



ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

DOTTORATO DI RICERCA IN
INGEGNERIA CIVILE, CHIMICA, AMBIENTALE E DEI MATERIALI
Ciclo 38

Settore Concorsuale: 04/A3 - GEOLOGIA APPLICATA, GEOGRAFIA FISICA E
GEOMORFOLOGIA

Settore Scientifico Disciplinare: GEO/05 - GEOLOGIA APPLICATA

**MULTI-SCALE NUMERICAL MODELLING OF TUNNELS INTERSECTING
LARGE AND ACTIVE LANDSLIDES**

Presentata da: Pietro Festi

Coordinatore Dottorato

Enrico Sassoni

Supervisore

Lisa Borgatti

Co-supervisore

Davide Donati

Abstract

The interaction between landslides and transportation infrastructure represents a critical challenge in mountainous regions worldwide, with significant implications for public safety, economic stability, and regional connectivity. This challenge is intensifying due to converging global trends: demographic growth driving infrastructure expansion into hazardous terrain, technological development requiring increasingly complex networks, and climate change amplifying landslide frequency and intensity. In this scenario, road tunnels, essential for traversing difficult topography, appear particularly vulnerable when intersecting active slope instabilities, although comprehensive analysis remains elusive due to fundamental methodological limitations.

This thesis addresses this issue by specifically focusing on a persistent research gap termed the *multi-scale challenge*: the difficulty of simultaneously modelling large-scale landslide processes (extending hundreds of meters) and localized infrastructure damage (manifesting at centimeter scale) within computationally feasible frameworks. Indeed, existing approaches sacrifice resolution for one system component to maintain tractability for the other. Landslide-centric methodologies, for instance, achieve sophisticated slope characterization but treat infrastructure as simplified boundary conditions. On the other hand, infrastructure-centric approaches attain high structural resolution but prescribe landslide-induced actions as uniform loads, oversimplifying complex slope processes. Even systemic approaches, which explicitly incorporate both elements, face computational constraints requiring compromises in mesh resolution, often focusing on smaller landslides or specific interaction mechanisms rather than complete system behavior.

To overcome this limitation, this research developed a comprehensive multi-scale modelling framework for landslide-tunnel interaction systems (LISs) analysis. The methodology adapts nested modelling principles, successfully employed in other science fields to address analogous scale-mismatch problems, to geomechanical and structural engineering applications. The approach explicitly separates spatial scales while establishing rigorous procedures for mechanical information transfer. A coarse-resolution landslide-scale model captures bulk slope behavior and stress distributions, while a fine-resolution infrastructure-scale model focuses on detailed structural response. These models connect through systematic extraction and application of velocity fields and stress tensors, enabling infrastructure boundary conditions to be derived directly from landslide simulations.

The methodology is then validated through application to the Passo della Morte landslide-San Lorenzo tunnel system in the Carnian Alps of Friuli-Venezia Giulia region, Italy. This site exemplifies the multi-scale challenge: a 24-million-cubic-meter active

rock-block slide (moving 2-3 cm/year) affecting a 2200-meter road tunnel serving as the sole transportation link of the area. The case provides extensive geological characterization, decades of monitoring data (inclinometers, GNSS, crackmeters), and detailed site documentation, all essential prerequisites for developing the multi-scale framework.

The landslide-scale model, developed using FLAC3D, encompasses the entire slope with strategic mesh refinement: 0.5-meter elements in a 108×30×30-meter extraction volume surrounding the tunnel, with progressively coarser discretization toward boundaries. The model successfully reproduces observed displacement gradients, with good comparison against inclinometer profiles and GNSS measurements, confirming rock-block slide kinematics.

The infrastructure-scale model, implemented in 3DEC, focuses on nine consecutive 12-meter tunnel segments centered on the most severely damaged section. This configuration enables analysis of within-segment deformation and inter-segment joint behavior critical for understanding the peculiar segmented lining design, intended to accommodate ongoing landslide movement.

Custom Python and FISH scripts extract velocity vectors and stress tensors from the landslide model, using proximity-based mapping to transfer mechanical information despite different spatial discretization. The tunnel model develops roto-translational deformation patterns consistent with field observations, namely displacement magnitudes matching annual landslide rates, tensile stress concentrations at the shear zone-tunnel intersection correlating with observed crack locations, and inter-segment joint behavior (closure/opening patterns) matching crackmeter measurements.

This research establishes that the multi-scale challenge can be effectively addressed through nested modelling strategies maintaining both computational feasibility and physical accuracy. However, successful implementation demands extensive site characterization, interdisciplinary expertise, significant computational resources, and custom coupling procedures. The methodology represents a solid pathway demonstrating technical feasibility and identifying requirements for advancing landslide-infrastructure interaction analysis toward mature frameworks supporting evidence-based infrastructure management in landslide-prone regions.

Keywords: *multi-scale challenge, nested modelling, infrastructure-landslide interaction, Passo della Morte, tunnel, damage, monitoring*

Table of Contents

Abstract.....	I
Table of Contents.....	III
List of Figures.....	VI
List of Tables	IX
1. Introduction.....	1
2. State of the art	4
2.1. Landslide-centric approaches.....	5
2.1.1. Landslide monitoring techniques.....	5
2.1.2. Landslide numerical modelling	7
2.1.3. Numerical methods applications in landslide-infrastructure interaction...	9
2.2. Infrastructure-centric approaches.....	11
2.2.1. Infrastructural damage assessment and characterization.....	11
2.2.2. Numerical analysis of structural response	13
2.3. Systemic approaches.....	15
2.3.1. Landslide-infrastructure integrated numerical frameworks	15
2.3.2. Physical modeling in systemic approaches	17
2.3.3. Classification and analytical frameworks for Landslide-Infrastructure Systems (LISs).....	18
2.4. The multi-scale challenge.....	20
2.4.1. Nested modelling: a strategy for scale integration.....	23
2.4.2. Nested modelling for the multi-scale challenge	25
3. A proposed multi-scale approach for LIS modelling.....	27
3.1. The proposed method	28
3.1.1. Validation through application	29
3.2. The Passo della Morte case study	30
3.2.1. Geographic and climatic context.....	31
3.2.2. Geological framework and structural overview.....	32
3.2.3. Landslide system.....	35

3.2.4.	San Lorenzo road tunnel	36
3.2.5.	Landslide Monitoring System.....	41
3.2.6.	Tunnel Monitoring System	45
4.	Numerical modelling of the Passo della Morte LIS	48
4.1.	Application of the multi-scale approach	48
4.1.1.	Identification of the most suited modelling technique	49
4.1.2.	Large-scale model definition and objectives	50
4.1.3.	Data transfer procedure development.....	50
4.1.4.	Small-scale model definition and objectives.....	51
4.2.	Landslide-scale model.....	52
4.2.1.	Data collection	53
4.2.2.	General model construction	55
4.2.3.	Geological model construction and refinement	56
4.2.4.	Mesh discretization and meshing.....	57
4.2.5.	Continuum modelling	59
4.2.6.	Comparison of the results with monitoring data and previous analyses	63
4.3.	Multi-scale data transfer procedure.....	67
4.3.1.	Fundamental requirements for data transfer	68
4.3.2.	Software architecture and compatibility challenges	70
4.3.3.	Data extraction from FLAC3D.....	71
4.3.4.	Data import strategy for 3DEC	73
4.3.5.	Stress transfer implementation	74
4.3.6.	Velocity transfer implementation	76
4.3.7.	Limitations and assumptions.....	78
4.4.	Infrastructure-scale model	79
4.4.1.	Mesh construction and geometric simplification	79
4.4.2.	Model import and material characterization.....	82
4.4.3.	Tunnel excavation and lining implementation	83
4.4.4.	Deformation analysis and monitoring data comparison	84
4.4.5.	Limitations and challenges.....	96
4.5.	Summary and outlook	97
4.5.1.	Landslide-scale model potential improvements	97
4.5.2.	Multi-scale data transfer procedure potential improvements.....	99

4.5.3.	Infrastructure-scale model potential improvements	100
5.	Conclusions	103
5.1.	Advantages of the multi-scale approach.....	104
5.2.	Challenges and requirements of the multi-scale approach.....	106
5.3.	Outlook and future development.....	107
	References.....	109
	Appendix A: FLAC3D scripts	121
	Appendix B: 3DEC scripts.....	126

List of Figures

Figure 1 - Schematic representation of the inclinometer tube equipped with a Smart Extensio-Inclinometer (SEI) using a New Smart Hybrid Transducer (NSHT) (Damiano et al. 2025).....	6
Figure 2 - 3D models generated from processed drone imagery: (a) Vegetation identification; (b) vegetation extraction; (c) generated 3D model after segmentation of vegetation (Sun et al. 2025).....	7
Figure 3 - Difference in landslide analysis and corresponding numerical methods and failure mechanisms (D. Stead et al. 2006)	9
Figure 4 -Two-dimensional FEM simulation of landslide plastic zone distribution steps alongside tunnels excavation; each tunnel cavity section is 15 m width and 9.8 m height (Zhang et al. 2015)	10
Figure 5 - Typical example of rectification of geometric distortion in 3D tunnel surface images. (a) Layout of lining crack distributions by a visual inspection in 1994. (b) Lining surface layout in an image obtained by an advancing laser scanner in 2006 for the same section as that in (a). (c) Interpreting results according to (b). (Lee et al. 2013)	12
Figure 6 - Finite element mesh and boundary conditions for the investigation of the Stillwater Tunnel (Utah, USA) (Shalabi 2005)	14
Figure 7 - FLAC3D numerical model mesh visualization and general description for the analysis of twin tunnels; each tunnel cavity section is 15 m width and 9.8 m height (Zhang et al. 2021)	16
Figure 8 - Complete physical model of a tunnel involved in a landslide (Wei et al. 2023)	17
Figure 9 - Schematic diagram of the four scenarios of tunnel interacting with landslide considered for the study (Li et al. 2025).....	18
Figure 10 - Model scale spectrum as seen through the State-of-the-art review	20
Figure 11 - A schematic example of a nested configuration involving both cascading and parallel child domains (Hellsten et al. 2021)	24
Figure 12 - Example of a 3D mesh discretization for: (a) global model, (b) reference model, and (c) sub-model (Zhao et al. 2019)	26

Figure 13 - (A) Geographical framework, with study area outlined by the small red rectangle; (B) Major transportation routes in the area; (C) case study area and the four landslides forming the Passo della Morte landslide system (Ballaera et al. 2024).....	31
Figure 14 - Chronostratigraphic chart of Passo della Morte area from Pisa (1972), revised by Marcato (2007) (Ballaera et al. 2024).....	33
Figure 15 - Geological map of the Passo della Morte area (Ballaera et al. 2024)	34
Figure 16 - Paleo-landslides recorded in the Passo della Morte area with Landslide 3, the commonly known Passo della Morte landslide, outlined in red (Ballaera et al. 2024)	36
Figure 17 - Countermeasures adopted in the aftermath of 1996 landslide acceleration	38
Figure 18 - Earlier geological cross sections AA' and BB' (cfr Figure 15) (Ballaera et al. 2024 after Marcato 2007).....	40
Figure 19 - Slope-scale monitoring system, with instrumentation both operating and decommissioned; Passo della Morte landslide labelled as Landslide 3 (Ballaera et al. 2024).....	42
Figure 20 - Engineering–geological cross-section indicating borehole locations and depth and shape of the sliding surface of the Passo della Morte landslide (cfr Figure 19 for location) (Ballaera et al. 2024)	43
Figure 21 - Inclinometers I-23 and I-24 data	44
Figure 22 - Passo della Morte landslide evolution stages and directions (Ballaera et al. 2024)	44
Figure 23 - Photographs of the resulting gap in sidewalks in different adjacent segment connection points	45
Figure 24 - Concrete crack pattern appeared after reopening to traffic in 2008; photos taken in late 2018.....	46
Figure 25 - San Lorenzo road tunnel positioning, with details on the shear surface segments crossing.....	47
Figure 26 - Overview of the San Lorenzo infrastructure-scale monitoring system	47
Figure 27 - Multi-scale framework applied to the Passo della Morte case study	52

