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Application of a nested modelling approach for the analysis of landslide-tunnel systems

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Abstract

The interaction between landslides and transportation infrastructure represents a critical challenge in mountainous regions worldwide, with significant implications for public safety, regional connectivity, and socio-economic sustainability. Professional geoscientists and engineers often take advantage of numerical simulations to investigate the correlation between landslide movement and structural response. However, one of the main challenges of the analysis of landslide-infrastructure systems (LIS) is related to the difficulty of reliably capturing localized infrastructure damage induced by large-scale landslide processes within computationally feasible frameworks, given the contrasting spatial scales involved.

In this work, we develop a nested numerical modelling approach and explore its capability to investigate a real case study, namely the Passo della Morte LIS. The Passo della Morte landslide is a 30-million-cubic-meter active rock-block slide (moving 2-3 cm/year) crossed by a 2200-meter-long road tunnel. Since its construction, the tunnel began showing evidence of damage and deformation at the intersection with the inferred landslide basal surface. In the developed approach, a landslide-scale model, built using the finite-difference code FLAC3D, is used to capture bulk slope behaviour and stress distributions within the landslide. Custom Python and FISH scripts are then used to extract velocity fields and stress tensors from the landslide-scale model in order to transfer them to a relatively smaller, high-resolution infrastructure-scale model, built using the distinct element code 3DEC. This multi-scale numerical analysis shows that the tunnel model develops deformation patterns consistent with field observations, landslide movement patterns, and monitoring data.

The results of this work demonstrate that numerical simulations can achieve computational efficiency and physical accuracy when nested approaches are used. They also show that multi-scale simulations represent a solid pathway for advancing LIS interaction analysis toward mature frameworks, supporting evidence-based infrastructure management in landslide-prone regions.

Keywords

Nested modelling, Infrastructure-landslide interaction, Passo della Morte, Tunnel, Damage.

1 Introduction

Transport infrastructure constitutes a fundamental component of modern society, as it underpins socio-economic development and territorial connectivity. However, when traversing morphologically complex environments such as mountainous regions, its construction, development and long-term serviceability may be significantly threatened by natural hazards, including landslides. In this context, road tunnels are particularly exposed: structural damage induced by landslide movements can range from minor deformations compromising their functionality to partial or complete collapse. The consequences extend beyond physical damage, as the closure of a critical tunnel can isolate entire communities and impose severe economic costs. The critical importance of such infrastructure, together with the complexity of landslide-structure interaction mechanisms, poses significant challenges for reliable assessment and long-term risk management.

Addressing this challenge through numerical modelling is fundamentally complicated by the inherent multi-scale nature of the problem: landslides deformation may extend over surface areas of hundreds of square meters, whereas infrastructure damage manifests at centimeter-to-meter scales. Simulating both elements simultaneously within a single model at meaningful resolutions is computationally prohibitive and rarely feasible for most real-world scenarios. Existing approaches consistently struggle to achieve adequate resolution for both slope processes and structural response simultaneously (Vassallo et al. 2019). Models focused on the landslide commonly treat infrastructure as simplified boundary conditions, while models focused on the infrastructure prescribe landslide-induced actions as loading assumptions, disconnecting structural damage from actual slope kinematics. To overcome this limitation, this study proposes a nested modelling framework specifically designed to bridge the scale gap. The approach adapts established nested modelling strategies for localized high-resolution analysis within large-scale numerical models (e.g., Ciptokusumo et al. 2009) to the analysis of Landslide–Infrastructure Systems (LIS). A landslide-scale model captures bulk slope behavior and stress distributions, and the results are systematically transferred to a high-resolution infrastructure-scale model through custom data transfer procedures. The approach is applied to the Passo della Morte LIS in Friuli Venezia Giulia (Italy), a well-characterized case study where an active rock-block slide affects a 2200m road tunnel.

2 Case study

The study area is located in the Tagliamento Valley, in the north-eastern Italian region of Friuli-Venezia Giulia, within the municipalities of Forni di Sotto and Ampezzo (Fig. 1).

