction of the tunnel lining. The methodological framework (Dahanayaka et al., 2026) starts from the approximation of the tunnel cross-section geometry as an ellipse. In this study, the geometry was constrained using point clouds obtained from the on-board LiDAR sensor, to which an ellipse fitting was applied. Once the cross-sectional geometry had been defined, each pixel of the linear images was projected into 3D space based on the acquisition geometry of the cameras, the vehicle trajectory, and the relative positioning of the

sensors within the inspection frame. Through this process, pixel intensity values were mapped onto 3D coordinates (x, y, z), resulting in a dense, high-resolution point cloud of the tunnel lining. The high-resolution allowed to observe sub-millimetric defects (~ 0.7 mm, Dahanayaka et al., 2026).

To ensure geometric continuity and computational efficiency, each tunnel was reconstructed as a sequence of 20 m segments, corresponding to the typical inspection span defined by tunnel safety guidelines in Italy. Segmenting the reconstruction improved the stability of the geometric fitting and reduced processing time. The resulting 3D blocks were subsequently aligned and merged to form a continuous model of the full tunnel alignment.

3.2.1. Trajectory reconstruction

To align the reconstructed point cloud with the actual geometry of the tunnel infrastructure, the straightened 3D model obtained from the image-based reconstruction was spatially curved along the reference trajectory of the tunnel. This process ensured that the reconstructed geometry accurately followed the real longitudinal alignment and slope of the tunnel axis. The procedure was implemented in Matlab (The MathWorks Inc., 2024) through a custom script, which interpolates the tunnel reference with a dense set of points and computes a stable local reference system along the curve. At each position of the interpolated centreline, an orthonormal triad (T, N, B) was constructed, where T is the tangent vector to the curve, and N and B span the normal plane (Fig. 5). The approach is based on the parallel transport frame formulation (Bishop, 1975; Hanson & Ma, 1995; Wang et al., 2008) which is propagated along the curve by minimizing the rotation of the normal-binormal plane around the tangent direction; this ensured smooth and consistent orientation even in nearly straight segments.

Each point of the tunnel cloud was then mapped from local coordinates onto this curvilinear reference system. The longitudinal direction is associated with the curvilinear abscissa along the centreline, while transversal and vertical offsets (u, v) are applied along N and B , respectively. The mapping operation is expressed as:

$$X(s, u, v) = C(s) + uN(s) + vB(s) \quad (1)$$

where $C(s)$ is the centreline parametrized by arc length s .

The longitudinal trajectory of each tunnel was reconstructed by applying curvature and slope information derived from a reference polyline representing the tunnel axis, defined in DXF format and interpolated to reproduce the real longitudinal gradient. This transformation enables the curving of the tunnel cloud so that it follows the real-world alignment. The result is a geometrically consistent, curved point cloud that reflects the actual trajectory of the tunnel, which can be used for immersive visualization, defect localization, and comparison with external geodetic data.

3.3. Inspection process

The inspection procedure adopted in this study follows the regulatory framework established in Italy for the assessment of existing tunnels. A first structured procedure was introduced with the Tunnel Inspection Manual, *Manuale Ispezione Gallerie* (MIT, 2020), which formalised the methodology for periodic inspections and adopted the IQOA (Quality Assessment of Civil Engineering Structures, *Image Qualité des Ouvrages d'Art*) classification system originally developed by the *Centre d'Etudes des tunnels* (French Tunnel Study Centre, CETU, 2015a, b). Under this framework, inspectors shall document defects through on-site visual analysis using standardized Inspection Forms (*Schede Identificative di Ispezione* - SII), mapping deterioration patterns every 20 m of tunnel length and assigning qualitative ratings based on defect type, extent, and severity.

The later issued guidelines *Linee Guida per la Classificazione e Gestione del Rischio, la Valutazione della Sicurezza ed il Monitoraggio delle Gallerie*

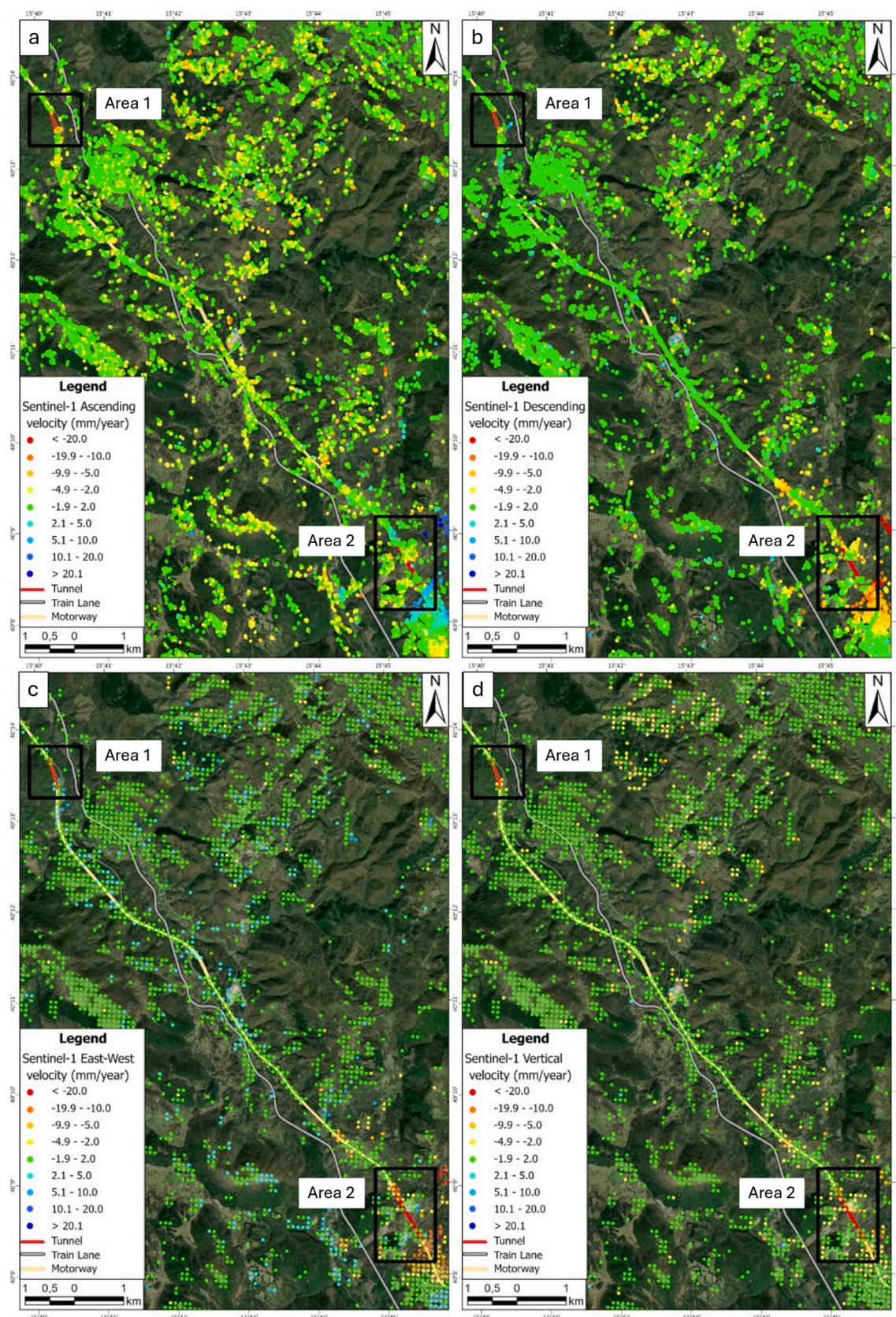


Fig. 4. Ground displacement velocity maps for Sentinel-1 Ascending (a), Descending (b), East-West component (c) and Vertical component (d) in the period 2019–2023. In black boxes are represented the areas where the analysed tunnels are located.

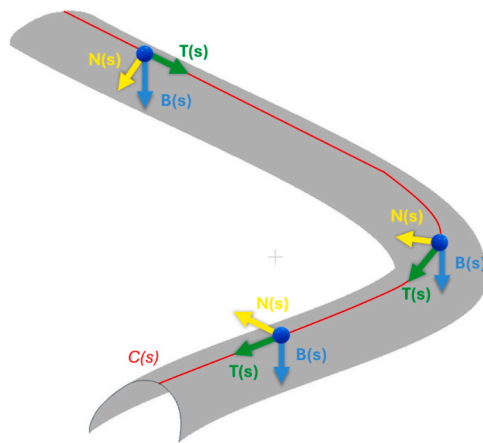


Fig. 5. Orthonormal frames $T(s)$, $N(s)$, $B(s)$ along the centreline $C(s)$ length of the tunnel.

Esistenti (MIT, 2022) further refined the national approach by introducing a risk-based methodology and formalizing the defect classification process (Carigi et al., 2025). The 2022 guidelines require the compilation of so-called *Schede di Difettosità* (Defect Sheets) for each homogeneous 20 m tunnel sector and prescribe to assign severity scores that account for defect intensity, spatial extension, and potential implications for structural performance and safety. The typical defect types encountered in concrete tunnels include: (i) cracking, classified by orientation (longitudinal, transversal, oblique), width, and continuity; (ii) joint deterioration, including open joints, displacement, or misalignment of segments; (iii) water ingress, distinguished by wet areas, dripping, running water, or calcite deposits; (iv) surface degradation, i.e., spalling, efflorescence, loss of material, or detachment zones.

In this study, the inspection process was adapted into a fully digital workflow using both 3D point cloud and 2D unrolled images extracted from the reconstructed model. Defects were mapped in 2D within a CAD (Computer-Aided Design) environment following the assessment criteria defined in the national guidelines. Each anomaly was intrinsically georeferenced through the tunnel chainage, starting from the entrance. This procedure reproduced the structure of the SII, where defects were identified, classified, and positioned along standardized 20-m sectors. In parallel, the 3D model allowed defects to be mapped and digitalized as polylines directly on the point cloud.

3.4. 3D data visualization

To enhance the interpretation of both internal and external monitoring results, an integrated 3D visualization environment was developed using the *Potree* software (Schütz, 2015). *Potree* is an open-source, web-based platform designed for the visualization and management of large-scale point cloud datasets. Its rendering engine allows interactive exploration of complex 3D models directly within a browser. The software has been widely adopted in the fields of geospatial analysis and cultural heritage documentation (e.g., Boutsi et al., 2019), owing to its ability to combine multiple spatial datasets within a single georeferenced environment. In this study, *Potree* was employed as an integration tool to visualize and correlate multi-source spatial information, including internal tunnel reconstructions, external topography, and InSAR ground deformation data. The 3D environment allows simultaneous visualization of the reconstructed tunnel from images, the mapped internal defects, the surrounding topography derived from the Digital Elevation Model (DEM), and the InSAR-derived MPs, colour-coded by deformation velocity.

Defects identified during internal inspections as polylines were converted into point clouds using the *Sample Points* function in

CloudCompare (Girardeau-Montaut, 2024). This conversion allowed their integration within the same georeferenced environment as the tunnel geometry. The surrounding terrain was represented by the *TINITALY DEM* (Istituto Nazionale di Geofisica e Vulcanologia, INGV, 2025), which provides a DEM with spatial resolution of 10 m. Finally, InSAR-derived MPs were imported as georeferenced 3D point datasets containing spatial coordinates and deformation velocities, used as intensity attributes for colour-coded visualization.