Figure 28 - Surfaces bounding the shear zone, showing the duplication and offset of the surface to create the 3D volume of the shear zone	56
Figure 29 - Passo della Morte landslide model relevant geological features; dolomite fractures are not activated within this work.....	57
Figure 30 - Passo della Morte model geometry after importing and group definition	58
Figure 31 - Passo della Morte landslide FLAC3D model group definition.....	59
Figure 32 - Comparison between displacement and velocity distributions of each sequential step, namely 3000, 6000, and 10000 cycles after equilibrium .	62
Figure 33 - Comparison between GNSS monitoring data and model outcome: it can be noticed that a good comparison can be made for GNSS4, while for GNSS2 the data show possibly differences related to aleatory component given by superficial movements and to continuum.....	64
Figure 34 - Comparison between inclinometer I-16 monitoring data and model outcome	65
Figure 35 - Comparison between displacements distributions of present work and Tedesco (2018) models	66
Figure 36 - FLAC3D extraction volume	71
Figure 37 - 3DEC import volume.....	73
Figure 38 - Comparison between FLAC3D and 3DEC stress distributions; the XX-stress component has been chosen as representative quantity; the discrepancy in values between FLAC3D and 3DEC outcomes is related to the difference in volumes dimensions.....	75
Figure 39 - Comparison between FLAC3D and 3DEC velocity distributions; the discrepancy in values between FLAC3D and 3DEC outcomes is related to the difference in volumes dimensions.....	78
Figure 40 - Tunnel cross-section simplification overview, as routinely used (Zhao et al. 2019; Jiao et al. 2013; Wang et al. 2020; Zhang et al. 2015)	80
Figure 41 - San Lorenzo tunnel 3DEC model group definition	81
Figure 42 - San Lorenzo tunnel 3DEC final 3-m-mesh output.....	82
Figure 43 – 3DEC model after tunnel excavation and lining positioning.....	83
Figure 44 - Displacement magnitude distribution.....	85

Figure 45 - Displacement distribution in X-direction.....	87
Figure 46 - Displacement distribution in Y-direction	88
Figure 47 - Displacement distribution in Z-direction	89
Figure 48 - Maximum principal stress distribution.....	90
Figure 49 - Minimum principal stress distribution	91
Figure 50 - Maximum principal strain increment distribution	91
Figure 51 - Minimum principal strain increment distribution.....	92
Figure 52 - Comparison between model resulting stress state and actual cracks pattern in the mostly damaged segments (i.e., segments 27 and 28)	93
Figure 53 - Comparison of crackmeter measurements with model-predicted crack opening/closing at corresponding locations	95

List of Tables

Table 1 - Points for the shear surface reconstruction where: B=Borehole, DES=Digitalized Engineering-Geological Section, DLP=Digitalized Landslide Perimeter	53
Table 2 - Material properties for the landslide-scale model	55
Table 3 -San Lorenzo concrete lining material properties	84

1. Introduction

The interaction between landslides and human infrastructure, especially linear infrastructure such as road transport networks, represents a critical area of study. The complex and destructive nature of landslide poses a risk to built environments and, consequently, to human activities and safety. Road networks as well as residential, logistic and public facilities are directly exposed to slope instabilities, notably in hilly and mountainous regions. The consequences of their partial or total failure extend from damage to the built environment and infrastructures, resulting in monetary loss or delays in the movement of goods and people, to severe and irreversible outcomes, including casualties and extensive landscape modification.

Although extensively investigated in the past, this topic is gaining renewed importance due to the convergence of three global trends: demographic growth, technological and urban development, and climate change. Each of these drivers has a direct impact on landslide risk.

Demographic growth creates unprecedented spatial pressures: the world's population is expected to reach a peak of around 10.3 billion people in the mid-2080s, up from 8.2 billion in 2024 (UN DESA/Population Division 2024), with over 68% concentrated in urban areas (UN Department of Economic and Social Affairs 2019). This demographic shift dramatically increases the demand for housing, transportation, access to resources (from food and water to raw materials for manufacturing), and safe means to transport all these materials.

Technological progress reinforces this expansion, requiring increasingly complex infrastructures and greater exploitation of natural resources and available space to sustain production and innovation. Consequently, this pressure has driven an almost constant increase in global urbanization and infrastructure investment over the past decade, often pushing development into previously avoided hazardous areas, including mountainous regions prone to slope instabilities (World Bank 2024) .

Climate change exacerbates these challenges by intensifying normal weather and climate trends in a system that is already under severe stress. As the European Environment Agency (EEA) notes, climate change acts as a risk multiplier that can worsen existing risks and crises (European Environment Agency 2024). This is particularly evident in mountainous regions, where more frequent and intense rainfall events are expected to increase landslide occurrence (Gariano and Guzzetti 2016) . The scale of this threat has already been substantial: landslides have caused approximately \$34.2 billion in annual economic losses between 2000 and 2023 (UNDRR 2025) .

Together, these demographic and climatic pressures are creating unprecedented uncertainty for both the maintenance and long-term performance of built assets and infrastructure systems, often manifesting in unexpected and severe ways.

In this rapidly evolving and interconnected scenario, the central role and vulnerability of transportation infrastructure become evident. Road transport currently represents 18% of total freight activity, and domestic non-urban transport will generate nearly 68 trillion of passengers by 2050, over three times higher than in 2015 (OECD 2019). Given this massive scale of road transport activity, the vulnerability of these networks to natural hazards like landslides has become a critical concern for global connectivity and economic stability. The disruption of critical transport links can have cascading effects on entire regional economies and communities.

Within this complex and challenging context, this work aims at focusing on road tunnels affected by large slope instabilities. The interaction between landslides and tunnels often results in various types of damage, ranging from minor structural deformations, which may compromise the tunnel's functionality, to partial or complete collapse, with the potential of posing a serious safety risk to users. This risk, combined with the crucial role played by these infrastructures, highlights the urgent need for a deeper understanding of this interaction. The complexities involved are manifold: the variety of possible scenarios and the heterogeneity of landslide kinematic behavior and geological settings quickly illustrate the multitude of variables and parameters that must be considered.

This thesis will first provide an overview of solutions, methodologies, and approaches developed to address the coexistence between anthropogenic infrastructures and slope instability phenomena, highlighting their strengths, limitations, and range of applicability. This review will show that while considerable progress has been made in understanding individual components of the landslide-infrastructure system (i.e., the slope and the tunnel), most approaches tend to treat these elements separately rather than as an integrated, interacting system.

In this review a research gap is highlighted, linked to the challenges that exist in performing numerically modelling characterized by significantly different scales, i.e., a landslide and a road tunnel. Indeed, current modeling approaches often struggle to adequately account for processes and mechanisms operating at the slope scales and local infrastructure damage, potentially resulting in suboptimal model detail or challenges in correlating simulation results with field data.

To address this challenge, this doctoral research explores a novel approach by the mean of a multi-scale modelling workflow that takes advantage of the nested modelling technique, a well-known numerical method that is, however, seldom used in the analysis

of landslide-infrastructure systems (LISs). The first step in the proposed methodology consists of investigating at the slope scale the geological processes and mechanisms that control the landslide. The obtained numerical results at the slope scale are then used as input for the infrastructure-scale model. To apply and corroborate the method, a real case study was employed, selected based on specific geological and structural criteria, in terms of scale mismatch between landslide and infrastructure, as well as data availability.

This thesis is structured to provide a comprehensive journey through the development and application of this approach, specifically delving into the considerations and scripting that are required for successfully and meaningfully transferring data between models. The proposed method will allow, at the slope scale, the analysis of the environmental and geomechanical factors controlling the evolution of the instability, at the infrastructure scale, the analysis of the impact of landslide deformation on the infrastructure in terms of displacement and progressive damage. In the end, the critical bottleneck was identified as the availability, quality, and reliability of existing geological and monitoring data, which are of critical importance for all stages of modelling: from the definition of input geometry, assumptions, and parameters, to the constraint, validation, and interpretation of the numerical model.

2. State of the art

As outlined in the Introduction, the topic of interaction between natural phenomena and human infrastructures has gained increasing importance in recent years. Many researchers and professionals have attempted to address natural extreme events-related issues using different techniques, tools, and procedures, yet significant challenges remain in understanding these complex interactions.

Among the variety of possible interactions between natural phenomenon and anthropic infrastructure, this work will focus on that between landslides and road tunnels, as this interaction has long drawn interest in various fields, from applied geology to geotechnical and infrastructure engineering. This attention stems from the inherent fragility of underground infrastructures, whose design must account for additional variables compared to open-air structures. In fact, tunnels must cope with the unpredictability of subsurface conditions, bearing the weight of the surrounding material, whether rock, earth or water. This condition makes them, on the one hand, sophisticated and advantageous solutions for overcoming difficult and adverse landscape settings, but, on the other hand, particularly exposed to landslide hazards. Furthermore, their predominant linear development makes them vulnerable even to relatively small landslides.

Despite the importance of this topic, its multilayered complexity has limited progress in the related research field, since an integrated understanding of landslide-tunnel interaction encounters several difficulties. The inherent complexity of natural extreme events is self-evident, and the multitude of variables involved illustrates the scale of the challenge. Landslides are complex processes characterized by the instability and downslope movement of material (Sun et al. 2025). They can be classified according to geometry (i.e., main features and extent), materials involved, state of activity, rate and type of movement, triggering factors, and process dynamics (Cruden and Varnes 1996). Conversely, tunnels are engineering works defined by parameters such as geometry (i.e., shape, size, and orientation), excavation and construction methods, as well as support type and lining composition.

In some cases tunnel excavation can significantly influence slope kinematics, particularly in the presence of pre-existing mass movements (Poisel et al. 1996). Similarly, tunnels can be affected by landslides, compromising their structural integrity at various levels and creating potential risks for users. Moreover, external and environmental conditions, notably meteorological and hydrogeological factors related to position in space and geographical location, can trigger or accentuate slope instability and thus increase tunnel vulnerability.

This complexity has inevitably produced substantial diversity in research methodologies and priorities. To systematically analyze existing research, studies in this field can be categorized into three main approaches, each emphasizing different components of the landslide-infrastructure system:

- *Landslide-centric approaches*, which prioritize the characterization of slope instability phenomena
- *Infrastructure-centric approaches*, which focus on the structural performance and health of infrastructures (i.e., tunnels) under landslide-induced stresses
- *Systemic approaches*, which explicitly attempt to integrate landslides and infrastructures within a unified framework

While each approach might consider the entire system, they differ fundamentally in the degree of detail and emphasis given to individual system components. The following sections examine each approach in detail, drawing attention to their strengths and limitations. This categorization provides a framework for understanding the evolution of research methodologies and for identifying persistent limitations that motivate the present work.