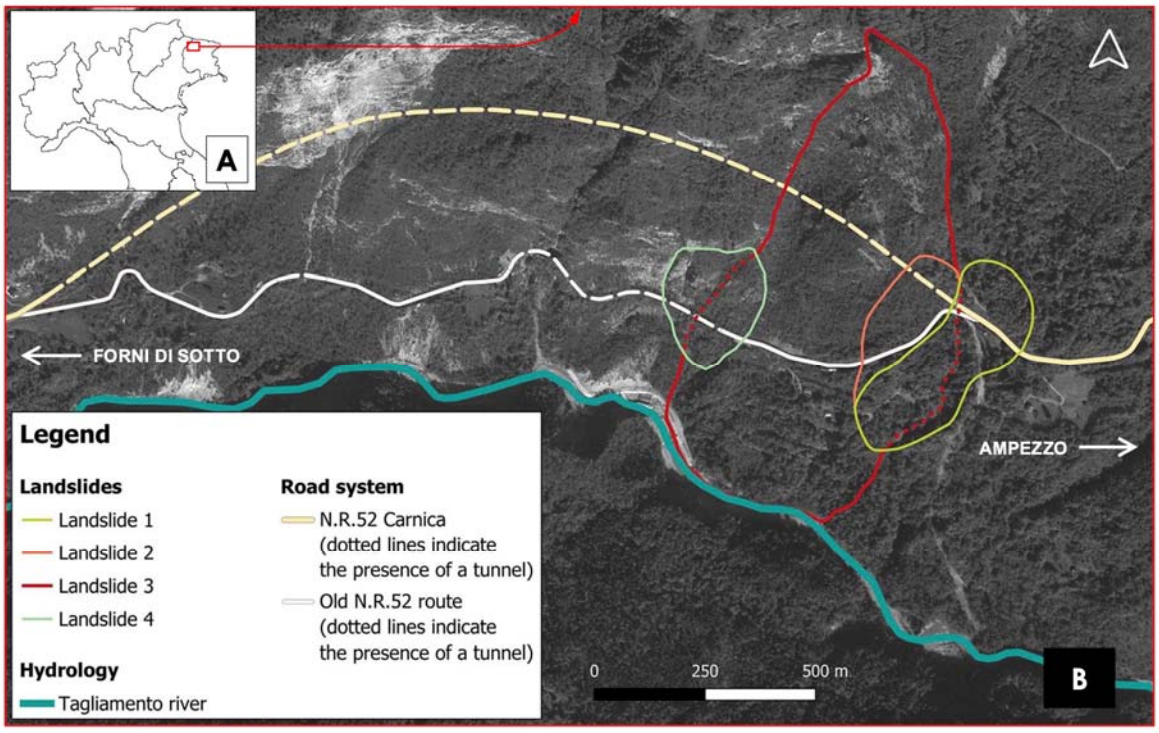


Fig. 1 a) Geographical framework, with study area outlined by the small red rectangle; b) case study area and the four landslides forming the Passo della Morte landslide system (Ballaera et al. 2024).

The area has a history of landslide hazard, as it is affected by a system of four distinct slope instabilities forming part of a larger Deep-seated Gravitational Slope Deformation (DsGSD) (Ballaera et al. 2024).Among these, the largest landslide (indicated as 'Landslide 3' in Fig. 1) commonly referred to as the Passodella Morte landslide, is classified as an active rock-block slide (Hungr et al. 2014). It extends from approximately 970 to 640 m a.s.l., with a surface area of 0.45 km², an estimated average sliding surface depth of approximately 60 m, and a volume of about 30 × 10⁶ m³ (Bossi et al. 2017). The landslide body consists predominately of a highly fractured and permeable dolomitic rock mass overlying plastic, clay-rich units. The contrast in competence between the two plays a key role in controlling slope dynamics: the weight of the fractured dolomite bears on the underlying clay-rich units, triggering slope movement. The landslide reports movements in a south-southwest direction at an average rate of 2–3 cm/year (Marcato 2007).