This multi-layered visualization enables the spatial correlation between external slope deformations and internal tunnel anomalies, providing an intuitive and interactive environment to support structural assessment and maintenance planning.

4. Results

In this section, the results of both external ground deformation analysis and internal tunnel inspections are presented for two areas of interest. The external investigation, based on satellite interferometry data, provided a large-scale overview of surface displacement patterns surrounding the tunnels, helping to identify potential ground instability processes. The internal inspection results, derived from high-resolution image-based reconstruction, provided detailed information on the condition of the tunnel lining.

4.1. External ground deformation from Sentinel-1 InSAR analysis

Ground deformation affecting the surroundings of the investigated tunnels was assessed using InSAR velocity maps derived from Sentinel-1 data. The analysis focused on localized deformation patterns in Areas 1 and 2, allowing for a detailed evaluation of surface displacement near the tunnel alignments.

In Area 1 (Fig. 6a-b), the velocity maps display a deformation sector located above the southern portal of the south tube, extending across the southeastern slope of the area. The affected zone covers roughly 150 m along the first section of the tunnel. Displacement signs are visible in both ascending and descending geometries. The ascending dataset showing higher deformation rates (up to -10.9 mm/year) and a denser point distribution, while the descending dataset shows more stable deformation (up to -2.1 mm/year). The deformation cluster is clearly delineated in both datasets, outlining a coherent motion field centred on the slope above the tunnel entrance. MPs located near the tunnel alignment were selected for time-series analysis of the most representative data. The corresponding displacement trends for ascending orbit (Fig. 6c) show a steady, nearly linear evolution over the 2019–2023 period, reaching cumulative displacement values of approximately -40 mm. Descending orbit time series (Fig. 6d) show a closely linear trend with a cumulative displacement of approximately -10 mm.

The East-West and vertical components (Fig. 7a-b) confirm the presence of ground motion in the same area. Positive values in the East-West component correspond to eastward displacement with maximum velocity registered of 5.8 mm/year, while negative values in the vertical component indicate a downward trend with a maximum velocity of -5.2 mm/year. The combination of both signals defines a localized deformation zone above the southern sector of the tunnel, with spatial continuity consistent across all datasets. The East-West time series (Fig. 7c) shows a gradual horizontal displacement of approximately 30 mm, consistent with the overall deformation rate observed in the LoS data, while the vertical component (Fig. 7d) registers a displacement of approximately -20 mm.

In Area 2, two primary deformation zones were detected (Fig. 8a-b). The first is situated near the northern portals of both tunnels, affecting the north tube. The displacement is coherent with the slope exposure, and it is observed in both geometries, with velocities of 8.3 mm/year in ascending and -4.3 mm/year in descending data. A second deformation area is located approximately midway along the alignment, corresponding to an area that is visible in the optical basemap. Motion away

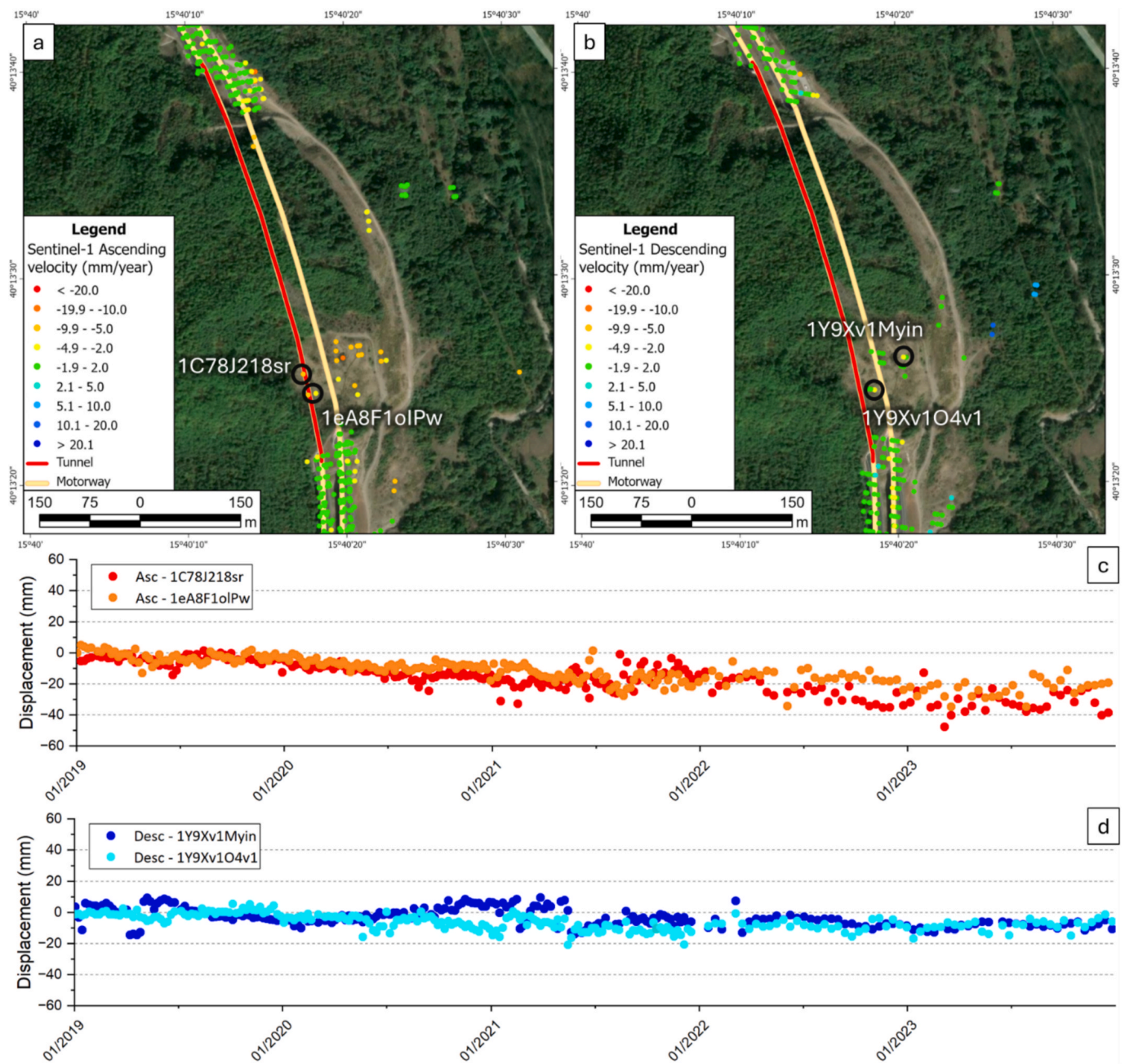


Fig. 6. Velocity maps of Sentinel-1 ascending (a) and descending (b) geometries for Area 1 and time-series analysis of the selected MPs from ascending (c) and descending (d) LoS data. The IDs of the MPs used in the analysis are reported in the maps.

from the satellite is recorded in both geometries, with maximum velocities of -11.3 mm/year (ascending) and -14.5 mm/year (descending). This zone is positioned at an elevation of approximately 95 m above the tunnel axis; therefore, it will not be further examined as it is not directly impacting the infrastructure interior.

Focusing on the first one, the time-series analysis at the northern portal of the north tube includes ascending and descending MPs with high coherence values located near the tunnel alignment. Points from ascending orbit show a progressive displacement trend toward the satellite, with approximately 30 mm of cumulative motion between 2019 and 2023 (Fig. 8c), whereas points from descending orbit indicate motion away from the satellite, with cumulative displacement of about -20 mm over the same period (Fig. 8d).

The East-West and vertical components show motion directed westward (maximum -14.6 mm/year) and downward (maximum -4.4

mm/year), outlining the deformation sector near the tunnel entrance (Fig. 9a-b). The East-West time series (Fig. 9c) displays a total displacement of approximately -30 mm, and the vertical component (Fig. 9d) remains nearly stable.

4.2. Internal inspection results from 3D image reconstruction

The internal inspection was carried out on both tunnel tubes using high-resolution images acquired by the mobile system. From the 3D image reconstructions, photomaps were generated to remove geometric distortions, providing a reliable and metrically consistent basis for the identification and documentation of millimetric surface defects. The circumferential reference used in the unfolded representation is defined from the fitted tunnel cross-sectional geometry obtained in the image processing step (Dahanayaka et al., 2026). Overall, the inspected tunnels

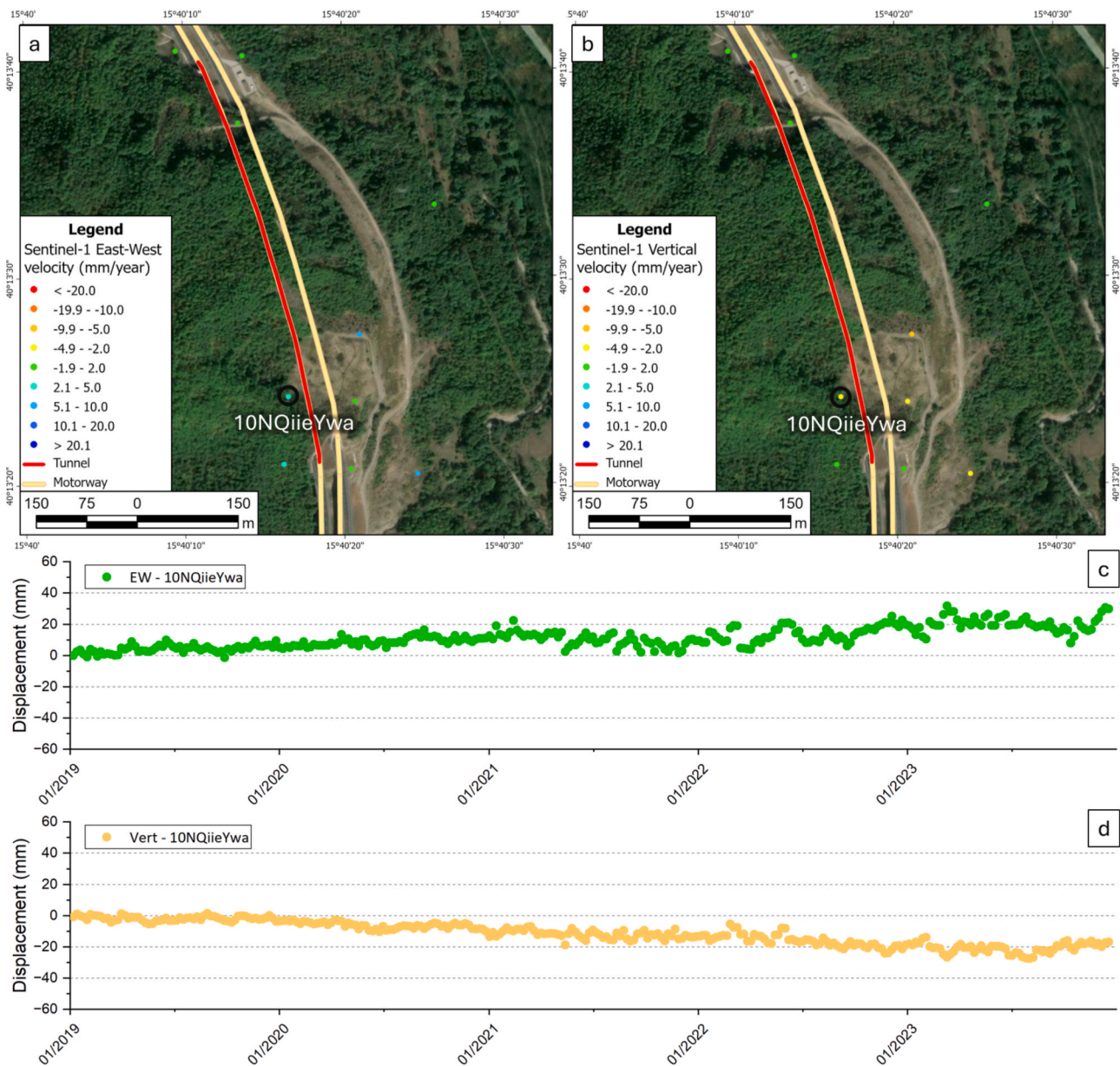


Fig. 7. Velocity maps of decomposed East–West (a) and Vertical (b) components for Area 1 and time-series analysis of selected MPs from East–West (c) and Vertical (d) data. The IDs of the MPs used in the analysis are reported in the maps.

are in good structural condition, with most of the lining showing no signs of significant distress. Nevertheless, some localized areas exhibited recurring defect patterns worthy of closer attention.