2.1. Landslide-centric approaches

Landslide-centric approaches address landslide-infrastructure interaction with primary emphasis on slope instability phenomenon. These studies focus mainly on characterizing slope behavior in terms of morphology, geology, hydrogeology, and kinematics through comprehensive slope monitoring and numerical modelling. Hence, this approach treats the landslide as the primary system component, aiming to provide accurate characterization of both the landslide and its behavior, enabling in this manner an assessment of potential impacts on infrastructure elements.

2.1.1. Landslide monitoring techniques

Data collection represents the foundation of landslide studies. Observing phenomena through time and collecting significant information about variables that properly characterize landslides behavior represents the first and most relevant activity. The clear purpose is not only collecting data but trying to control the inner geologic uncertainty and related subjectivity by multiplying the data sources and diversifying their nature (Eberhardt 2012).

Landslide activity can be assessed in terms of spatial extent, environmental context (climatic and hydrogeological conditions), kinematics, and failure mechanisms, across

multiple temporal (months to decades), spatial (local slopes to regional settings), and volumetric scales (small slides to massive movements) (Auflič et al. 2023). Recent technological progress has dramatically increased data acquisition capabilities, bringing significant improvements to traditional tools. Extenso-inclinometers, which couple conventional inclinometer tubes with distributed fiber optic strain and temperature sensors have been used to monitor landslides and reconstruct 3D movement fields over time (Figure 1) (Damiano et al. 2025).

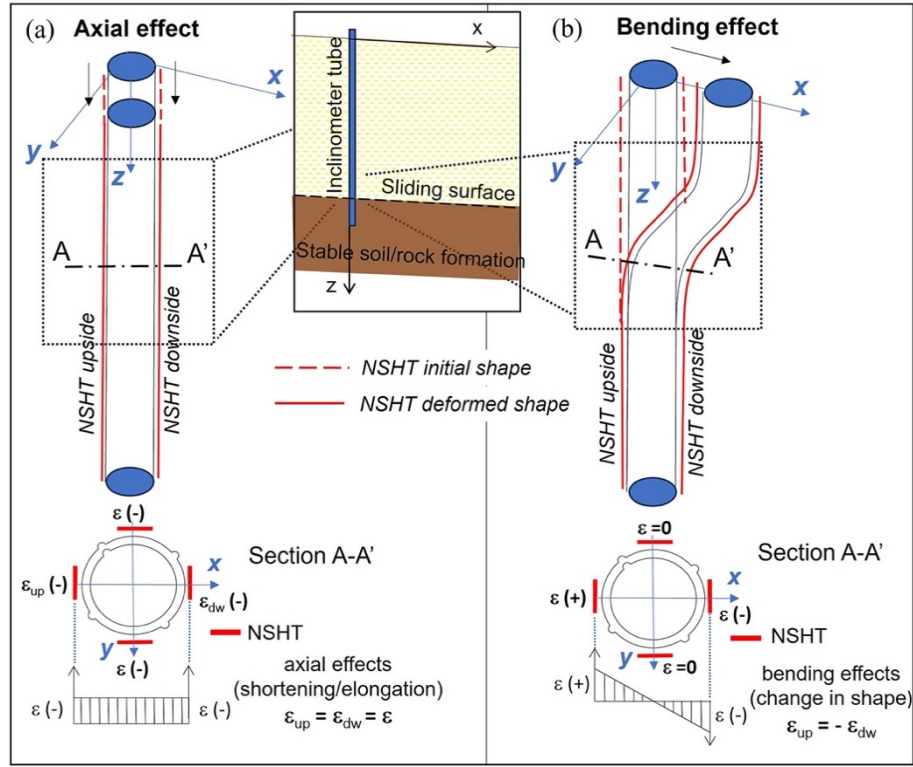


Figure 1 - Schematic representation of the inclinometer tube equipped with a Smart Extenso-Inclinometer (SEI) using a New Smart Hybrid Transducer (NSHT) (Damiano et al. 2025)

Remote sensing tools, especially UAV (Unmanned Aerial Vehicle), LiDAR (Laser Imaging Detection and Ranging), and GPR (Ground-Penetrating Radar), have enhanced landslide characterization with operational flexibility and cost effectiveness (B. Chen et al. 2025). UAV-based surveys, for instance, can create high-resolution 3D terrain models even in densely vegetated areas, allowing precise detection of slope deformation and surface change patterns (Figure 2) (Sestras et al. 2025; Sun et al. 2025; Lucieer et al. 2014).

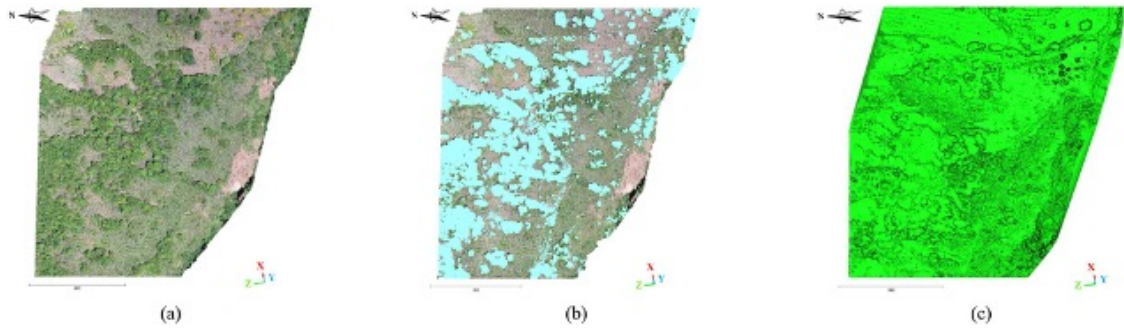


Figure 2 - 3D models generated from processed drone imagery: (a) Vegetation identification; (b) vegetation extraction; (c) generated 3D model after segmentation of vegetation (Sun et al. 2025)

Automated algorithms based on deep learning image recognition can map cracks and other signs of incipient instability, and conduct preliminary consequence assessments (Cheng et al. 2021). Satellite-based monitoring through advanced InSAR (Interferometric Synthetic Aperture Radar) techniques have enabled regional-scale landslide monitoring with remarkable precision. Time-series InSAR approaches, including Persistent Scatterer/Distributed Scatterer (PS/DS)-InSAR and Small Baseline Subset (SBAS)-InSAR, enable monitoring of large-area slope displacement with millimeter precision over extended periods (Xu et al. 2023; Ferretti et al. 2001; Berardino et al. 2002).

This significant general improvement has enabled the employment of a variety of monitoring techniques and styles that can change from case to case (Tofani et al. 2013; Pecoraro et al. 2019; Notti et al. 2015; Del Soldato et al. 2024). Therefore, the challenge today lies not in data acquisition, but in integrating these heterogeneous sources into coherent datasets to constrain models and support predictive analysis.

2.1.2. *Landslide numerical modelling*

The significant technological progress of recent decades has not only revolutionized landslide monitoring but has also expanded the use and reliability of numerical modelling. In parallel to monitoring, numerical modelling plays a crucial role in landslides studies, by providing controlled and reproducible environments for representing and understanding this natural process complexity. Indeed, using mathematical formulations and computational tools, numerical models allow researchers to simulate the evolution of slope instabilities, explore different triggering scenarios, and assess potential consequences. In this sense, numerical modelling acts as a complementary tool to monitoring activities, enabling deeper understanding of landslide initiation, failure mechanisms, and post-failure dynamics (Crosta et al. 2003).

A wide range of numerical approaches have been developed, each with specific purposes, assumptions, and complexity levels. While simple Limit Equilibrium Methods (LEM) remain widely applied for rapid stability assessment, also due to their evident limitations in three-dimensional scenarios (Cai and Ugai 2001), other numerical approaches have gained substantial adoption and can be essentially categorized in two main groups: continuum and discontinuum approaches (Augarde et al. 2021).

Continuum-based approaches, such as finite element method (FEM), finite difference method (FDM) and boundary element method (BEM), represent slopes as continuous media governed by constitutive models, with the possibility of incorporating coupled hydro-mechanical processes. BEM approaches suit fracture propagation analysis, while FEM and FDM simplify handling material heterogeneity and non-linearity (Stead and Coggan 2012; van Asch et al. 2007).

Discontinuum methods, such as distinct element method (DEM) or discontinuous deformation analysis (DDA), consider the material involved as an assembly of particles able to interact with each other, thus explicitly accounting for block and particle interactions, making them particularly suited for rockslides and structurally controlled failures (Stead and Coggan 2012; van Asch et al. 2007).

Recent decades have seen mesh-free and particle-based methods (e.g., smoothed particle hydrodynamics) gain traction due to their ability to simulate large deformations and complex landslide behaviors, such as crack propagation, thanks to their ability to eliminate issues associated with spatial-dependent solutions (Ceccato et al. 2024; Tran et al. 2019). These approaches are closely linked to runout and flow simulation models, which quantify extent, velocity, and impact forces of landslides after failure.

Given the complexity of landslide processes, hybrid and multiphysics approaches have been developed, coupling mechanical, hydraulic, and sometimes thermal aspects, or integrating continuum and discontinuum solvers within the same framework to enhance respective advantages (D. Stead et al. 2006). Coupled finite-/discrete-element models enable in-depth simulation of heterogeneous and complex landslides, revealing the prevailing fracture mechanism in the simultaneous presence of materials with brittle and ductile fracture behavior (Figure 3) (Bossi et al. 2016).

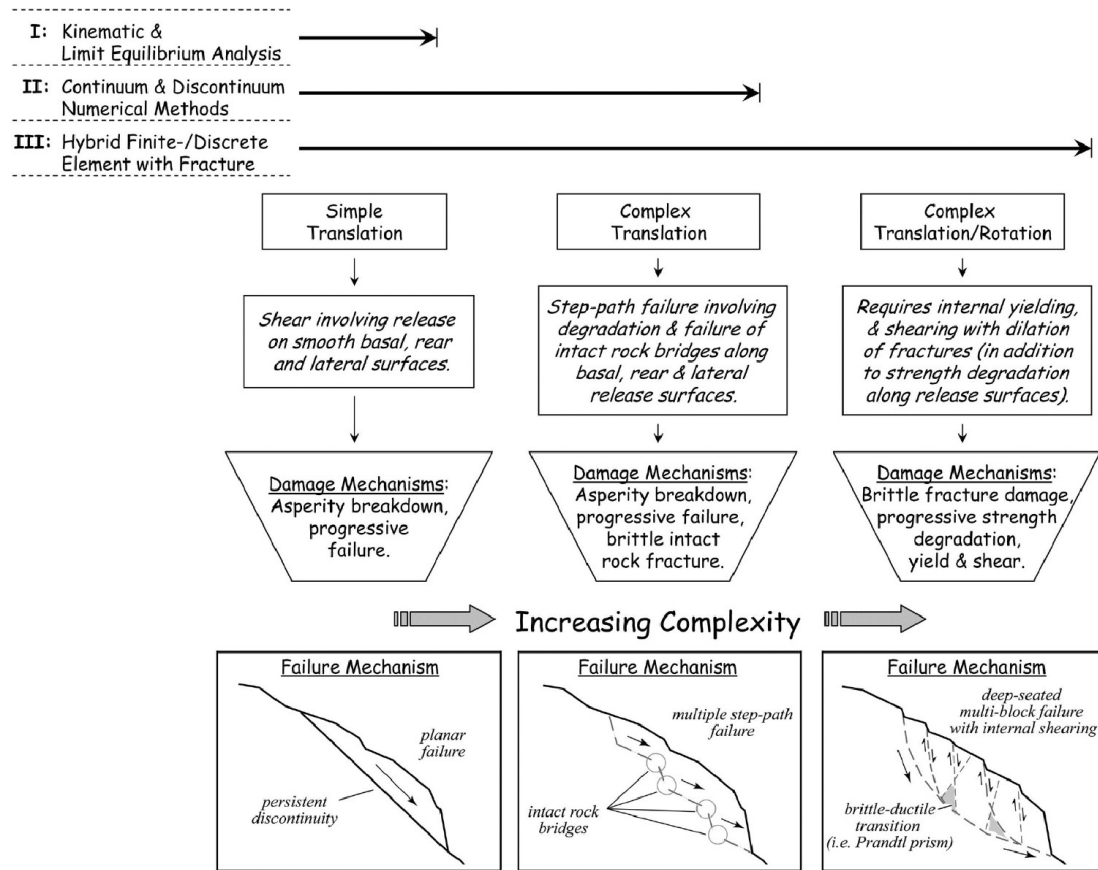


Figure 3 - Difference in landslide analysis and corresponding numerical methods and failure mechanisms (D. Stead et al. 2006)

2.1.3. Numerical methods applications in landslide-infrastructure interaction

Numerical approaches provide a comprehensive toolbox, allowing landslide processes to be studied across different spatial and temporal scales, from initiation mechanisms to runout behavior and interactions with infrastructure. Within landslide-tunnel interaction research, numerical models have been developed focusing predominantly on landslide phenomenology (Z. F. Wang et al. 2020).