The study area is crossed by the National Road 52, a critical lifeline for local and regional connectivity. To bypass a section of this road affected by frequent small rockfalls, shallow landslides, and snow avalanches, the San Lorenzo road tunnel was built. It features a horseshoe section, approximately 11.50 m in width, 8.50 m in height, and an excavation area ranging from 85 to 95 m². In 1996, a heavy rainfall event resulted in a partial reactivation of the Passo della Morte landslide, causing widespread structural damage inside the tunnel, including lining cracks and concrete detachments (Fig. 2). Construction works were suspended from 1997 to 2006 while investigations and mitigation measures were carried out. The lining in the damaged portion, approximately the first 400 m from the eastern entrance (on the Ampezzo side), was entirely rebuilt using a succession of 12-m-long independent segments, designed to accommodate ongoing landslide-induced deformation, with a fully reinforced lining. A drainage tunnel was also excavated approximately 40 m below the road tunnel to reduce groundwater pressures. Despite these measures, new damage reappeared after the tunnel opening in 2008, particularly at segments 26–29 (numbered from the Ampezzo entrance), suggesting that the landslide sliding surface intersects the tunnel structure approximately at 360 m from the eastern entrance (Tedesco et al. 2020).

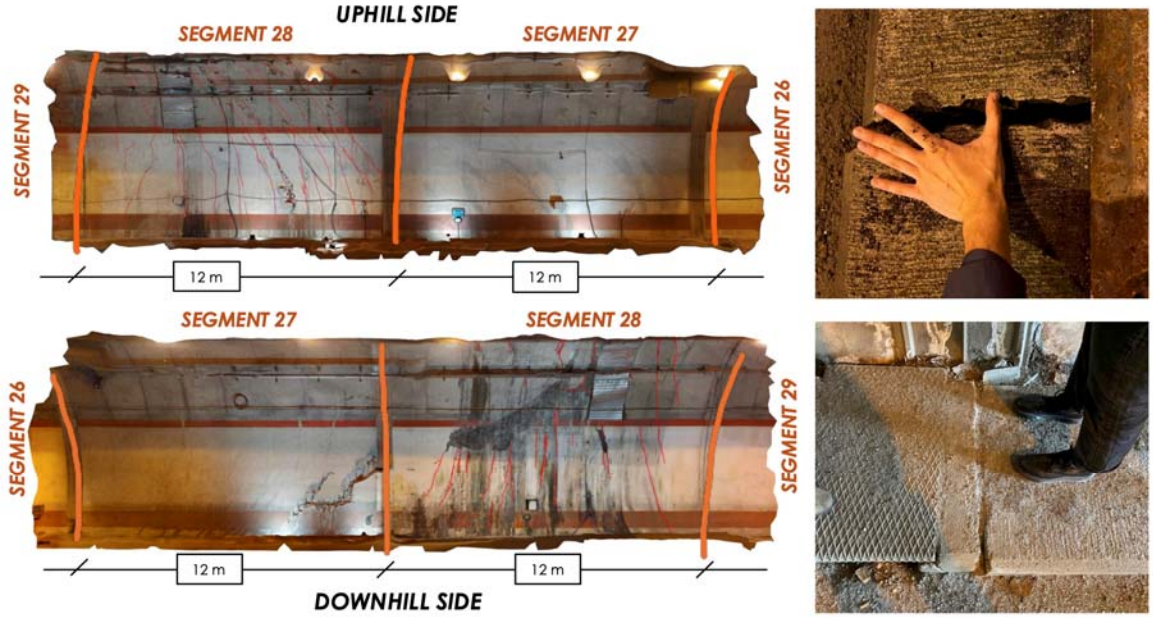


Fig. 2 Cracks pattern in segments 27 and 28, with a close-up of two concrete fractures on sidewalks at inter-segments positions; an opening of 2-3 cm is visible, revealing a discrepancy with landslide displacement rate (2-3 cm/year) and, thus, the indirect nature of landslide-tunnel interaction.