In the south tube of Area 1 (Fig. 10), the highest concentration of deterioration was observed near the northern portal, where numerous minor water seepages were detected along the longitudinal joints between the sidewalls and the vault. These seepages (e.g., Fig. 10b) are typically low in intensity but spatially clustered in a limited section of approximately 140 m from the entrance. Additional defects were identified near the southern portal, particularly between km 0+460 and km 0+560, where deteriorated joints and minor seepage traces are visible, especially along the right sidewall. In these zones, the deterioration often extends from the base of the sidewall to the crown (Fig. 10c), with limited water percolation along pre-existing discontinuities.

High-resolution image analysis allowed the estimation of defect dimensions: deteriorated areas reach up to approximately 6 m² (mainly seepage marks), while individual cracks (e.g., Fig. 10a) are limited and display lengths of up to 60 cm and sub-millimetric widths, typically

lower than 0.5 mm. The extent and intensity of the observed defects in this section is classified as moderate to low, with no signs of severe structural distress or advanced degradation.

In the north tube of Area 2 (Fig. 11), the distribution of defects is more discontinuous and less concentrated, with most anomalies located near the southern and northern portals. Between km 0+000 and km 0+100, a few longitudinal cracks and light water seepages were detected, often associated with thin calcite deposits along the joints (Fig. 11a). Further along the alignment, in the section between km 0+960 and km 1+060, several vertical cracks of large extent but low severity were recorded, particularly between km 0+960 and km 1+005, often associated with limited water infiltration. These vertical cracks, sometimes extending over large portions of the vault (e.g., Fig. 11c), display a uniform orientation and low aperture and reach lengths up to 21 m. Water-related concretions were identified on the vault and sidewalls, forming affected areas up to approximately 14 m². Additional minor defects were detected near the northernmost section (km 1+100–km 1+260), where scattered seepage marks and fine cracking were

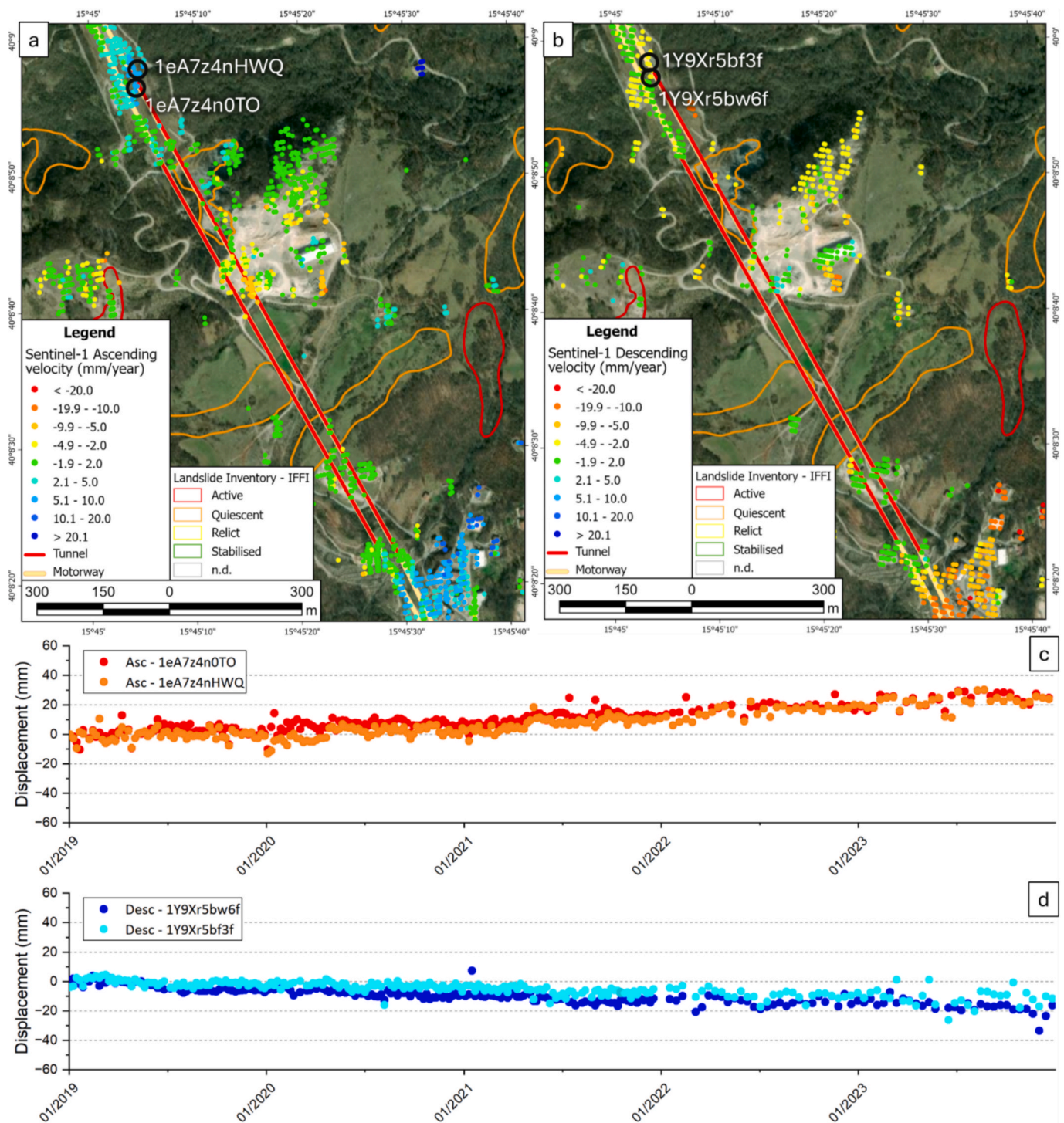


Fig. 8. Velocity maps of Sentinel-1 ascending (a) and descending (b) geometries for Area 1 and time-series analysis of the selected MPs from ascending (c) and descending (d) LoS data. The IDs of the MPs used in the analysis are reported in the maps.

observed along the walls (Fig. 11b), together with vertical cracks developed along the tunnel vault. Despite their extent, these features remain of moderate to low severity according to the classification criteria, as the maximum opening width of the measured cracks does not exceed 2 mm.

A visual inspection was also performed for the south tube of Area 2; however, the lining appeared largely intact, with no significant defects observed.

For clarity, a representative example of an original high-resolution

image corresponding to a 20 m tunnel segment (km 1+180 to km 1+200) is shown in Fig. 12. This image, characterized by sub-millimetric pixel resolution, illustrates the level of detail available in the source data used for defect mapping.

5. Discussion

The integration of satellite and image-based datasets provided a comprehensive framework for assessing tunnel behaviour within its

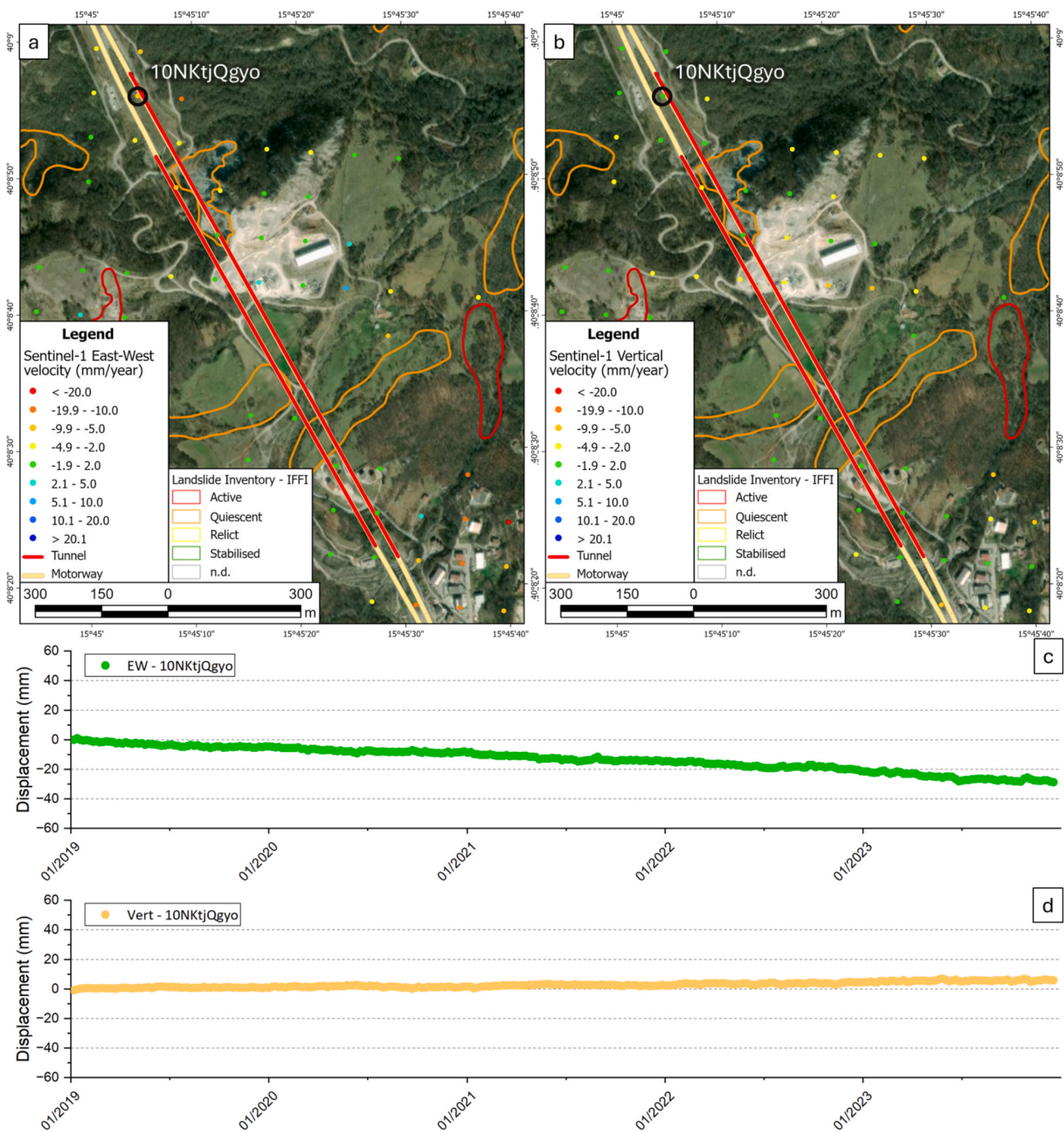


Fig. 9. Velocity maps of decomposed East–West (a) and Vertical (b) components for Area 2 and time-series analysis of selected MPs from East–West (c) and Vertical (d) data. The IDs of the MPs used in the analysis are reported in the maps.

geomorphological context. The results obtained from the InSAR analysis and 3D reconstruction offer complementary insights into external and internal processes affecting the investigated infrastructures.