Representative studies demonstrate this focus. Zhu et al. (2020) used smoothed particle hydrodynamics (SPH) methods to study a rock avalanche that buried the Chengkun railway in China, causing several casualties and damage to the trainline infrastructure. Zhang et al. (2015) simulated a landslide induced by the construction of a large-span multi-arch tunnel using a 2D FEM approach, considering excavation and consequent tunnel presence as major triggering factors (Figure 4).

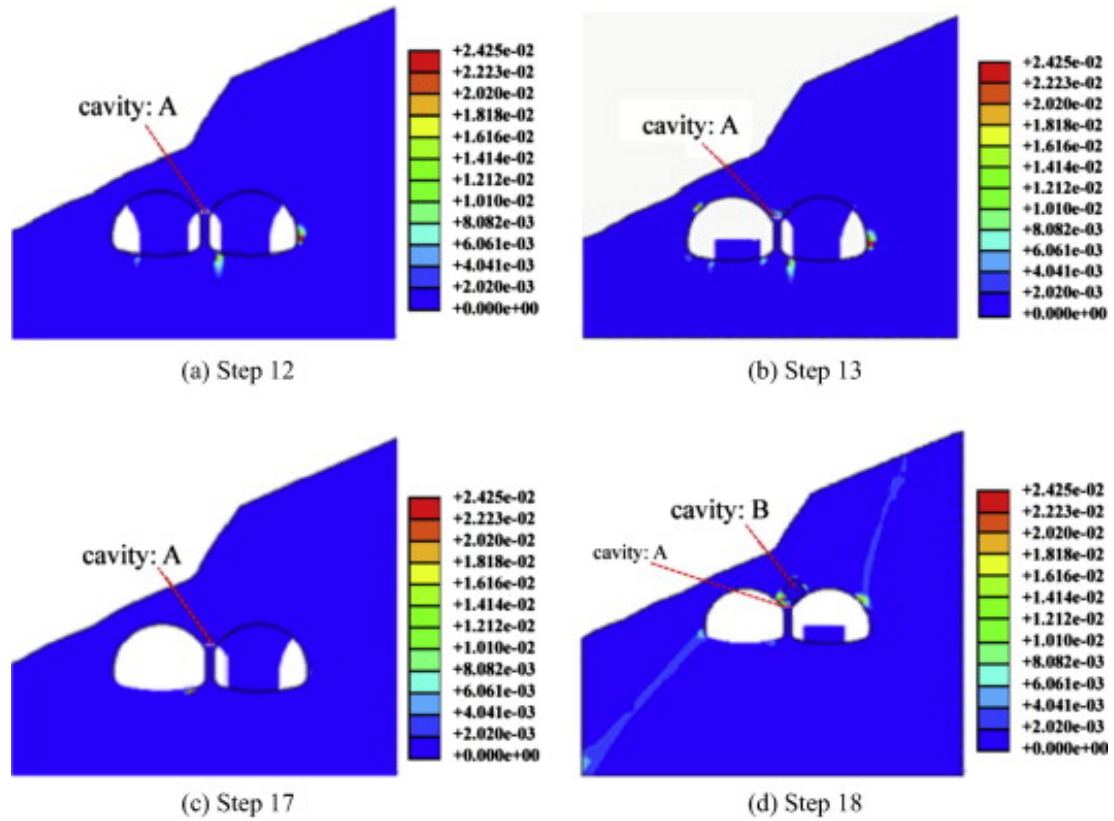


Figure 4 -Two-dimensional FEM simulation of landslide plastic zone distribution steps alongside tunnels excavation; each tunnel cavity section is 15 m width and 9.8 m height (Zhang et al. 2015)

Koizumi et al. (2010) studied the influence of distance between sliding surface and tunnel on landslide onset through 2D numerical simulations employing FDM. In the same context, Ota et al. (2013) selected DEM to model a landslide, aiming to estimate tunnel position effects on instability dynamics by separately simulating landslide occurrence before and after tunnel construction.

Jiao et al. (2013) performed extensive analysis of the Dazhai landslide, which severely affected two tunnels in Faer Coal Mine (Guizhou, China). The investigation involved a 3D numerical model using the FDM-based software FLAC3D (Itasca Consulting Group, Inc. 2023) to obtain landslide dynamics insights and compare them with field measurements, and a 2D numerical model using LEM to calculate the safety factor under critical and extreme conditions. Many other studies (e.g., Duan et al. 2021; Komu et al. 2020; Fan et al. 2022; Wang et al. 2020) demonstrated the wide range of numerical modelling applications focusing on slope instability phenomenology.

This brief overview of the available techniques and tools clearly shows both the potential and the wide range of applications that numerical modelling can achieve by focusing on the phenomenology of landslides. Despite sophisticated treatment of landslide processes, these approaches fundamentally constrain integrated understanding by

treating infrastructure elements as simplified boundary conditions or external constraints, while little attention is paid to the consequences of landslide movement on infrastructure, limiting detailed analysis of tunnel structural response mechanisms.

2.2. Infrastructure-centric approaches

Infrastructure-centric approaches, on the other hand, address the effects of slope-induced ground movements on infrastructure, with particular emphasis on structural damage assessment and health monitoring of tunnels. In contrast to those with a landslide-centric perspective, these approaches consider structural assets as primary system components, shifting focus from slope instabilities phenomenology to built environment performance and resilience.

Central to this kind of approaches is the development of monitoring strategies tailored to capture the response of structures to ground deformations, including the use of sensors, geodetic surveys, and non-destructive testing methods. Cracks and concrete detachment are the first and most significant signs of structural distress and can be easily identified as mainly caused by landslide-related movements (Konagai et al. 2005; Usman and Galler 2013). To thoroughly investigate this relationship, sophisticated methodologies for damage detection, characterization, and monitoring have been developed within this research field, as well as modelling and prediction of landslide consequences. In fact, analytical and numerical models are often employed to simulate the mechanical behavior of tunnels under differential ground movements, thus providing a framework for predicting damage evolution and defining mitigation or maintenance strategies. This enables the evaluation of serviceability, safety, and long-term functionality of infrastructure exposed to landslide activity.

2.2.1. Infrastructural damage assessment and characterization

Underground infrastructures are naturally exposed to chemical and physical effects related to their surrounding environment. The outbreak of visible damage represents the primary indisputable evidence of instability in tunnel vicinity. Tunnel linings may suffer various damage types including cracking, joint opening, offsets, or global deformation due to differential movements in surrounding ground. Hence, within infrastructure-centric approaches, monitoring, characterization, and assessment of damage have become the principal methods to investigate landslide-infrastructure interaction.

Advanced damage detection technologies exemplify this perspective. Lee et al. (2013) provided an image-mosaic technology that enables rectification of geometric distortion in 3D tunnel surface images, generating mosaicked images of tunnel wall surfaces

(Figure 5). Similarly, Pu et al. (2024) developed an approach using mobile 3D laser scanners to capture tunnel inner surfaces and examine cracks through detection algorithms, while Wang et al. (2009) applied the profile image method to measure tunnel deformation. These technologically sophisticated techniques concentrate on quantifying structural response without establishing explicit connections to causative landslide process features.

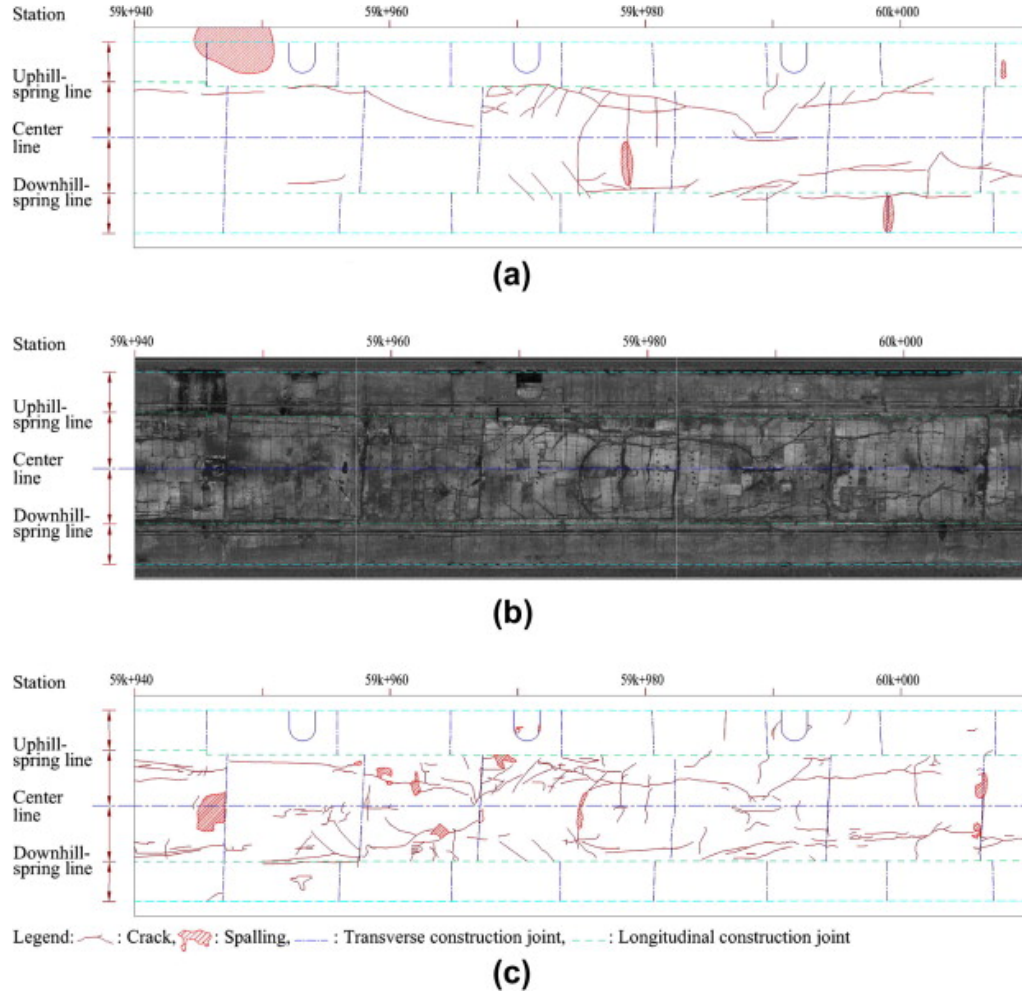


Figure 5 - Typical example of rectification of geometric distortion in 3D tunnel surface images. (a) Layout of lining crack distributions by a visual inspection in 1994. (b) Lining surface layout in an image obtained by an advancing laser scanner in 2006 for the same section as that in (a). (c) Interpreting results according to (b). (Lee et al. 2013)

Long-term monitoring strategies follow similar patterns. Chiu et al. (2017) examined crack evolution in a double-lane highway tunnel in Taiwan crossing a deforming slope, collecting high-resolution images of tunnel wall surfaces every half-year from 2008 to 2015 to interpret concrete crack layouts. Bossi et al. (2017) implemented a structural health monitoring (SHM) network composed of plastic optical fibers to monitor crack evolution in a road tunnel intersecting a landslide, while Minardo et al. (2018) conducted long-term monitoring of a railway tunnel affected by an active earthflow using

distributed fiber-optic sensors. Despite these sustained observation campaigns, characterization of damage patterns rarely feeds back into refined understanding of the driving landslide mechanics or of the mutual influence between slope movement and tunnel presence.