Consequently, a comprehensive monitoring system operated by CNR-IRPI (Italian National Research Council-Research Institute for Geo-Hydrological Protection) has been active since 2012, comprising inclinometers (both in-place and in-hole), piezometers, and a GNSS network to characterize slope kinematics. Since 2014, a dedicated monitoring system was also installed inside the tunnel, consisting of 24 crackmeters and 4 bi-axial clinometers, located at the most damaged segments (i.e., segments 26-29) to document the temporal evolution of structural damage.

3 Methodology

The Passo della Morte case study embodies the multi-scale integration challenges that motivate this research: landslide monitoring system operates at spatial scales of hundreds of meters, whereas tunnel monitoring targets centimeter-scale crack propagation within specific structural elements. This pronounced scale disparity, combined with the availability of comprehensive characterization and monitoring data at both scales, makes this case study suitable as a testbed for the nested framework.

The proposed workflow is structured as a hierarchical numerical strategy: a landslide-scale model captures bulk slope behaviour and provides the boundary conditions required to drive a smaller, high-resolution infrastructure-scale model. The core of the approach lies in the systematic extraction and transfer of velocity fields and stress tensors from the slope model to the tunnel model, concentrating fine-scale resolution only where structural analysis is necessary. This strategy enhances computational efficiency while preserving the mechanical consistency of the loading conditions applied to the infrastructure. Fig. 3 gives an overview of the models' geometry and constituting elements.

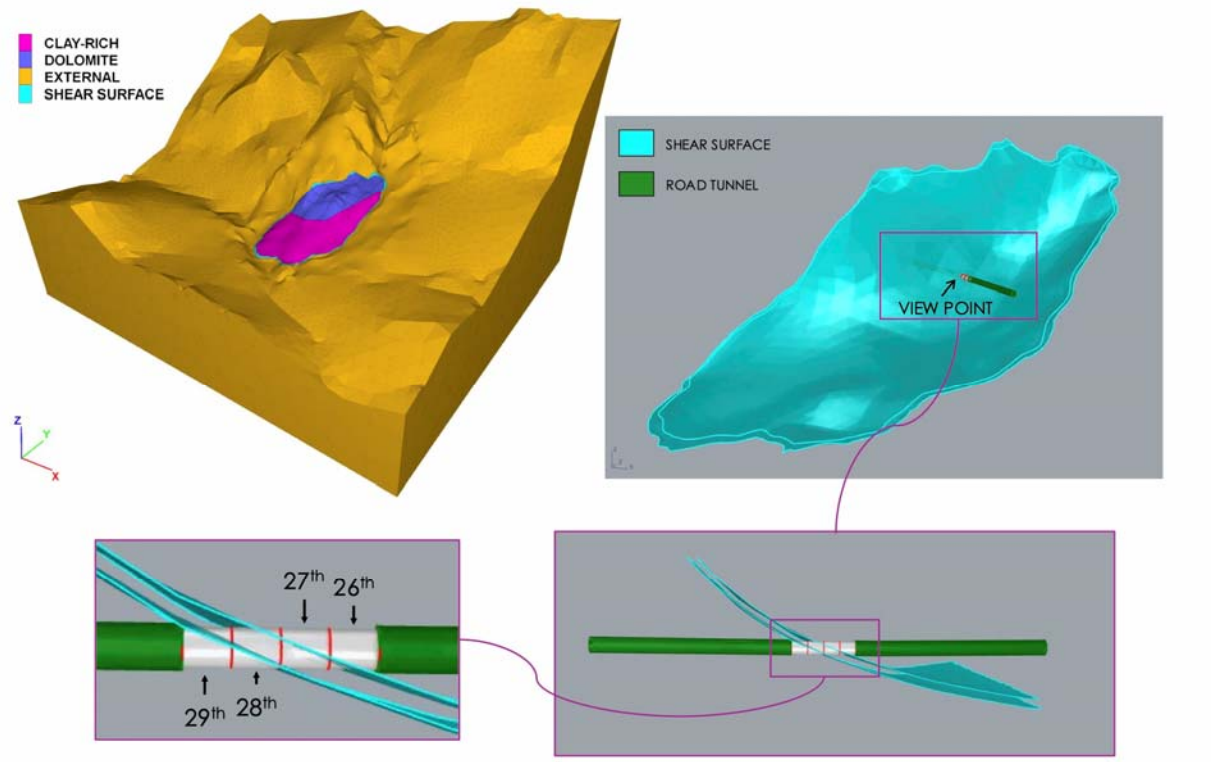


Fig. 3 Modelling elements of both the landslide-scale and the tunnel-scale model; overview of the general relative positioning of the San Lorenzo tunnel and the shear zone (represented as two identical surfaces 6 m apart).