The InSAR analysis provided valuable information on the spatial distribution and temporal evolution of ground deformation around the tunnels. The use of both ascending and descending Sentinel-1 geometries enabled the identification of slope sectors affected by displacements. The decomposition of LoS data into horizontal and vertical components proved particularly useful to better constrain motion direction and reduce interpretation ambiguities. However, InSAR is a remote sensing technique whose reliability depends strongly on acquisition geometry, viewing direction, and surface coherence. Its ability to capture the full motion field is limited by vegetation, geometrical

distortion, and the one-dimensional nature of radar measurements (Notti et al., 2010). In addition, in steep or densely vegetated sectors, coherence loss and geometric effects may reduce the density of reliable MPs, locally weakening the deformation picture. These constraints are particularly relevant for translational slope movements, where only the motion component aligned with the satellite view direction is measurable. Despite these limitations, the joint use of both orbits and the derivation of horizontal and vertical components represent an effective strategy to improve deformation characterization. Overall, the InSAR data successfully defined localized deformation areas that may interact with the analysed tunnel structures, demonstrating the potential of satellite monitoring for large-scale, long-term assessment of geotechnical processes affecting underground infrastructures. InSAR offers a

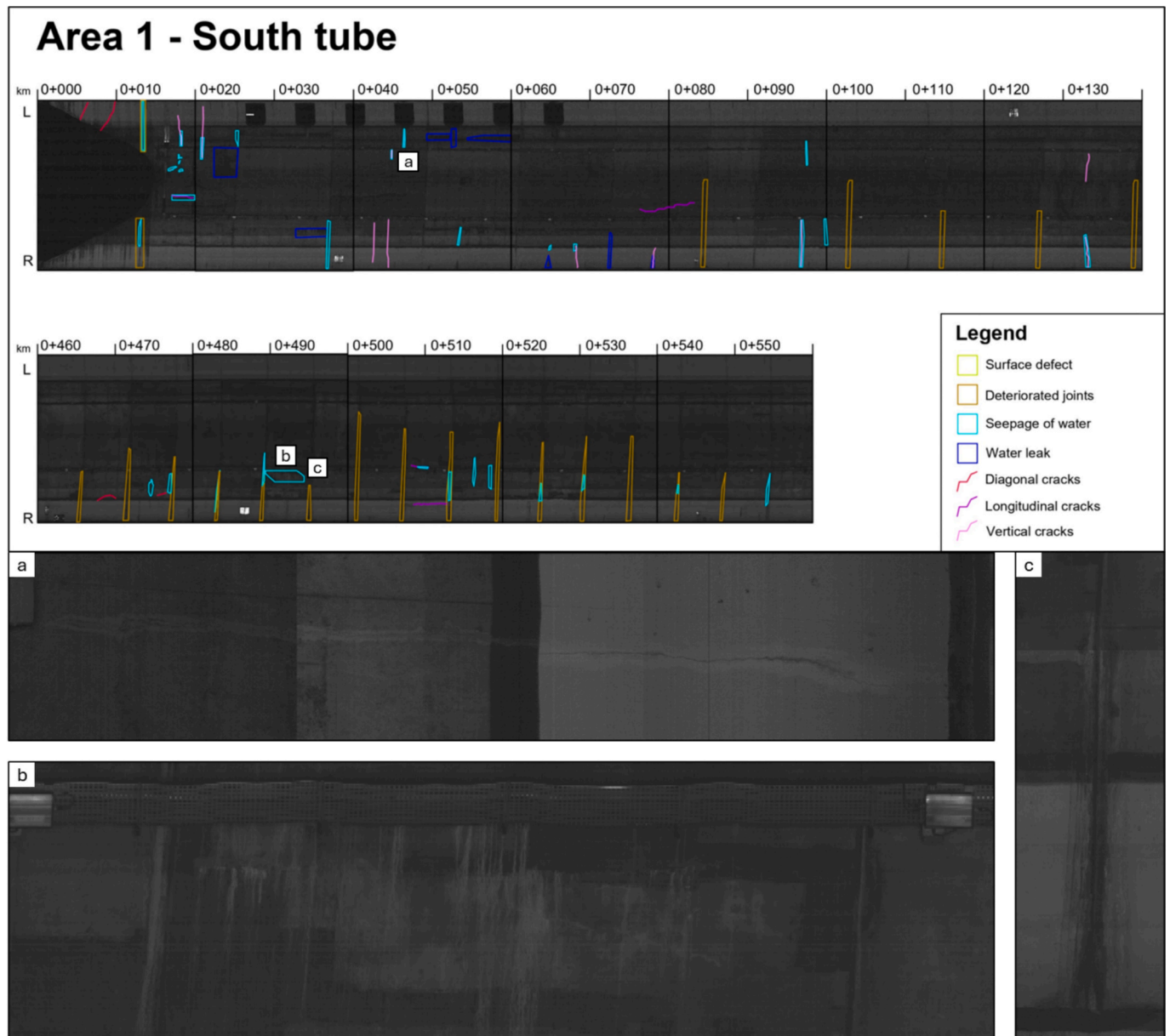


Fig. 10. Inspection maps for the most critical tunnel 20 m-blocks in the south tube (Area 1) and examples of defects detected: a) crack at km 0 + 045, b) water seepages at km 0 + 490 and c) deteriorated joints at km 0 + 495. The chainage (in km) is reported along the tunnel axis, with km 0 + 000 at the portal corresponding to the driving direction; for the south tube, km 0 + 000 is located at the northern portal. Labels “L” and “R” indicate the left and right side of the lining with respect to the travel direction.

practical advantage for preliminary screening, as it provides retrospective deformation information over wide areas without the need for invasive or pre-installed monitoring systems, helping to prioritize field checks and targeted internal inspections in potentially unstable sectors.

The image-based 3D reconstruction of the tunnels enabled a detailed inspection of the internal linings, providing metrically consistent models suitable for defect mapping and measurement. The results confirmed that the analysed tunnels are globally in good structural health, with degradation mainly associated with surface weathering, water ingress, and minor joint deterioration. From a geological perspective and considering the lithological setting of the area (see Fig. 1), the occurrence of several water leaks within the tunnel in Area 1 can be interpreted as a consequence of the presence of an arenaceous unit. This formation is relatively porous, allowing rainfall to infiltrate and migrate homogeneously through the layer. In contrast, Area 2 is characterised by a fractured calcareous layer through which groundwater primarily flows

along preferential fracture pathways. As a result, water leaks in this area are less spatially distributed but occur as more intense and localized events (see Fig. 11). The predominance of longitudinal and vertical cracks suggests that subtle ground-structure interaction processes could influence the tunnel lining. The high-resolution defect maps of Fig. 10 and Fig. 11 offer objective, georeferenced documentation of the internal conditions, serving as a valuable input for combined analyses with external deformation data.

To compare the spatial observations derived from the mapped defects and InSAR data, a segment-based analysis was performed along the full tunnel alignment for Area 1, South tube and Area 2, North tube. The analysis was carried out on 20 m blocks, and for each segment both the average InSAR velocity and defect density indices were computed. Mean InSAR velocities were calculated using MPs from ascending and descending geometries within a 30 m buffer from the segment centroid, in order to consider possible georeferencing uncertainties and to better

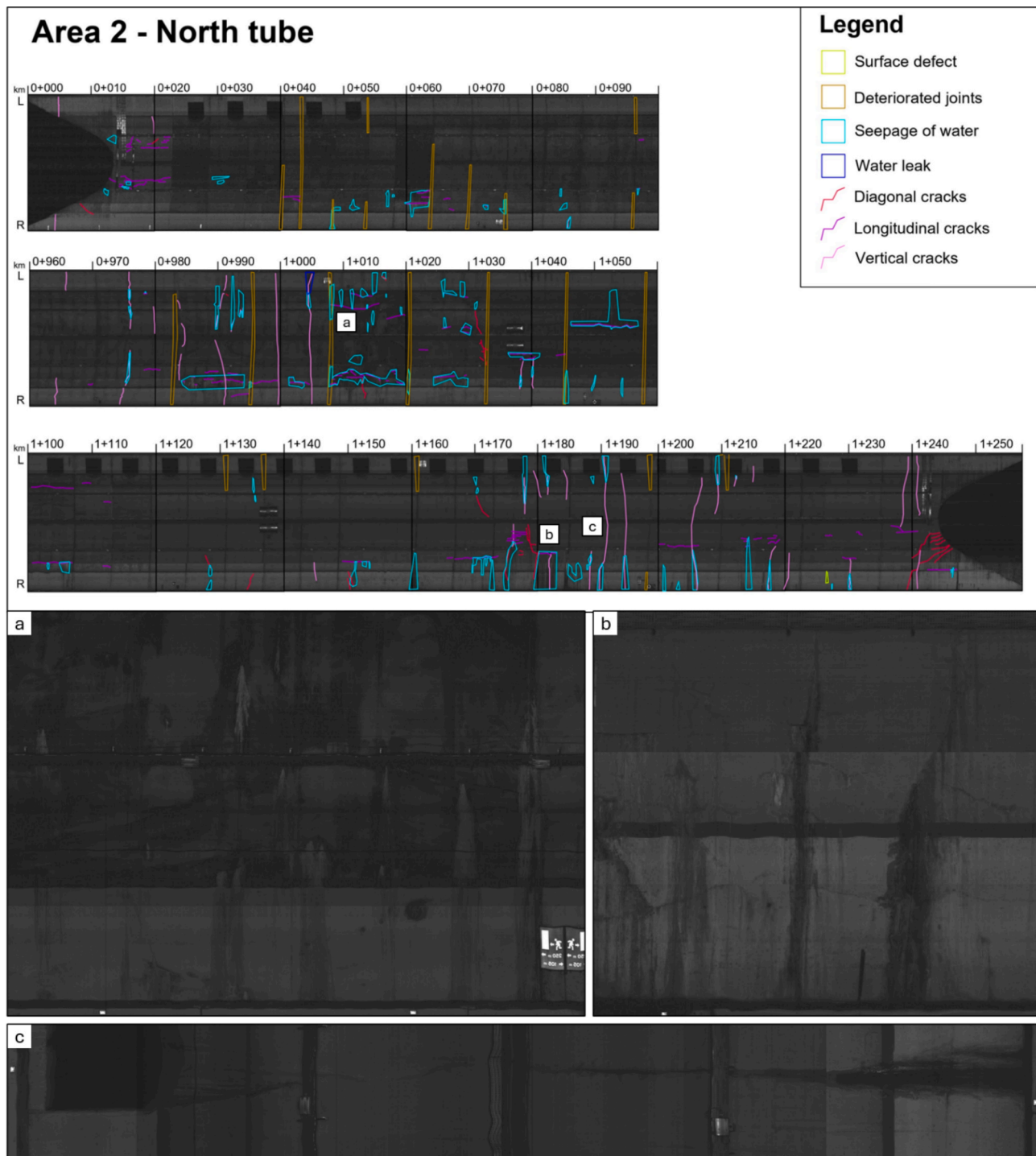


Fig. 11. Inspection maps for the most critical tunnel 20 m-blocks in the north tube (Area 2) and examples of defects detected: a) spread water seepages at km 1 + 010, b) cracks and water leaks at km 1 + 180 and c) crack propagating along the tunnel section at km 1 + 190. The chainage (in km) is reported along the tunnel axis, with km 0 + 000 at the portal corresponding to the driving direction; for the north tube, km 0 + 000 is located at the southern portal. Labels “L” and “R” indicate the left and right side of the lining with respect to the travel direction.