Even when researchers attempt to link damage to causative mechanisms, the analysis typically remains unidirectional. Huang et al. (2010) developed a complex technique to obtain net deformational displacements of tunnel profiles to infer loading conditions and changes in ambient stress which caused them. Wang (2010) analyzed four tunnels affected by slope instability, identifying anomaly layouts and three-dimensional spatial distributions of cracks on tunnel lining surfaces to interpret possible causes of lining anomalies. Fan et al. (2021) built a physical tunnel model to study lining structural failure mechanisms related to rainfall-induced water pressure. While these studies acknowledge landslide-related triggers, they treat them as prescribed loading conditions rather than as dynamic processes that might themselves be influenced by tunnel geometry, stiffness, or construction sequence.

2.2.2. Numerical analysis of structural response

As seen for landslides, numerical modelling has become widespread in infrastructure studies, enabling implementation of sophisticated mechanical models to analyze crack formation and propagation in tunnel linings and study tunnel response to landslide-induced forces and stresses. However, these analyses typically prescribe landslide-related loads as static or simplified dynamic boundary conditions, treating the slope as a source of external forcing rather than as a coupled component whose behavior might be influenced by tunnel structural characteristics and vice versa.

The group of studies with a predominant focus on concrete failure mechanics exemplifies this perspective. Huang et al. (2022) proposed the double-K fracture criterion to evaluate concrete lining safety, studying fracture processes with advanced numerical techniques such as the extended finite element method (XFEM). Amorim et al. (2014) proposed a method based on lumped damage mechanics (LDM) theory that allows the characterization and quantification of concrete lining damage state (i.e., crack opening displacement quantification) through the use of FEM numerical modelling. While these approaches demonstrate sophistication in modelling material failure at the structural scale, they rely on assumed loading histories without explicit connection to evolving landslide kinematics.

Studies examining specific tunnel responses to underground movement follow similar patterns. Shalabi (2005) investigated ground squeezing and consequent pressure on the lining of Stillwater Tunnel (Utah, USA), performing a FEM analysis with creep models that showed reliable prediction of lining behavior over time (Figure 6).

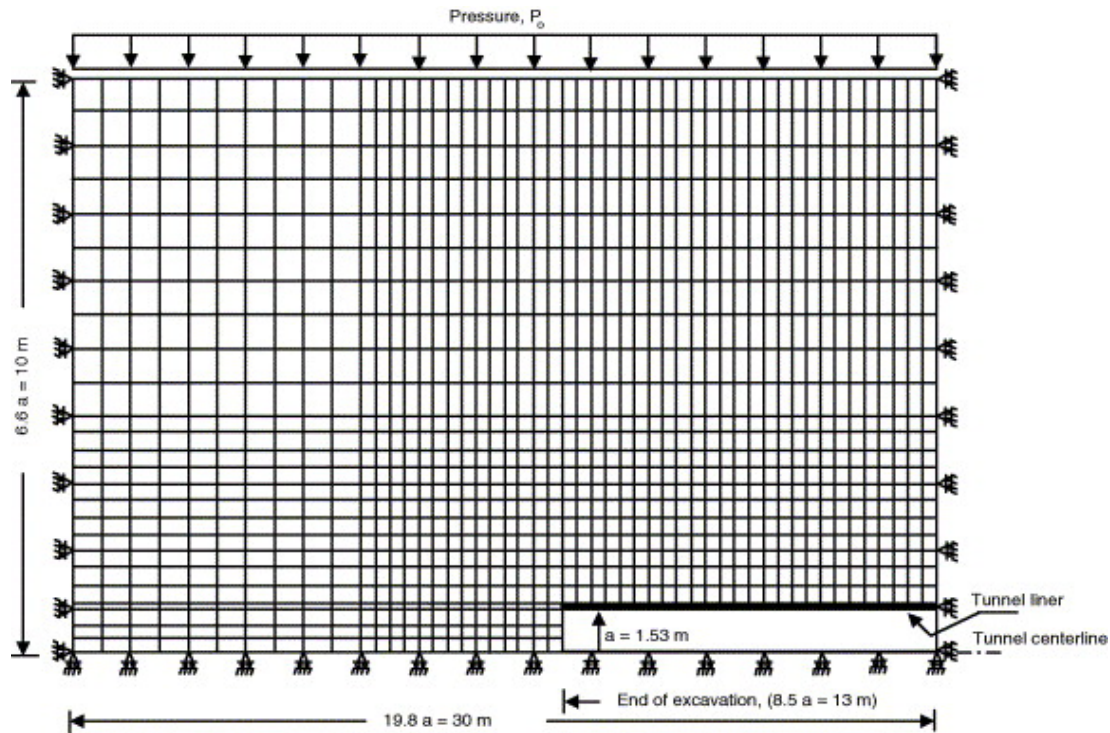


Figure 6 - Finite element mesh and boundary conditions for the investigation of the Stillwater Tunnel (Utah, USA) (Shalabi 2005)

Shi et al. (2001) tested a finite element approach to model multiple lining cracks for a concrete waterway tunnel under distributed loads applied to the side walls. In both studies, ground pressures or movements were input parameters derived from field observations or simplified geotechnical assumptions, rather than more complex landslide-induced actions.

Even when the complexity of landslide-tunnel interaction is acknowledged, analytical efforts remain primarily infrastructure-focused, and landslide forces and stresses are simplified. Vassallo et al. (2016) studied the interaction between the Calabrese railway tunnel and a landslide at Varco d'Izzo, located in Potenza, Italy. The authors conducted in situ investigations and laser scanner measurements to analyze tunnel deformation state. Eventually, a 2D FEM model was created with soil beneath the tunnel simulated using linear elastic springs, highlighting the complex three-dimensional nature of the landslide-structure interaction and the need for further in-depth studies.

Although essential for structural design and safety assessment, this infrastructure-centric perspective fundamentally constrains the integrated understanding of the coupled system. Advanced treatment of structural mechanics stands in sharp contrast to the simplified representation of landslide-induced actions. By prioritizing structural response over characterization of acting forces, and by neglecting potential feedback mechanisms between tunnel and slope, these approaches capture only one side of the interaction. Often less emphasis is placed on the underlying slope dynamics, capturing

structural response in isolation from the broader slope-structure system, thus precluding a more global analysis of the mechanism that may govern the interaction.

2.3. Systemic approaches

The third line of inquiry is represented by the systemic approaches, which explicitly attempt to treat landslides and infrastructure as interdependent components within a holistic framework. Unlike landslide-centric or infrastructure-centric perspectives, these approaches seek to integrate slope processes and structural responses within a unified analytical scheme. The common purpose of the studies employing a systemic approach is to capture the mutual conditioning of landslide movements and tunnel behavior. Fostering methodologies capable of integrating data and models, they seek to advance towards a more complete representation of the interaction system and support the development of truly integrated mitigation and design strategies.

2.3.1. *Landslide-infrastructure integrated numerical frameworks*

Recognition of the coupled nature of landslide-tunnel interaction has motivated several researchers to develop numerical frameworks that simultaneously model both slope and structure.

Zhou et al. (2023) analyzed a system of two 300 m-long highway tunnels in China that suffered cracking and damage propagation during construction as a consequence of slope instability. By combining site investigation, monitoring, and 3D FDM numerical modelling (domain extending 266 m north to south and 640 m east to west), they extensively analyzed the damage mechanism of tunnel collapse and slope instability interaction. Barla (2016) illustrated the case of a deep-seated landslide reactivated by the excavation of two large twin tunnels (each with 160 m² cross section). To explore the interaction between tunnel excavation and surface movements, a 3D FEM model using Midas GTS (MIDAS IT Co., Ltd 2024) code was performed. Compared with monitoring data, this model provided insights on the reactivation of the dormant landslide due to tunnel excavation. Tian et al. (2025) focused on deformation distribution and reinforcement measures for tunnel-slope systems, using the Hanshankou tunnel as the case study. A sliding body with a volume of approximately 110000 m³ affected the construction of a separate, two-way, six-lane highway tunnel. Through on-site monitoring and numerical simulation, the authors identified failure causes and evaluated the effectiveness of temporary and permanent reinforcement measures. Shreedharan and Kulatilake (2016) used the distinct element method to create a 50 m x 57 m x 50 m numerical model and analyze stability of two tunnels in a coal mine, estimating the adequacy of current supports and suggesting possible improvements. Zhang et al.

(2021) investigated the landslides-tunnels interaction, focusing on railway tunnels in unstable mountainous areas. Selecting the case of twin tunnels involved in a 12000 m³ landslide, through a combination of long-term on-site monitoring and numerical analysis, the authors studied how factors such as extreme rainfall, earthquakes and the tunnel construction itself affect landslide stability and, consequently, tunnel structure safety (Figure 7).