Considering case study characteristics and modelling requirements, FLAC3D (Itasca Consulting Group, Inc. 2023) and 3DEC (Itasca Consulting Group, Inc. 2023) were selected for landslide-scale and infrastructure-scale modelling respectively. The use of two codes from the same developer facilitates the implementation of data transfer procedures, since both packages offer extensive customization capabilities through the FISH programming language and Python integration essential for implementing the multi-scale data transfer. The resulting scripts add flexibility tothe proposed methodology, as they can be readily reproduced for workflows involving different software packages.

The FLAC3D landslide model domain was defined by a bounding box approximately 3 km × 2 km × 2 km encompassing the entire Passo della Morte landslide body and extending sufficiently beyond its volume to avoid boundary effects. This domain was divided in dolomite, clay-rich units, shear zone, and the bedrock material external to the landslide body. A spatially variable mesh refinement strategy was adopted, with the finest discretization applied in a user-defined extraction volume in the immediate tunnel surroundings, ensuring a reduction of computational effort and the accurate representation of stress and deformation gradients for subsequent transfer. Lithological and geomechanical characterization from geological mapping, borehole logging, and laboratory testing data informed the selection of constitutive models and parameters. Particular attention was given to the competence contrast between dolomite and clay-rich units, which has been suggested to control landslide behaviour (Ballaera et al. 2024; Bossi et al. 2017).

Data extraction was performed within the defined volume (108 m × 30 m × 30 m) centered on segment 28, encompassing nine 12-m tunnel segments, providing a sufficient buffer around the tunnel to avoid boundary effects during data transfer. Likewise, an import volume (108 m × 20 m × 20 m) was defined in 3DEC purposely smaller than the extraction volume to ensure complete spatial mapping coverage and avoid assignment of inappropriate boundary parameters near the edges. Custom Python and FISH scripts were developed to extract velocity fields (from gridpoints) and stress tensors (from zone centroids) from the extraction volume. To ensure data integrity, the procedure incorporated redundancy strategies to prevent data loss, proximity-based mapping algorithms to maintain spatial relationships, and a visual validation to confirm that transferred fields reproduce the expected mechanical state.

The 3DEC tunnel model incorporated the San Lorenzo tunnel structure and its immediate surrounding: stable bedrock material, landslide material (entirely composed by the clay-rich units), shear zone, and tunnel lining. The model explicitly represents the independent 12-m tunnel segments as discrete blocks, enabling simulation of relative inter-segment movements. Boundary conditions were derived directly from the transferred velocity and stress fields, replacing the simplified loading assumptions typically used in tunnel analysis. Damage mechanism simulation targeted the reproduction of structural deformation and crack patterns observed in monitoring data, enabling direct validation of the nested multi-scale approach.

4 Results

Model predictions at the landslide scale were validated against field monitoring data. Virtual monitoring points placed at the coordinates of GNSS stations (Ballaera et al. 2024) GNSS2 (upper, dolomitic domain) and GNSS4 (lower, clay-rich domain) reproduce the observed landslide spatial gradient: virtual GNSS4 exhibits greater displacement than virtual GNSS2, consistent with the rock-block slide classification in which the weaker underlying clay-rich units accommodate most of the deformation. Comparison with inclinometer I-16 (Ballaera et al. 2024) confirms good agreement in both displacement magnitude and direction at the shear zone depth.