represent the volume of ground potentially interacting with the tunnel. Linear densities (m/m) were determined for cracks, while areal ratios (m^2/m^2) were calculated for surface-related defects, based on the length/area of each segment. The results, represented as bar plots in Fig. 13, south tube, and Fig. 14, north tube, provide a continuous overview of the relationship between ground deformation and internal lining conditions.

Analysing Area 1 (Fig. 13), the first portion of the South tube

(segments from 1 to 5, km 0+000 to 0+100) shows opposite trends between ascending and descending velocities, suggesting a surface deformation component dominated by horizontal movement. In contrast, segments from 25 to 27 (km 0+460 to 0+520) exhibit similar trends in both geometries, indicating a predominantly vertical displacement component. This sector corresponds to one of the areas where higher defect densities are observed, particularly in terms of deteriorated joints and water-related anomalies. From block 8 to 23 no



Fig. 12. Unfolded view of the tunnel block from km 1 + 180 to km 1 + 200. Minor misalignments are related to the acquisition process and do not affect the suitability of the images for inspection purposes (see [Dahanayaka et al., 2026](#)).

significant external deformation and internal defects were recorded.

In Area 2 ([Fig. 14](#)), the analysis of the North tube highlights a more extended sector (segments from 49 to 63, km 0+960 to 1+252) characterized by contrasting signals between ascending and descending datasets, again pointing to a dominant horizontal deformation component. In this sector, the average velocities reach the highest values observed along the tunnel, with descending measurements up to approximately -12 mm/year and ascending values around 8 mm/year. This portion of the tunnel also shows the highest concentration of internal defects, especially cracks, suggesting a possible link between horizontal ground movement and the development of discontinuities in the lining.

Overall, although the correlation between deformation rates and defect density is not strictly linear, the segment-based approach highlights consistent spatial correspondences between zones of larger deformation and higher concentrations of defects. These results support the interpretation that even moderate and slow ground movements, particularly with a significant horizontal component, may contribute to localized stress redistribution and progressive deterioration of the tunnel lining.

As a final step, the integrated 3D visualization environment was developed in *Potree* software to couple and display the datasets acquired for each study area. The model includes the reconstructed tunnel with mapped defects overlaid, the surrounding topography represented by a DEM, and the InSAR MPs coloured according to their velocity values. Based on the results, two representative sectors were selected for detailed visualization: (i) the southern portal of Tunnel 1 - Area 1, south tube, and (ii) the northern portal of Tunnel 2 - Area 2, north tube. Both

zones exhibit local anomalies that make them suitable for better representing correlations between external slope deformation and internal structural conditions. The limited ground cover in these areas strengthens the interaction between surface deformations and the underlying tunnel structure.

In Area 1, the integrated 3D scene highlights the slope southeast of the tunnel corresponding to the deformation zone in the InSAR velocity maps. MPs exceeding the ± 2 mm/year stability threshold are concentrated along this east-facing slope ([Fig. 15](#), [Fig. 16](#)). The ascending and East-West components consistently indicate eastward displacement, while in the corresponding tunnel section (km 0 + 460 - km 0 + 560) several cracked joints and water seepages were mapped ([Fig. 17](#)) on the images. The planimetric overlap between these defects and the slope deformation zone allowed a direct spatial comparison, suggesting a potential link between shallow slope movement and minor stress redistribution within the tunnel lining. In fact, the few ascending MPs detected in the deforming sector are located exactly above the tunnel section where the defects were observed and mapped ([Fig. 15](#), [Fig. 17b](#)).

In Area 2, the visualization emphasizes a deformation sector affecting the slope east of the northern portal of the north tube ([Fig. 18](#), [Fig. 19](#)). The DEM shows a northwest-facing slope intersecting the tunnel alignment. The ascending geometry indicates motion toward the satellite, consistent with west-directed displacements in the East-West component. The highest velocities are concentrated above the portal, where the internal inspection mapped vertical cracks and minor seepages on the sidewall facing the slope ([Fig. 18](#), [Fig. 20b](#)). This spatial alignment may indicate again that shallow movements, although of small magnitude, may contribute to localized stress redistribution or

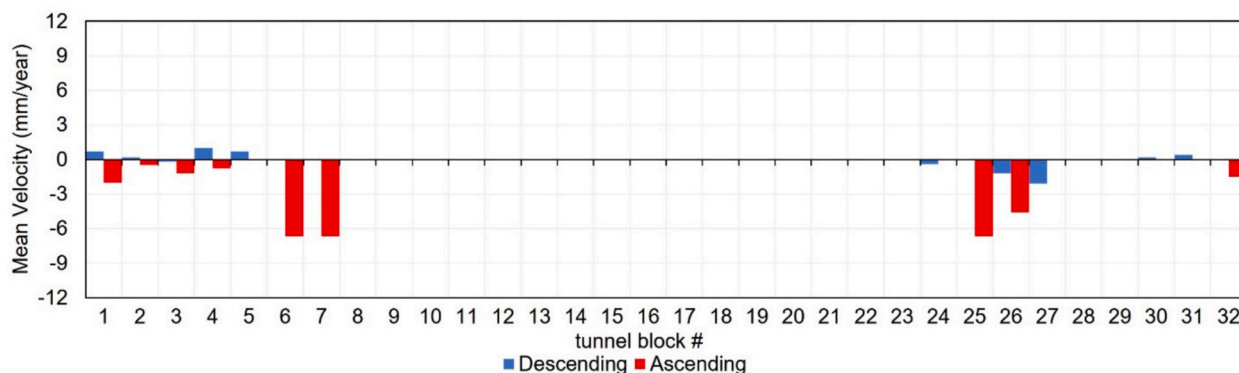
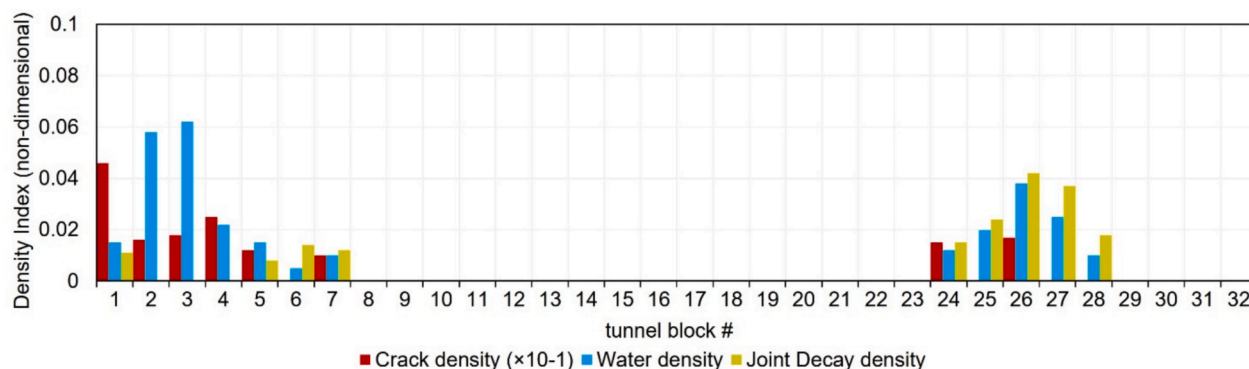
Area 1 - South tube: InSAR external monitoring**Area 1 - South tube: Defects internal inspection**

Fig. 13. Segment-based comparison between InSAR velocities and internal defect densities for Area 1 (south tube).

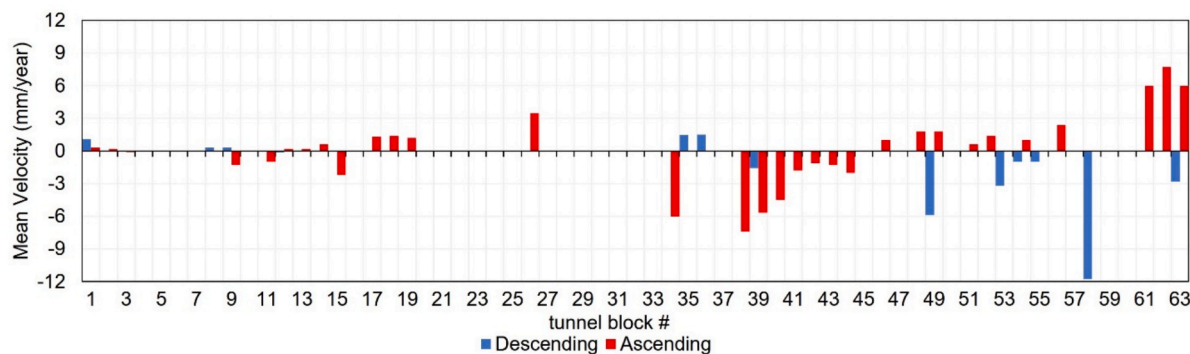
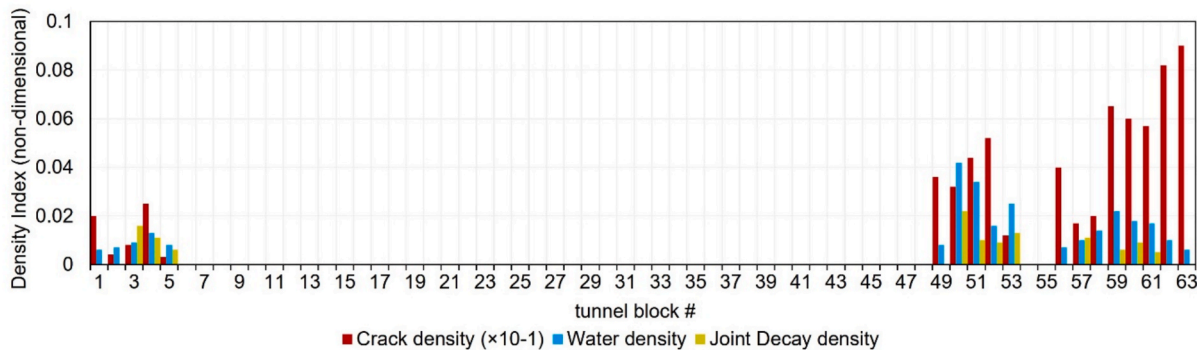
Area 2 - North tube: InSAR external monitoring**Area 2 - North tube: Defects internal inspection**

Fig. 14. Segment-based comparison between InSAR velocities and internal defect densities for Area 2 (north tube).