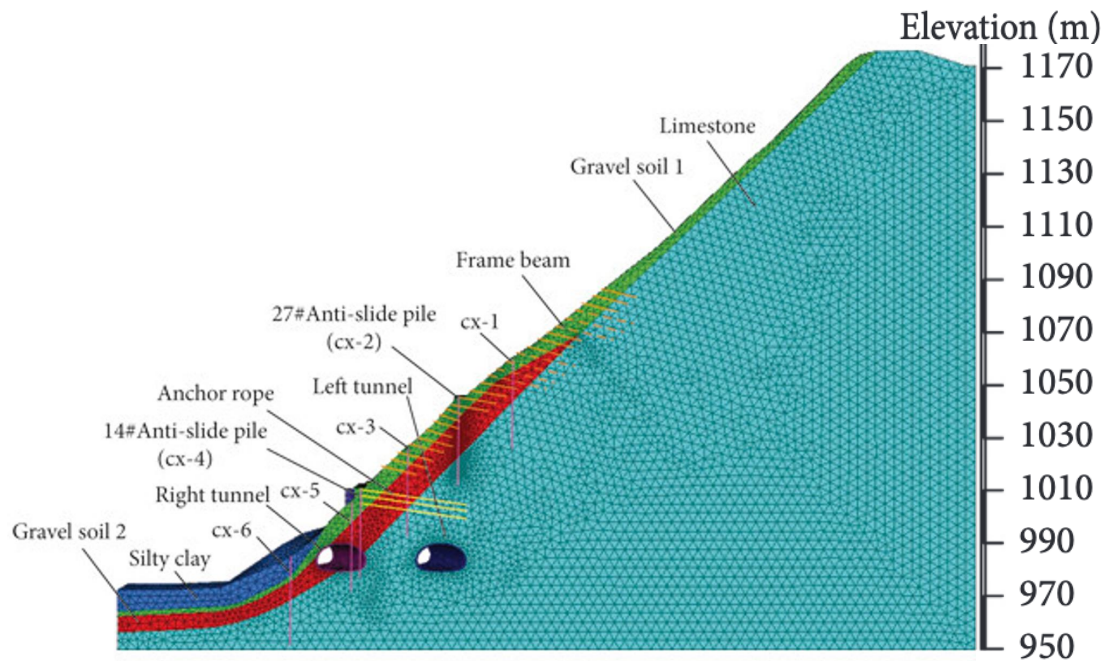


Figure 7 - FLAC3D numerical model mesh visualization and general description for the analysis of twin tunnels; each tunnel cavity section is 15 m width and 9.8 m height (Zhang et al. 2021)

Feng et al. (2025) introduced an innovative dynamic seismic analysis method for tunnels crossing faults, specifically considering co-seismic displacement as a dynamic process, integrating numerical simulation (using finite difference method) of seismic wave propagation into dynamic soil-structure interaction analysis.

Other researchers successfully used numerical modelling combined with monitoring to gain deeper understanding of the relationship between slope instability and tunnel damage (Ashtiani et al. 2010; Wenjiao Zhou et al. 2025; Poisel et al. 2016; Y. Chen et al. 2024; Vassallo et al. 2019; Giovanni Barla 2018; Bao e Wei 2023).

While these integrated numerical frameworks represent significant advances in capturing landslide-tunnel interaction, they face inherent challenges that constrain their applicability and accuracy. The computational demands of 3D models capable of representing both regional slope processes and localized structural behavior remain substantial, often necessitating simplifications in geometry, material heterogeneity, or in general dimension of the model. Most critically, validation of these integrated models

remains constrained by the limited availability of comprehensive monitoring data that simultaneously captures both slope kinematics and structural response at appropriate spatial and temporal resolutions.

2.3.2. *Physical modeling in systemic approaches*

Parallel to numerical approaches, physical modelling has been employed to investigate fundamental mechanisms governing landslide-tunnel interaction under controlled conditions.

Several scholars used physical model tests to infer the relationship underlying disasters caused by landslides in tunnels. Wei et al. (2023) selected a highway tunnel involved in a landslide in Chongqing, China, to elucidate the co-evolution mechanism of the tunnel-landslide system, eventually highlighting how tunnel deformation relates to slope deformation as a result of multiple force couplings (Figure 8).



Figure 8 - Complete physical model of a tunnel involved in a landslide (Wei et al. 2023)

Ma et al. (2023) studied deformation and failure mechanisms of an orthogonal tunnel-landslide system—configuration where tunnel axes intersect landslide slip surfaces almost perpendicularly—through a physical model. Zhou et al. (2019) investigated the effects of the direction of dynamic impacts on stability and failure modes of cracked tunnels through laboratory physical experiments and models, and numerical simulations using ABAQUS (Dassault Systemes Simulia Corp. 2025).

Physical models offer valuable insights by enabling direct observation of coupled behavior in simplified, reproducible scenarios. However, they face inherent limitations that constrain their generalizability. Scaling laws governing similitude between model and prototype introduce distortions, particularly for time-dependent processes and material behavior. The need to simplify geometry, boundary conditions, and material properties to achieve experimental feasibility means that physical models capture idealized interactions rather than the full complexity of field-scale heterogeneity. Furthermore, instrumenting physical models at sufficient resolution to simultaneously observe both regional slope kinematics and localized tunnel damage patterns presents significant practical challenges, often forcing researchers to focus measurements on one aspect of the system.

2.3.3. *Classification and analytical frameworks for Landslide-Infrastructure Systems (LISs)*

Recognizing the diversity of possible interaction scenarios and the difficulty of comprehensive modelling, several researchers have pursued classification and analytical approaches to systematize knowledge.

Minglei et al. (2022) examined deformation and failure modes of tunnels affected by related landslides through the analysis of numerous cases in China. From this analysis they identified five basic tunnel deformation modes, namely longitudinal pull, longitudinal shear, transverse pull, transverse shear, and transverse ship. Li et al. (2025) studied dynamic response characteristics of tunnel linings within landslide-tunnel systems, identifying four scenarios based on tunnel-sliding surface relative location, and providing a scientific basis for the differentiated reinforcement of tunnels in earthquake-prone mountainous areas (Figure 9).

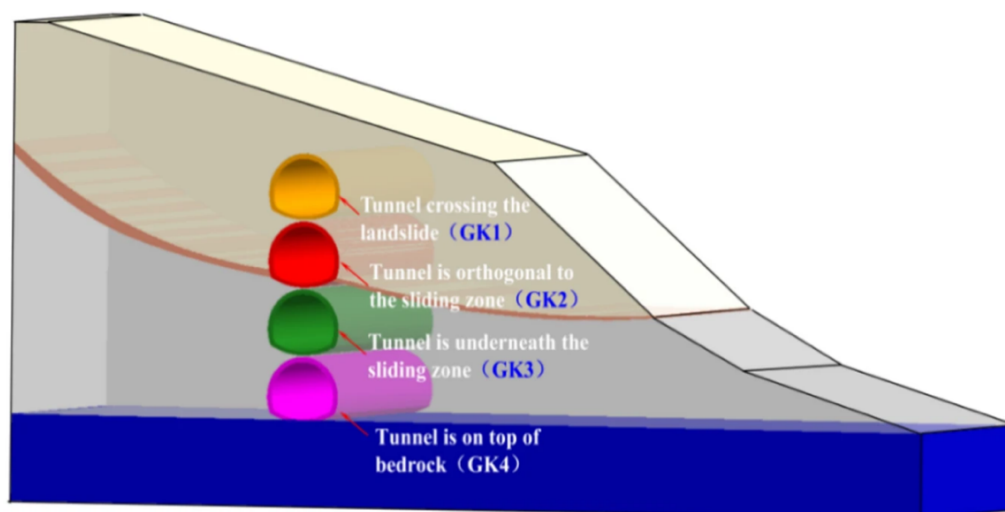


Figure 9 - Schematic diagram of the four scenarios of tunnel interacting with landslide considered for the study (Li et al. 2025)

Zhang et al. (2017) proposed an analytical method for determining the minimum safe distance between tunnels and landslide slip surfaces. Based on the theory of slip lines and mechanical analysis of decompressed rocks above the tunnel, the authors derived expressions for the minimum safe distance and validated them through numerical modelling. Causse et al. (2015) used numerical simulations to study how tunnel position relative to slope topographic surface affects both slope stability and tunnel damage in the context of deep-seated gravitational slope deformation.

These classification and distance-based approaches offer practical design guidance and help organize diverse case histories into coherent frameworks. However, they typically emerge from empirical observations or simplified analytical solutions rather than from comprehensive understanding. Classifications based on geometric configuration provide useful typologies but do not fully capture the influence of material properties, hydrogeological conditions, construction methods, or temporal evolution that govern actual interaction behavior. Distance-based criteria, while valuable for preliminary design, often rely on assumptions about stress redistribution and failure mechanisms that may not hold across the range of geologic and geometric conditions encountered in practice.

Systemic approaches, eventually, represent conceptual progress in recognizing landslide-tunnel interaction as a coupled phenomenon requiring integrated analysis. They represent a step toward more holistic strategies of analysis and mitigation, providing a more realistic representation of the interaction system. Yet very few studies have achieved adequate levels of detail and accuracy for both slope processes and tunnel structural response simultaneously, even when employing sophisticated numerical, physical, or analytical methods (Vassallo et al. 2019). Some relevant limitations emerge in dealing with this type of interaction, with a fundamental obstacle lying in the scale disparity, inherent to this interaction and highlighted several times in this review. Capturing simultaneously both entities features in a single model inevitably requires compromises. Either landslide representation must be simplified to achieve sufficient tunnel detail, or structural mesh must be coarsened to capture slope-scale processes. Landslides extend hundreds of meters and involve complex, heterogeneous materials with time-dependent hydro-mechanical coupling. Tunnels, by contrast, exhibit damage at a localized scale. It is therefore not surprising that most published studies have involved small- to medium-sized landslides, or have focused on specific aspects, e.g., seismic wave propagation, as achieving adequate resolution for both simultaneously, within a single numerical domain, remains computationally prohibitive for realistic scenarios.

Existing systemic approaches typically address this scale disparity through either global models that represent both components but sacrifice resolution, particularly for

structural details (Tian et al. 2025), or focused studies of specific mechanisms (e.g., construction-induced triggering, seismic loading; Feng et al. 2025) that illuminate particular aspects while leaving the broader interaction partially characterized.

The development of approaches explicitly designed to address the coupling of different scales therefore emerges as a critical frontier in advancing the state of knowledge on landslide-tunnel interaction.

2.4. The multi-scale challenge

While all the previously discussed studies tackle interaction between slope instability and infrastructure by considering whole system components, specific strategies that give targeted attention to individual components are often preferred (Figure 10). Even those systemic approaches, attempting to fill this gap, struggle to achieve sufficient detail for all components or are applied to relatively small-sized cases.

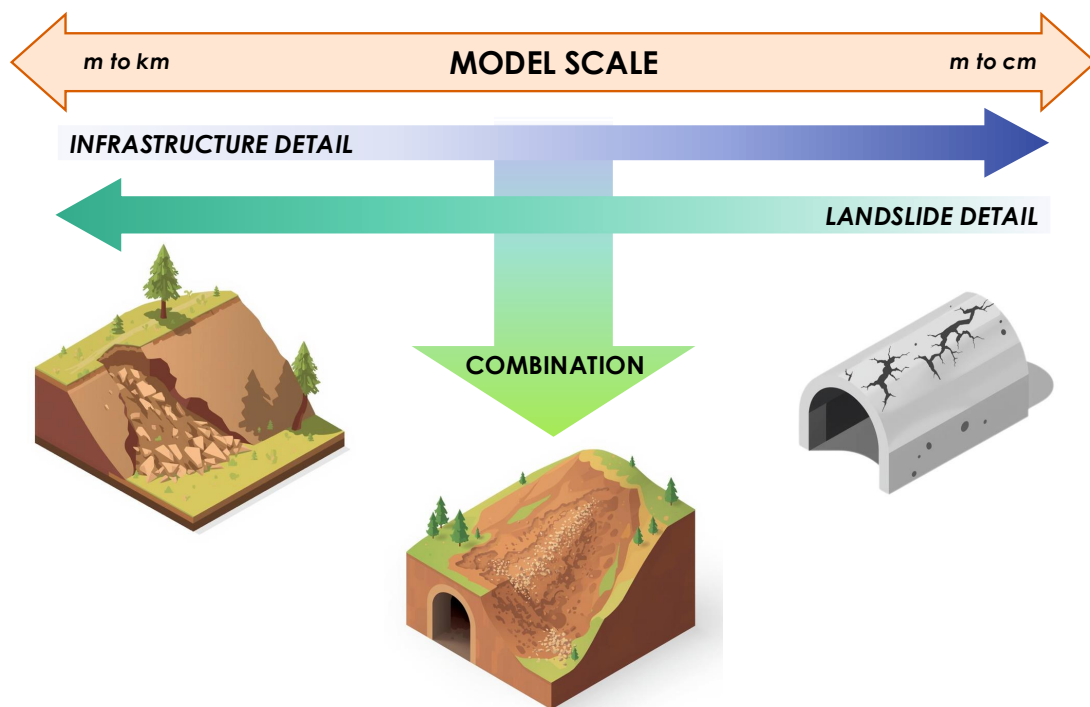


Figure 10 - Model scale spectrum as seen through the State-of-the-art review

Landslide-centric approaches can provide sophisticated understanding of slope processes but inherently face a scale mismatch challenge by treating infrastructure as secondary. Tunnels are typically represented as geometric voids, or simplified boundary conditions, or external loading (Yongxing Zhang et al. 2015; Koizumi et al. 2010; Ota et al. 2013), precluding analysis of tunnel response. The consequence is accurate landslide characterization but inability to predict actual infrastructure performance.