At the tunnel scale, the 3DEC model show spatial correlation between tensile stress concentrations, principal strain increments, and maximum displacement magnitudes, all focused on the shear zone intersection, consistent with the roto-translational deformation mechanism anticipated for the tunnel as a response to the landslide kinematics. Direct comparison with crackmeter data provides further quantitative validation: on the downhill side of the tunnel, the model predicts closure between segments 29 and 28 and opening between segments 28 and 27, in agreement with monitoring data from inter-segment crackmeters. The spatial correspondence between the oblique tensile stress band in the numerical model and the documented crack distribution in the tunnel (Fig. 4) further confirms that the nested approach reproduces global structural response mechanisms.

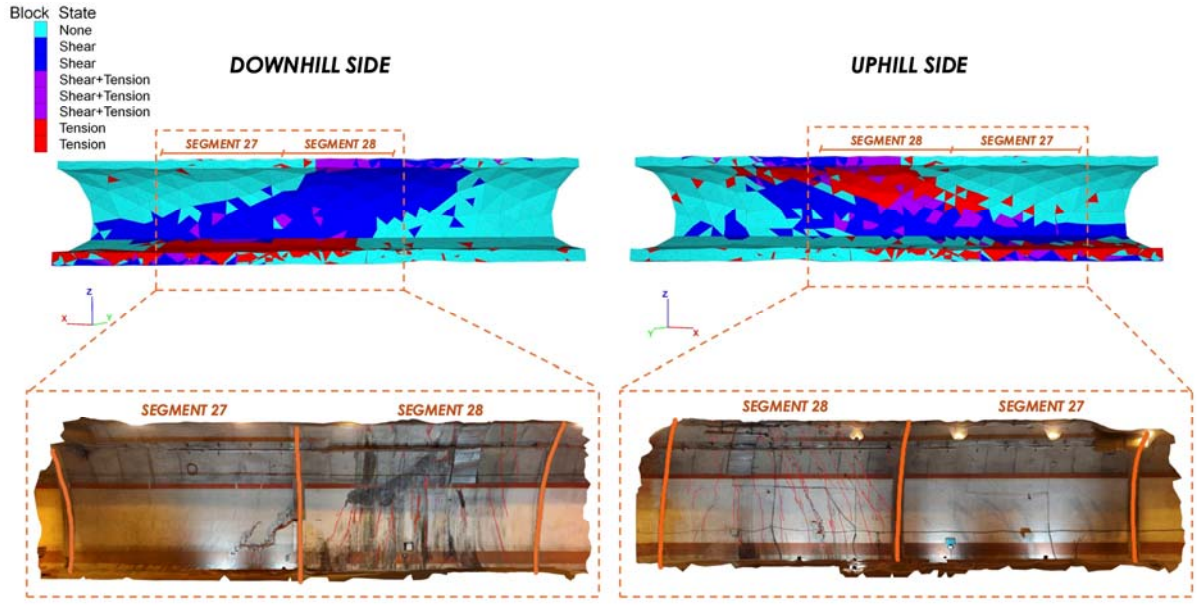


Fig. 4 Comparison between model resulting stress state and actual cracks pattern in the mostly damaged segments.

5 Conclusions

This work demonstrates the feasibility of a nested modelling approach for the analysis of landslide-infrastructure interaction. Applied to the Passo della Morte case study, the workflow successfully reproduced first-order landslide kinematics at the slope scale and structural deformation patterns at the tunnel scale. The qualitative agreement between numerical predictions and crackmeter monitoring logs not only validates the data transfer procedure but also confirms that velocity fields and stress tensors extracted from a landslide-scale model can provide physically meaningful initial state and boundary conditions for an infrastructure-scale model.

The deliberate use of two different numerical methods, FDM at the slope scale and DEM at the tunnel scale, demonstrates that the framework can integrate heterogeneous modelling paradigms, broadening its applicability to scenarios where a single numerical approach would be inadequate to account for the physical or structural characteristics of each system component.

At the same time, the approach is not yet a ready-to-use solution for routine engineering practice. Its successful application demands comprehensive site characterization spanning both scales, interdisciplinary knowledge, and substantial computational resources. The value of this work lies therefore not in providing an immediately deployable tool, but in establishing a viable methodological pathway and identifying the data, tools, and expertise required to advance the understanding of landslide-infrastructure interaction.

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