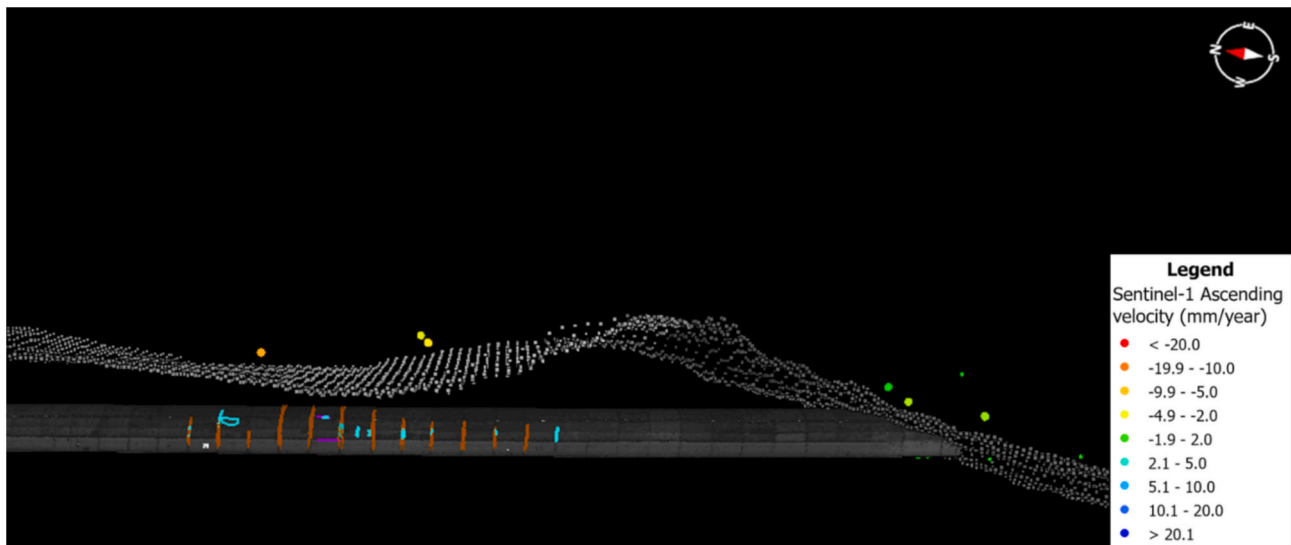


Fig. 15. Cross-sectional view of Area 1 extracted from Potree. The figure shows the reconstructed tunnel profile, the surrounding terrain surface, and the spatial distribution of Sentinel-1 InSAR MPs from the ascending geometry, coloured according to velocity values. The visualization highlights the relative position between the deformation sector above the slope and the underlying tunnel section where internal defects were mapped.

minor shear effects near the portal area.

To better interpret the detected ground motion, polar plots were produced and represented with the 3D views for both sites (Fig. 16c, Fig. 19c) using the decomposed InSAR velocity components developed in Festa et al. (2022) and Fibbi et al. (2025): the horizontal and vertical velocities were combined to represent the magnitude and direction of movement vectors for each MP. For Area 1 (Fig. 16c), vectors are mainly oriented eastward and downward, consistent with the east-facing slope and suggesting a downslope translational movement, with maximum velocities reaching 8 mm/year. For Area 2 (Fig. 19c), vectors predominantly point westward, with a slight downward component, in line with the northwest-facing exposure above the tunnel portal, where most vectors show velocities around 5 mm/year, except for one registering 15 mm/year.

The combined analysis supports the interpretation of potential links between slope dynamics and tunnel response. In both sites, the 3D integration revealed a spatial correspondence between zones of higher InSAR velocities and tunnel sections exhibiting recurring defects. At this stage, the proposed workflow is intended as a screening and decision-support framework rather than a quantitative slope-tunnel interaction model, supporting a multi-scale interpretation. Qualitative correlations offer meaningful preliminary evidence of geomorphological control on the distribution of internal damage. These observations also help to better interpret the processes controlling the different types of defects observed along the tunnel. In Area 1, the co-location of slope deformation and internal deterioration may indicate that progressive slope adjustment induces shallow stress variations in the arenaceous rock mass. In this sector, the predominance of water seepages and joint deterioration suggests that degradation is mainly driven by infiltration processes, facilitated by the relatively porous nature of the arenaceous formation, which allows water to percolate more uniformly. In Area 2, the orientation of vertical cracks mirrors the slope direction: the pattern seems consistent with the mechanism described by Wang (2010), who related cracks on tunnel linings to shear deformation induced by adjacent slope instability. In this case, the dominance of cracks and their alignment with the slope indicate that horizontal ground movements may play a more important role, generating localized shear stresses in the lining. The fractured calcareous setting further promotes ground-water flow along discontinuities, leading to more localized but intense defects.

The evidence suggests that even moderate slope movements can

influence tunnel lining behaviour, especially near portals or in areas with reduced cover. Nevertheless, further validation through *in-situ* measurements, e.g., extensometers, inclinometers, piezometers, would be required to quantify the interaction mechanisms. A relevant benchmark is provided by Ramirez et al. (2022), who validated Sentinel-1 PS-InSAR deformation results against levelling measurements in a tunneling case study, highlighting the added value of independent ground-based control for quantitative validation. By contrast, in the case studies presented in this paper, ground-based displacement measurements (e.g., levelling, total station, or GNSS) were not available to cross-check the InSAR-derived trends. The integration of such data, together with geotechnical instrumentation, would help better constrain the deformation mechanisms and strengthen engineering interpretation of the observed patterns.

From an operational perspective, this case study demonstrates the advantages of integrating multi-scale and multi-source datasets within a unified framework. To date, most published works have focused either on surface deformation monitoring through InSAR (e.g., Barla et al., 2016; Della Ragione et al., 2023) or on detailed 3D inspection of tunnel linings using optical or LiDAR-based systems (e.g., Attard et al., 2018; Chaiyasarn et al., 2016), but very few attempts have been made to the integration of the two datasets. The existing studies generally address newly built or instrumented tunnels, while applications to existing infrastructures remain limited. One of the main advantages of InSAR analysis is its ability to provide retrospective deformation measurements without the need for any pre-installed target, by exploiting stable radar reflectors naturally present on the ground. Both InSAR monitoring and image-based internal inspection represent key technologies for assessing the condition of underground infrastructures and are explicitly acknowledged in the Italian regulation. The combination of the two techniques bridges the gap between surface-scale geomorphological processes and internal structural observations for existing tunnel infrastructures, which is still unexplored in scientific literature and represents a step forward toward digital and multi-scale monitoring of existing tunnels in accordance with current guidelines. The integration in Potree enables users to intuitively explore spatial relationships between datasets, improving both engineering interpretation and communication of results to infrastructure managers. Such visualization tools enhance decision-making for maintenance prioritization and preventive monitoring.

The combination of satellite remote sensing, mobile imaging, and 3D

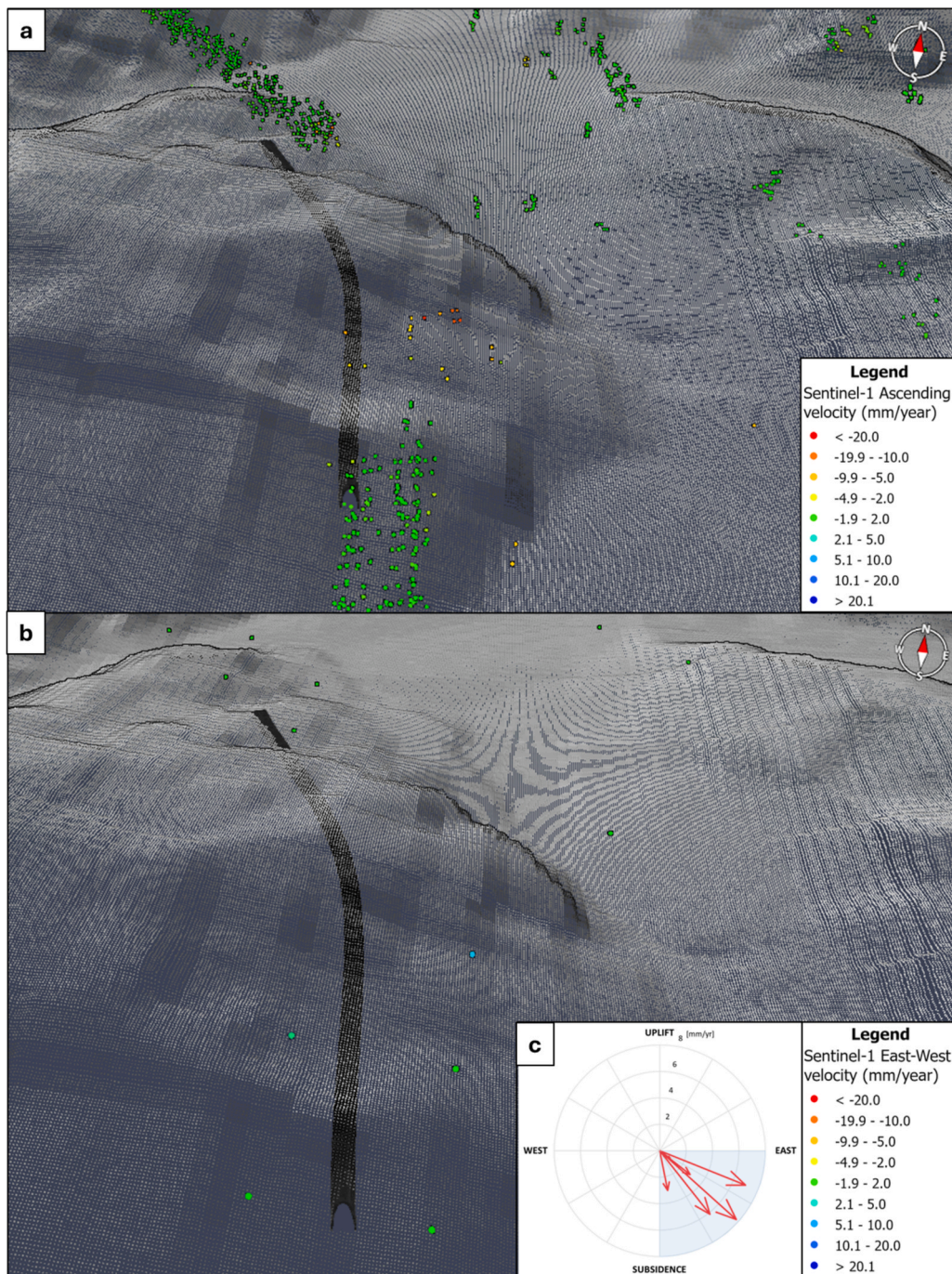


Fig. 16. (a) 3D view of the southern portal of Area 1 showing the DEM, tunnel model, and MPs from the ascending geometry; (b) 3D view of the same sector with MPs from the East-West component; (c) polar plots representing the velocity vectors obtained from East-West and Up-Down MPs located in the deformation area.