Almost equally, infrastructure-centric approaches achieve high resolution for structural response (C. Huang et al. 2022), but must prescribe landslide-induced actions as simplified boundary conditions as uniform or linearly varying displacements or pressures (Shalabi 2005; Shi et al. 2001). This oversimplifies the complex spatial heterogeneity and temporal evolution of slope processes that drive infrastructure damage. The result is an accurate structural analysis, but with load assumptions that may not represent actual landslide-imposed conditions, particularly for large, spatially variable slope movements.

Systemic approaches represent the most direct attempt to address the mentioned scale mismatch challenge, as they explicitly acknowledge the coupled nature of the landslide-tunnel interaction. However, even these approaches struggle to achieve adequate resolution across all relevant scales simultaneously, requiring compromises. These involved either accepting reduced resolution for structural details (Wangwang Zhou et al. 2023), focusing on smaller landslides where the scale gap is less severe (Tian et al. 2025; Yufang Zhang et al. 2021), or analyzing specific interaction mechanisms rather than complete system behavior (Feng et al. 2025). Vassallo et al. (2019) explicitly acknowledged that achieving adequate resolution for both sub-systems simultaneously remains a critical challenge.

The preceding literature review reveals a consistent pattern across all three research approaches, as each excels at characterizing one system component while necessarily simplifying the other. This fundamental asymmetry does not reflect methodological deficiency but rather manifests an underlying challenge that pervades LIS research, that in this work it has been termed the multi-scale challenge.

This peculiar complexity that accompanies landslide-tunnel interaction has contributed to the highlighted diversity in research activities, also emphasizing the fundamental difficulty in bridging the scale gap between landslide processes and infrastructure damage. This scale mismatch manifests in several critical ways:

- Modeling entire landslide systems at the spatial resolution required for detailed infrastructure analysis (centimeter to meter scale) becomes computationally prohibitive.
- Accurately transferring boundary conditions between models operating at different scales presents significant challenges; displacement fields, stress distributions, and material state variables must be mapped across scale transitions without introducing spurious effects or losing critical information about local heterogeneity.
- Ensuring mechanical equilibrium and compatibility across scale transitions demands careful attention to constitutive models and boundary conditions specification, and

validation procedures; simplified assumptions applied at one scale may reflect unrealistic conditions when transferred to another scale.

- Integrating models with different constitutive assumptions, numerical methods, and time-stepping schemes requires coupling strategies that preserve bidirectional feedback mechanisms while maintaining computational efficiency.

Therefore, it clearly emerges that advancing in the understanding of landslide-tunnel interaction fundamentally requires methodological innovation to address the multi-scale challenge. An effective approach must satisfy several requirements:

- The approach should be adaptable to diverse geological settings, landslide types, tunnel configurations, and interaction scenarios rather than being limited to specific cases.
- The approach must remain practical for realistic case studies involving large landslide bodies and complex tunnel geometries. This necessitates strategic allocation of computational resources, concentrating fine-scale resolution only where needed for structural analysis while maintaining coarser but adequate resolution for slope-scale processes.
- The approach must enable modeling of landslide processes at appropriate coarse scales while preserving information necessary for fine-scale structural analysis. This demands systematic procedures for extracting, transferring, and applying boundary conditions across scale transitions.
- The approach must maintain mechanical equilibrium and kinematic compatibility across scale transitions. Boundary conditions transferred from coarse to fine scales must represent physically realistic loading scenarios, not artifacts of the scale transition process.
- The approach must produce predictions that can be validated against field observations at both slope scale (displacement patterns, kinematic evolution) and infrastructure scale (crack patterns, structural deformations).

Among the tools mentioned and most widely used within this research topic, numerical modelling appears as the most flexible and suitable, enabling systematic parametric analyses and scalable simulations across different spatial and temporal resolutions. It allows to explore multiple scenarios, material properties, and boundary conditions with controlled repeatability, providing insights that are often impractical or uneconomical to obtain through other techniques (Crosta et al. 2003; Iverson and George 2015). However, most existing numerical methodologies fail to satisfy these requirements simultaneously, particularly the combination of computational feasibility with preservation of fine-scale structural detail. This recognition motivates investigation of

alternative methodological frameworks capable of addressing the multi-scale challenge more effectively.

2.4.1. *Nested modelling: a strategy for scale integration*

Turning to potential solutions, among possible approaches and strategies, the concept of nested modelling has emerged in other scientific fields as an effective approach for bridging scale gaps.

Nested modelling, also known as sub-modelling, is a hierarchical numerical strategy employed to achieve detailed and accurate analyses within specific regions of large-scale models (Ciptokusumo et al. 2009). It is based on extracting a local portion of a global model corresponding to the area of interest, and analyzing it independently with specific refined geometry, mesh density, or constitutive descriptions. This hierarchical approach enables the investigation of local phenomena while maintaining the boundary conditions and overall influence of the large-scale system (C. Zhao et al. 2019), addressing situations characterized by substantial scale differences between elements involved. By transferring relevant information from one scale to another, nested modelling strategies can significantly reduce computational requirements while obtaining targeted solutions with high accuracy and detail even for complex problems (D. Wang et al. 2018). The efficiency gain stems from concentrating computational resources only where high resolution is required, rather than applying fine discretization uniformly throughout a large domain. Nested modelling creates a numerical data flow between models at different scales, enabling simultaneous treatment of processes operating at disparate scales without the computational burden of fine resolution throughout. Thanks to these abilities, nested modelling approaches have been successfully implemented across diverse scientific fields facing similar multi-scale challenges.

In atmospheric research, Hellsten et al. (2021) addressed large complex turbulent processes by implementing a nesting method coupling multiple numerical models with different grid sizes. This approach supported domains of various sizes, reducing computational costs while enabling different scales to be simulated in parallel or in cascade with high resolution. The analogy to landslide-tunnel interaction is direct, as large-scale atmospheric circulation influences local turbulence, requiring nested treatment (Figure 11).

Within environmental studies, Flipo et al. (2014) expanded the understanding of the stream-aquifer interfaces by implementing a nested technique to enhance modelling accuracy. Formulating multi-scale modelling of the interfaces between watercourses and aquifers, they simulated local-scale processes within larger regional and continental models to better assess climate change effects on hydro-systems.

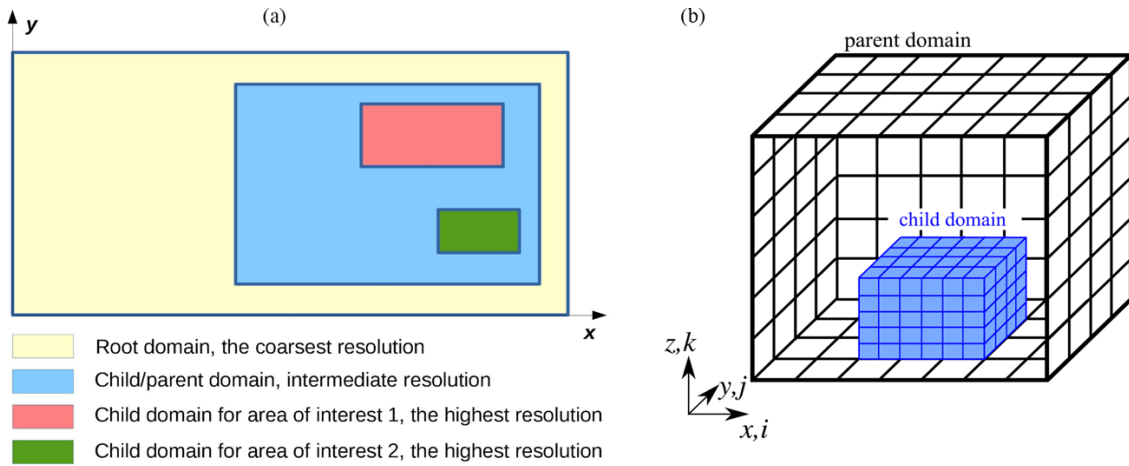


Figure 11 - A schematic example of a nested configuration involving both cascading and parallel child domains (Hellsten et al. 2021)

In the hydrology field, Wang et al. (2018) validated a nested discretization strategy for distributed hydrological models, enabling detailed local hydrological simulations with significantly higher computational efficiency. By applying finer resolution grids only in selected areas and coarser grids elsewhere, the authors accurately replicated aquifer and streamflow estimates compared to a simulation based entirely on fine grids. This demonstrates the principle of strategic allocation of resolution based on the spatial distribution of critical processes, directly applicable to other kinds of modelling. Giudici et al. (2002) presented a nested modelling application in groundwater flow studies, using results from a large-scale model of entire groundwater flow in the municipality of Milan to constrain a small-scale model of a single pumping station.

In coastal engineering, Abbas et al. (2025) combined two different wave models to study waves' impact on the southern coast of Mediterranean coast. They used a coarser offshore model to provide boundary conditions for a more refined nearshore model, estimating storm wave peaks and providing useful data for coastal protection. This exemplifies the hierarchical information transfer principle: coarse-scale boundary forcing drives detailed local analysis.

In offshore engineering, Zhang et al. (2023) introduced a nested multi-scale numerical model to analyze complex flow characteristics around monopile foundations of offshore wind farms. Recognizing that existing models struggle to accurately simulate different physical processes on varying spatial and temporal scales, the researchers coupled a large-scale hydrodynamic model with a small-scale fluid dynamics code, with data from the large-scale model providing initial and boundary conditions for the small-scale model.

Applications of nested techniques have also been proposed in medical diagnostics. Berahmand et al. (2025) introduced a nested deep learning model to improve accuracy

in predicting gynecological cancer risk. The model employed a hierarchical framework with two levels: “base learners” extracting diverse features from cervical smear images, and a “meta-classifier” refining predictions to capture intricate relationships between them and improve diagnostic accuracy. While this application differs fundamentally from physical modelling, it demonstrates the broader principle of hierarchical information processing across analytical scales.