visualization platforms enhances not only the diagnostic capability but also the efficiency and safety of inspection activities. In practical terms, the adopted workflow proved particularly advantageous for existing infrastructures where traffic interruption was not feasible. In the analysed tunnels, inspections were explicitly required to be performed without road closures, and the digital, non-contact acquisition strategy allowed data collection to occur during normal traffic flow. By reducing the need for extensive on-site operations, the workflow limits personnel exposure to potentially hazardous environments and maintains the continuity of essential transport services. This operational benefit is especially relevant for long and strategic highway corridors, where maintaining full functionality is a critical requirement. The digital nature of the process further accelerates both data collection and analysis,

lowering operational costs and supporting more frequent and objective assessments of tunnel conditions. The approach also remains adaptable to other linear infrastructures, including railway tunnels, where similar constraints related to safety and service continuity exist. With appropriate adaptations, the image 3D reconstruction methodology could be extended to natural or non-standard underground cavities, where more irregular shapes may be represented through LiDAR-based modelling or through complex geometric models. Moreover, the incorporation of InSAR data in this field serves as an effective preliminary screening tool, allowing rapid identification of potentially unstable areas and guiding detailed internal inspections where they are most needed. In the present case studies, the density of EGMS MPs was limited; therefore, a locally tuned MT-InSAR processing of Sentinel-1 data, with sensitivity tests on

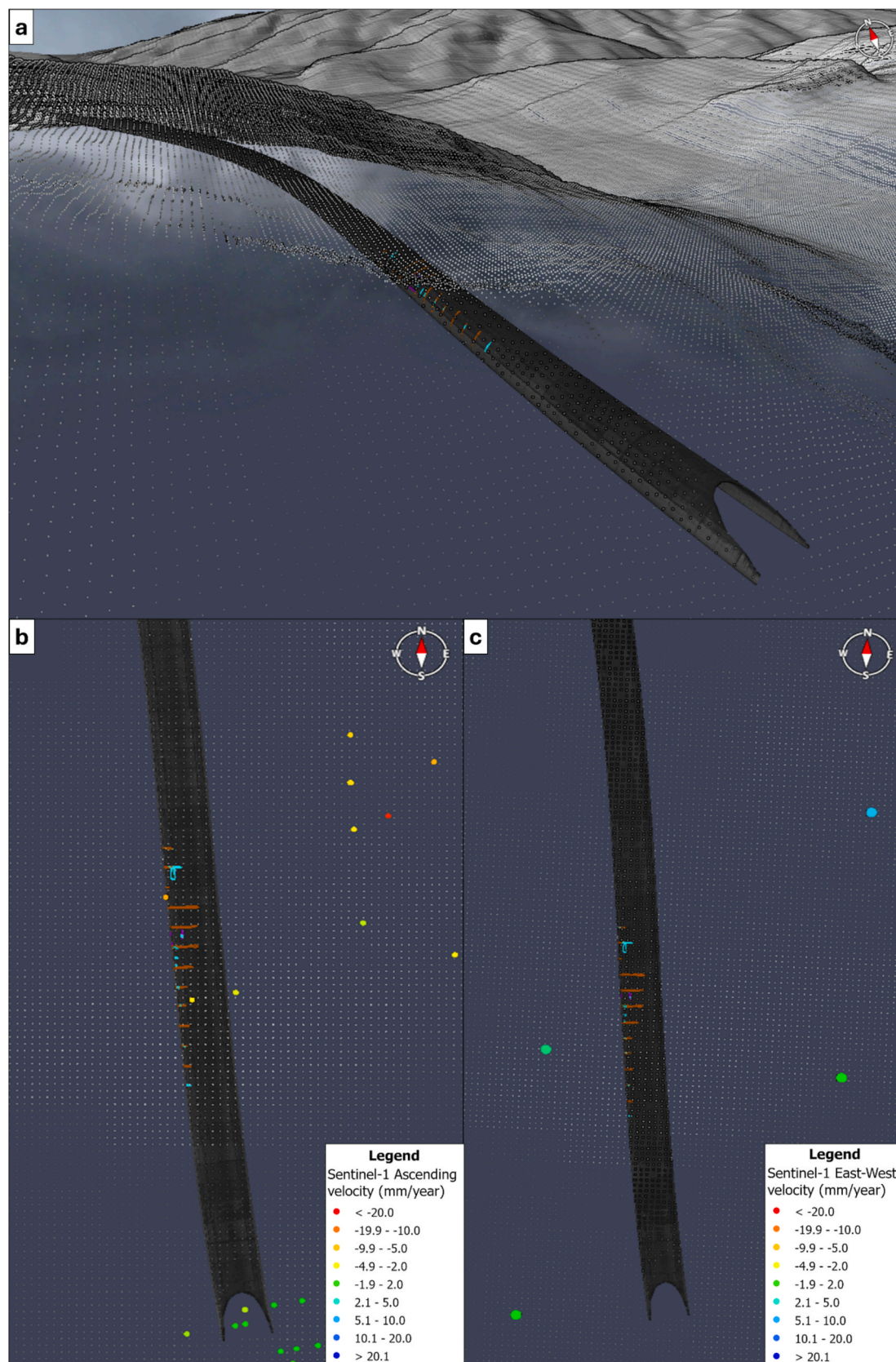


Fig. 17. (a) 3D view of Area 1 with the DEM and the reconstructed tunnel with mapped internal defects; (b) plan view of the southern tunnel sector showing the overlap between defects and ascending geometry MPs; (c) plan view of the same area with defects and East-West component MPs.

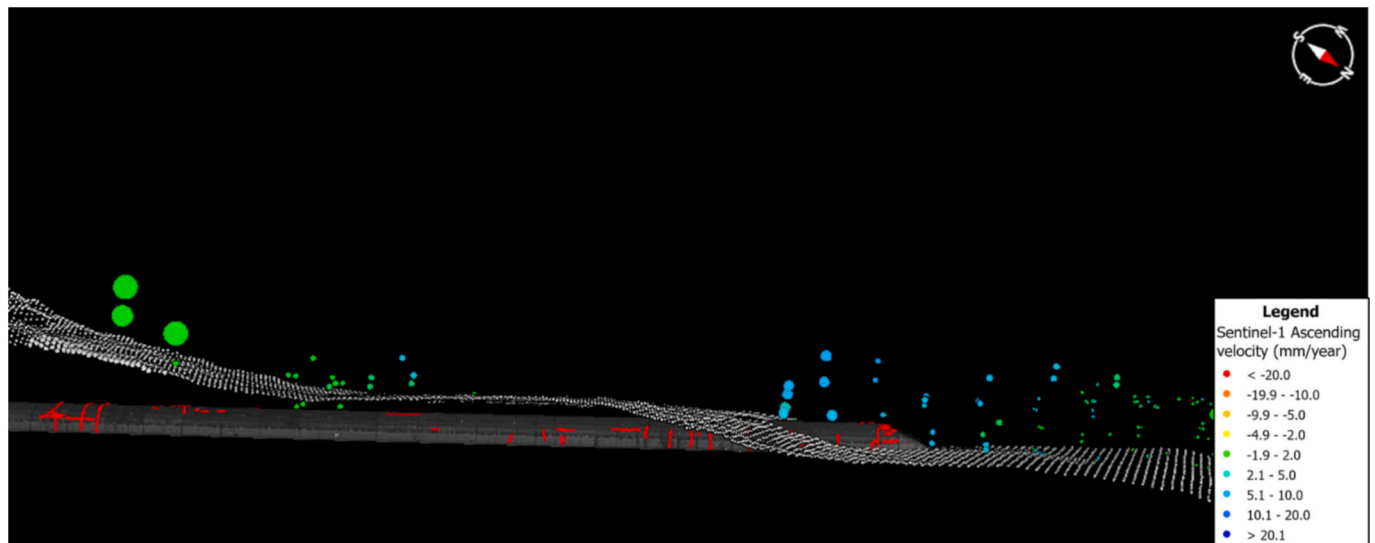


Fig. 18. Cross-sectional view of Area 2 extracted from Potree. The figure combines the tunnel geometry, terrain profile, and Sentinel-1 InSAR MPs, coloured by velocity. The representation provides a simplified view of the deformation pattern affecting the slope above the portal and its spatial relationship with the tunnel section where internal anomalies were observed.

point selection thresholds, could be explored to increase point density and to further verify the robustness of the observed spatial patterns.

In this study, the InSAR products cover January 2019 to December 2023, whereas the acquisition of interior images was carried out in September 2024. The InSAR results therefore represent long-term deformation trends up to the end of 2023, while the lining condition is documented afterwards. This time offset is acceptable for a first-order screening of slow-moving processes, but it may miss short-term changes occurring between the end of the InSAR observation window and the inspection date. Future applications should reduce this mismatch by extending the InSAR time series to the inspection period where possible. However, satellite InSAR mainly provides retrospective deformation information and may not always be available with minimal latency, especially when relying on open-access products. For this reason, periodic inspections and complementary *in-situ* monitoring could capture more recent or short-term changes.

From a methodological perspective, the proposed approach should be interpreted as an application-oriented workflow that integrates established remote sensing and image-based 3D reconstruction techniques within a unified framework. The main contribution lies in the effective combination of multi-scale datasets to support the interpretation of tunnel behaviour within its geomorphological context. In this sense, the study highlights the potential of combining satellite-based deformation measurements with high-resolution internal inspections, enabling a more comprehensive understanding of the interaction between surface processes and underground structures. The integration and visualization strategy provides a practical tool for linking external and internal observations, supporting engineering interpretation and data digitalization for decision-making.

Further research should explore data fusion techniques to derive numerical indicators linking surface displacements and structural distress, ultimately contributing to risk-based asset management of tunnel infrastructures. An important next step would be the development of quantitative and automated models able to relate deformation magnitude and trends to specific defect categories, with the aim of moving from qualitative spatial correspondence to reproducible metrics. In this perspective, the digital environment can be progressively enriched with additional datasets, such as thermal images, ground-penetrating radar profiles, or measurements from structural monitoring sensors, enabling a multi-parameter interpretation of tunnel conditions. When combined with machine-learning-based approaches

for automated defect recognition and pattern analysis, these complementary layers could support semi or fully automated inspection workflows and strengthen early-detection capabilities. Recent advances have shown that Artificial Intelligence (AI)-based algorithms are already capable of reliably detecting and classifying cracks on 2D imagery (Al Shafian et al., 2024; European Commission, 2022; Foria et al., 2022; Lu et al., 2025), and their integration with 3D reconstruction models would enable the automatic identification, measurement, and classification of defects directly within the tunnel digital environment. Future developments will also aim to integrate these AI-based outputs directly into the 3D model as georeferenced labels and attributes, allowing automated updating of defect inventories and more consistent comparisons across inspection campaigns. This approach provides a promising pathway toward more autonomous, predictive, and objective inspections. Finally, the proposed framework should be tested on additional case studies spanning different geological settings and a wider range of linear infrastructures (e.g., railway tunnels and other underground assets), in order to better assess its operational value.

In this work, the absence of direct trajectory measurements required the development of a dedicated, simplified procedure for curving the straightened tunnel point cloud. The adopted solution relied on an externally provided polyline representing the tunnel centreline, along which a parallel-transport frame was constructed to map the reconstructed geometry into a realistic spatial configuration. This approximation proved effective for restoring the overall alignment and enabled a coherent geo-referencing of internal defects along the tunnel chainage. However, the polyline-based approach cannot fully capture local variations in sensor motion, such as minor rotations, vibrations, or deviations from the designed axis. For this reason, ongoing developments of the reconstruction workflow will focus on the integration of trajectory data acquired from Inertial Measurement Units (IMUs). Incorporating pitch, roll, and yaw measurements will allow a more realistic modelling of the tunnel curvature and alignment, while correcting distortions induced by vibration or irregular motion. Such integration would automate part of the reconstruction process, providing a more robust and consistent geometric representation.

6. Conclusions

This paper presents an integrated framework for the assessment of existing tunnel infrastructures through the combined use of satellite-

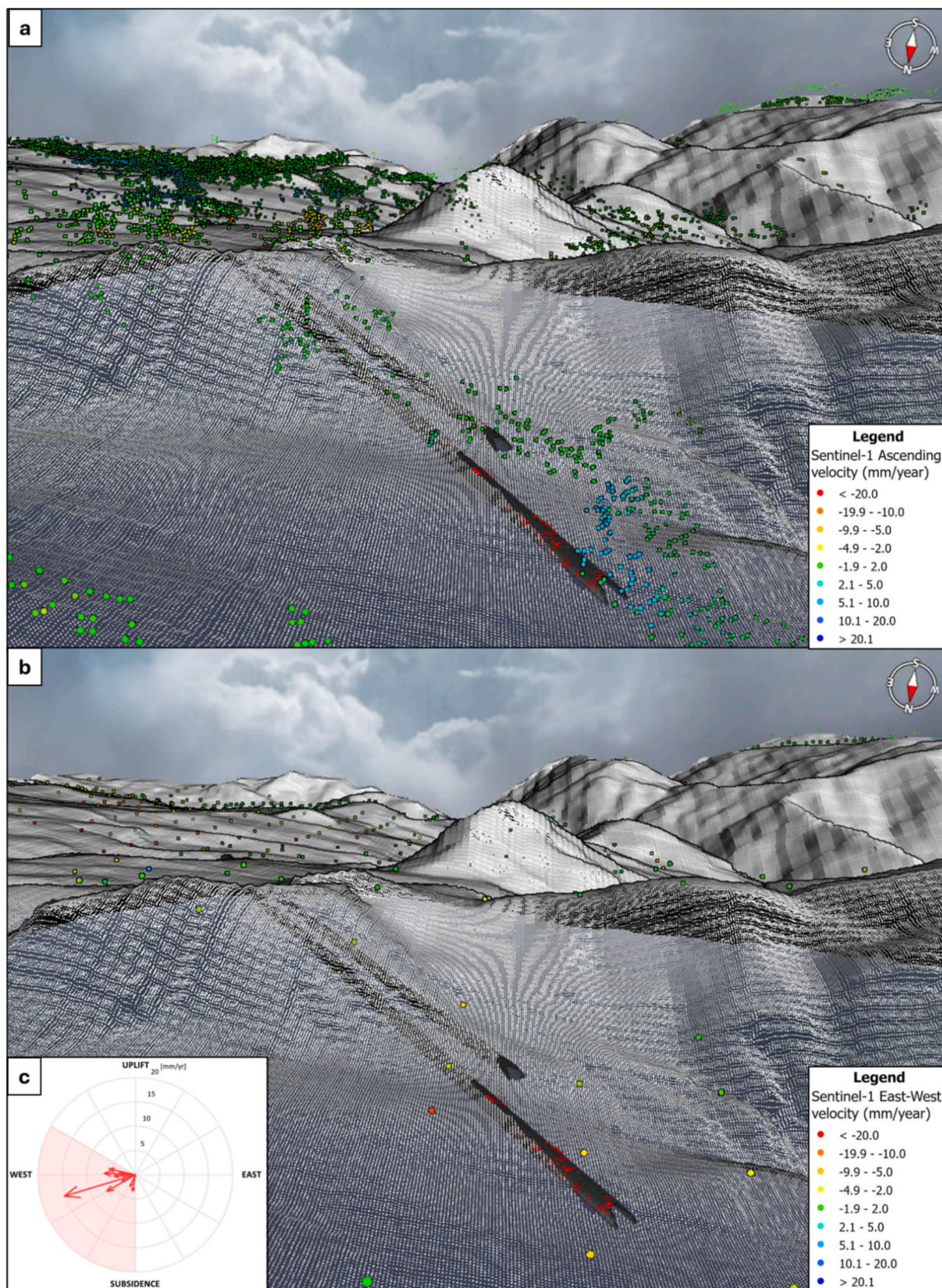


Fig. 19. (a) 3D view of the northern portal of Area 2 showing the DEM, tunnel model, and MPs from the ascending geometry; (b) 3D view of the same sector with MPs from the East-West component; (c) polar plots representing the velocity vectors obtained from East-West and Up-Down MPs located in the deformation area.

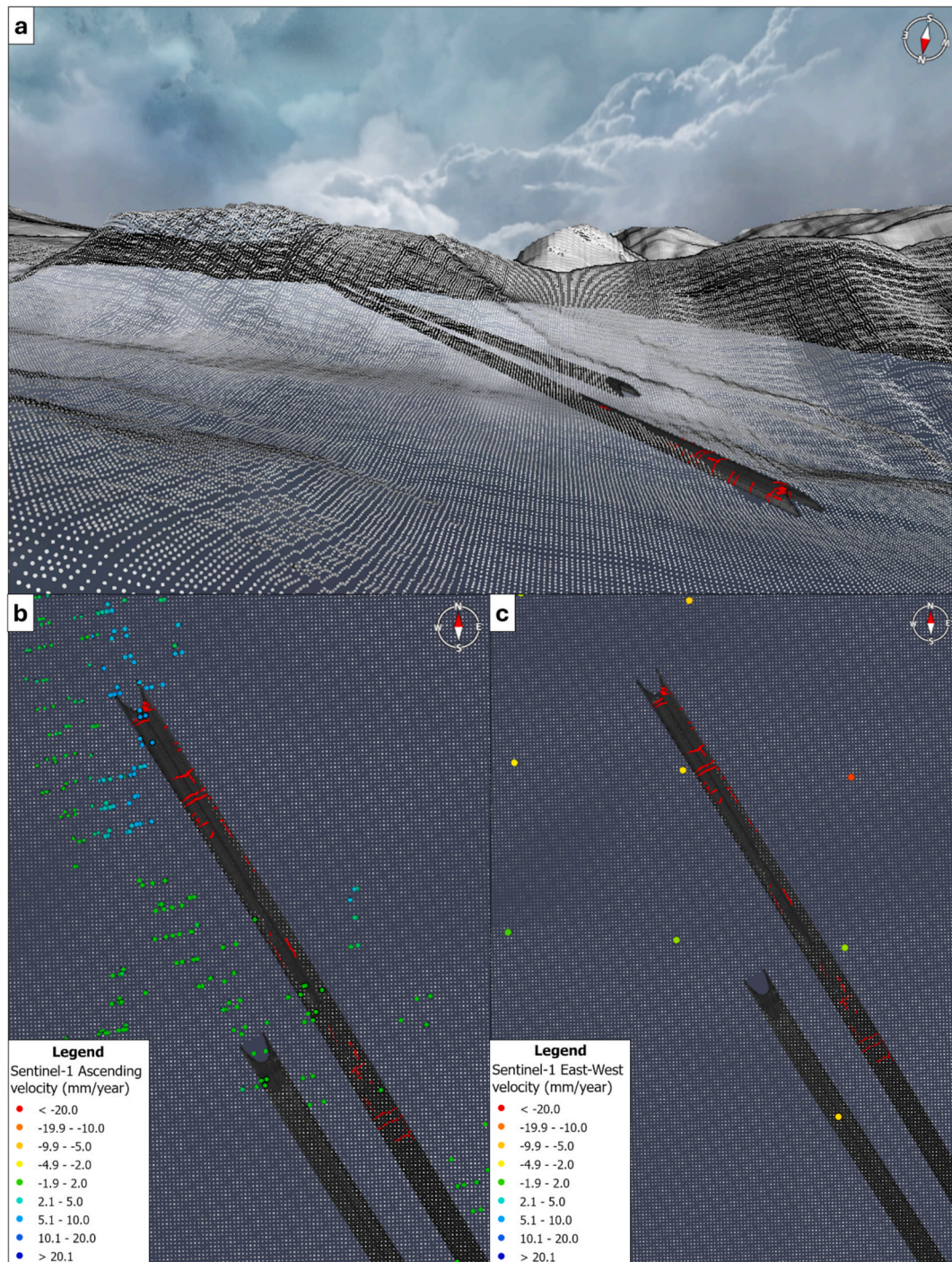


Fig. 20. (a) 3D view of Area 2 with the DEM and the reconstructed tunnel with mapped internal defects; (b) plan view of the northern tunnel sector showing the overlap between defects and ascending geometry MPs; (c) plan view of the same area with defects and East-West component MPs.

based interferometric data and high-resolution image-based inspections. The proposed approach links large-scale ground deformation monitoring with detailed 3D reconstruction of tunnel linings, connecting surface and subsurface information within a unified spatial environment.

The methodology presented in this work extends the application of these techniques through innovative processing and visualization strategies. The application to two tunnel sites demonstrated the effectiveness of this approach in identifying areas where external slope deformations and internal structural anomalies may coexist. The combination of multi-source datasets provided a coherent picture of the

interaction between geomorphological processes and tunnel response, enabling a more comprehensive understanding of infrastructure behaviour. This integration strengthens the role of 3D image reconstruction methodologies and remote sensing techniques in supporting the assessment of complex infrastructure systems.

The integration within a 3D environment such as *Potree* offers the possibility to explore spatial relationships between datasets, i.e., tunnel geometry, mapped defects, slope deformation, and local geological features, thus improving engineering interpretation and facilitating communication with infrastructure managers. Such visualization tools can support decision-making for maintenance prioritization and

promote preventive monitoring strategies, ultimately contributing to risk mitigation in hydro-geologically sensitive settings. The approach also aligns with recently released national guidelines for digital and multi-scale infrastructure assessment. Beyond highway tunnels, the proposed method shows strong potential for application to other linear infrastructures, such as railway tunnels or natural underground cavities where similar constraints on safety, access, and service continuity apply.

Future developments will focus on refining the quantitative relationship between external and internal observations, integrating additional *in-situ* geotechnical measurements and temporal analyses. The presented framework represents a step toward a multi-scale, digital monitoring system capable of supporting more informed decision-making and long-term resilience of underground infrastructures.

CRediT authorship contribution statement

Saduni Melissa Dahanayaka: Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Conceptualization. **Gabriele Fibbi:** Writing – review & editing, Visualization, Supervision, Resources. **Alessia Vecchiatti:** Writing – review & editing, Supervision, Resources, Project administration, Conceptualization. **Matteo Del Soldato:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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