Some examples can be found also in the mining and extractive field. Insana et al. (2016) developed a microstructure-based model to investigate fracture propagation through rock masses. Recognizing the need to accurately predict this phenomenon for deep geothermal wells, the researchers adopted the Distinct Element Method (DEM) coupled with Voronoi tessellation. Microparameters governing the behavior of contacts between Voronoi sub-blocks were calibrated against laboratory test results for different rock types, and an upscaling procedure was subsequently proposed to build reliable and representative numerical models at in situ scale. Similarly Sinha and Walton (2021) developed an integrated modelling approach to study the damage process in a granite pillar at the Creighton Mine in Sudbury, Canada. Recognizing the computational limitations of fully three-dimensional discontinuum models for practical mine-scale applications, the researchers coupled a calibrated mine-scale FLAC3D continuum model with a two-dimensional Bonded Block Model (BBM) in UDEC. The load path and boundary conditions extracted from the large-scale FLAC3D model were applied to the detailed BBM cross-section of the pillar, enabling the researchers to analyze how support density and complex loading conditions influenced the progressive damage evolution and stability of the pillar.

2.4.2. *Nested modelling for the multi-scale challenge*

These applications from diverse fields demonstrate the viability of nested approaches in addressing similar scale-mismatch challenges. Just as atmospheric models nest local turbulence within regional circulation (Hellsten et al. 2021), or hydrological models nest local aquifer details within watershed-scale flow (Giudici et al. 2002), landslide-tunnel analysis can nest tunnel-scale structural response within slope-scale deformation. Hydrological studies (Wang et al. 2018) additionally demonstrate that strategic application of fine resolution only where needed produces accurate results at fraction of computational cost compared to uniformly fine discretization. For landslide-tunnel problems, this means applying fine mesh resolution only in the tunnel vicinity while maintaining coarser resolution for the broader slope domain.

Coastal and offshore engineering applications (Abbas et al. 2025; J. Zhang et al. 2023) illustrate how nested modelling offers the capability of transferring boundary conditions from coarse to fine models, ensuring that local detailed models reflect the influence of

larger-scale processes. Successful nested modelling applications also maintain physical realism across scale transitions, as groundwater flow studies (Flipo et al. 2014) ensure that local models conserve mass and maintain hydraulic equilibrium consistent with regional flow fields.

Finally, applications in the mining field demonstrate how nested modelling frameworks enable both a detailed characterization of rock mass behavior at the micro-scale (Insana et al. 2016), and the feasibility of integrating different numerical methods to investigate localized damage processes within large-scale mining systems (Sinha and Walton 2021).

The critical insight is, thus, that nested modelling has successfully addressed scale mismatch problems comparable in nature to the landslide-tunnel multi-scale challenge. While the specific physical processes differ, the fundamental challenge can be considered analogous (Figure 12).

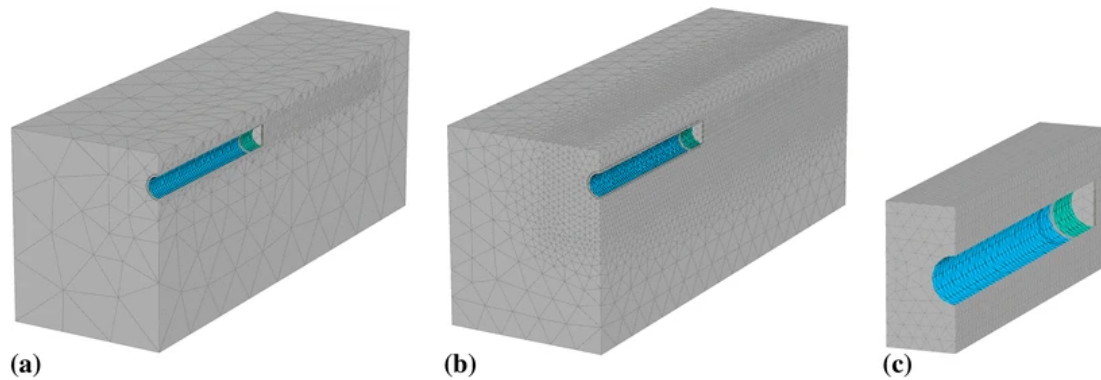


Figure 12 - Example of a 3D mesh discretization for: (a) global model, (b) reference model, and (c) sub-model (Zhao et al. 2019)

Developing a new approach that allows for satisfactory reproduction of both landslide dynamics and consequent tunnel structural responses, through the use of multiple models that form a virtuous chain in which one provides data to the other, represents the promising research direction that this work had explored and tested. Thus, the challenge lied in adapting nested modelling concepts to the specific requirements of geomorphological and infrastructural analysis, ensuring that information transfer between scales preserves critical physical phenomena while maintaining computational feasibility.

3. A proposed multi-scale approach for LIS modelling

Building on the recognition that nested modelling offers a promising strategy for addressing the multi-scale challenge, this research proposes a comprehensive modelling approach specifically designed for landslide-tunnel interaction analysis. This approach adapts nested modelling principles to combine slope-scale and infrastructure-scale modelling through systematic information transfer procedures. The fundamental aim of the proposed multi-scale approach is to enable accurate representation of both landslide processes and tunnel structural response through hierarchical modelling, that maintains physical consistency across scales while remaining computationally feasible. Thus, the primary objective of this research is the development of a functional workflow for investigating the impact of large-scale landslide deformation on localized infrastructural damage. This workflow must:

- Enable accurate representation of slope processes (geometry, kinematics, hydrogeology).
- Facilitate efficient transfer of relevant geological and geomorphological information from slope-scale to infrastructure-scale models.
- Maintain physical consistency and mechanical equilibrium across scale transitions.
- Enable structural analysis of tunnel response, including damage formation and propagation, based on landslide-induced boundary conditions.
- Remain computationally feasible for realistic case studies.
- Support validation of the outcomes by comparing them with field observations at both slope and infrastructure scales.

To validate the proposed multi-scale approach and demonstrate its practical applicability, two secondary objectives are established:

- Application to a real case study, integrating available monitoring data to calibrate and validate model predictions at both slope and infrastructure scales.
- Assessment of the methodology for future developments, evaluating strengths, limitations, and computational requirements of the multi-scale approach through the case study application, identifying areas for future refinement and potential extensions to other types of infrastructure or natural hazard.

3.1. The proposed method

The multi-scale approach involves a systematic sequence of modelling steps designed to progressively refine analysis from slope-scale to infrastructure-scale.

Step 1: Landslide-scale model

Develop a 3D numerical model representing the entire landslide body and surrounding geological context. This coarse-scale model incorporates geological characterization, material property distributions, and relevant structural features (bedding, discontinuities, tectonics related) and simulates slope-scale processes including stress redistribution, groundwater flow, and deformation patterns. In this way, spatial distributions of displacements, stresses, and material state variables are provided throughout the landslide domain. The results must be calibrated and validated against slope-scale monitoring data. Tunnel presence is captured as simplified geometry without detailed structural representation

Step 2: Multi-scale data transfer procedure

Extract relevant information from the slope-scale model to define boundary conditions for the infrastructure-scale model. This starts by identifying the critical zone around the tunnel, where detailed analysis is required, and extracting displacement fields, stress distributions, or other relevant quantities along boundaries of this refined domain. While ensuring mechanical consistency through equilibrium checks and compatibility verification, extracted information must be processed and formatted as boundary conditions to the fine-scale model.

Step 3: Infrastructure-scale model

Develop a refined numerical model focusing on the tunnel and immediate surrounding domain. This fine-scale model features significantly finer spatial discretization enabling representation of tunnel geometry, lining details, and potential crack locations, while incorporating constitutive models appropriate to simulate concrete damage, crack propagation, or other structural failure mechanisms. Boundary conditions extracted from slope-scale model are applied on the tunnel-scale model, ensuring that local analysis reflects actual landslide-imposed conditions. Tunnel structural response is simulated and validated against infrastructure-scale monitoring data.

Step 4: Validation and iteration

Compare predictions at both scales with available monitoring data. This means validating slope-scale predictions against displacement monitoring, surface

deformation patterns, and kinematic observations, and infrastructure-scale predictions against concrete cracks patterns, tunnel deformations, and structural damage observations. If necessary, models must be refined based on validation outcomes and analysis repeated to improve agreement.

This systematic workflow addresses the multi-scale challenge by separating scales while keeping them connected through carefully designed information transfer protocols. The approach concentrates computational resources strategically, defining coarse but adequate resolution for slope processes, and fine resolution only in the critical zone around the infrastructure.

As previously stated, the primary objective of the proposed modelling framework is the development and demonstration of a robust and transferable methodology, rather than the exact numerical reproduction of a specific site. Accordingly, the results presented in this study should be interpreted as realistic representations of landslide-tunnel interaction rather than exact simulations. The latter, in fact, are inherently affected by uncertainties associated with modelling assumptions, parameter estimation, and the limitations of available geological, geotechnical, and structural data. In this context, detailed knowledge of the study site plays a crucial role in assessing the reliability of model inputs and, more importantly, in identifying the uncertainty within which the results can be meaningfully interpreted.

Moreover, an additional and collateral target was to obtain a working system of models explicitly allowing interoperability between different numerical codes. Although the entire modelling chain could, in principle, have been implemented within a single software environment by progressively refining and extracting sub-domains, such a strategy would have not allowed assessment of model-to-model and code-to-code transitions. The use of different numerical tools at different scales represents a key methodological challenge addressed in this work and was therefore intentionally adopted to expand the applicability of the proposed approach.

3.1.1. *Validation through application*

The development and validation of the multi-scale methodology require application to a real-world case study with specific characteristics. The selected site must satisfy several essential criteria:

- Presence of large and well-characterized active landslide with documented long-term displacement behavior.
- Tunnel infrastructure that interacts with the landslide body and exhibits measurable structural effects.

- Geological and geotechnical characterization data supporting detailed numerical modelling.
- Monitoring datasets spanning both landslide process and infrastructure response.
- Historical documentation enabling understanding of spatio-temporal evolution of both landslide and infrastructure behavior.

The Passo della Morte landslide–San Lorenzo tunnel system in Friuli Venezia Giulia, Italy, meets these criteria and provides a suitable testing ground for the proposed methodology. This case study not only exemplifies many slope-tunnel interactions in mountainous terrain but also offers a comprehensive dataset collected over several decades of slope monitoring and infrastructure observations, exploitative to methodology development and validation.

The following section presents the detailed implementation and validation of the multi-scale methodology. First, the Passo della Morte case study will be introduced, explaining the rationale behind its selection and the characteristics of available data sources. Subsequently, the methodological workflows developed to apply the proposed framework will be described, demonstrating how the multi-scale nested modelling derived strategy addresses the computational and physical challenges identified throughout this review in a robust and reproducible manner.

Through the application to this real-world case study, this work will ultimately demonstrate that the multi-scale challenge can be effectively addressed through carefully designed modelling strategies. Furthermore, both computational efficiency and physical accuracy will be maintained, while achieving a more comprehensive understanding of LISs, that has remained elusive in previous research efforts.

3.2. The Passo della Morte case study

The case study selected for the employment of the proposed multi-scale framework is that of the Passo della Morte. This case is about a system of four distinct landslides part of a large Deep-seated Gravitational Slope Deformation (DsGSD) located in the Carnian Alps, Italy, which has historically posed a significant threat to the road infrastructures in the area. As confirmation of this, since its construction in the '90s, the San Lorenzo road tunnel has been severely affected by the largest of the four landslides mentioned above. This landslide, colloquially known as the Passo delle Morte landslide (Landslide 3 in Figure 13), has caused several incidences of damage to the tunnel, including water seepage and concrete lining detachments, that triggered numerous studies and projects to better understand the phenomenon. Several surveys, monitoring systems

and programs have been designed to investigate the evolution of slope instability and manage the landslide risk affecting the road tunnel.

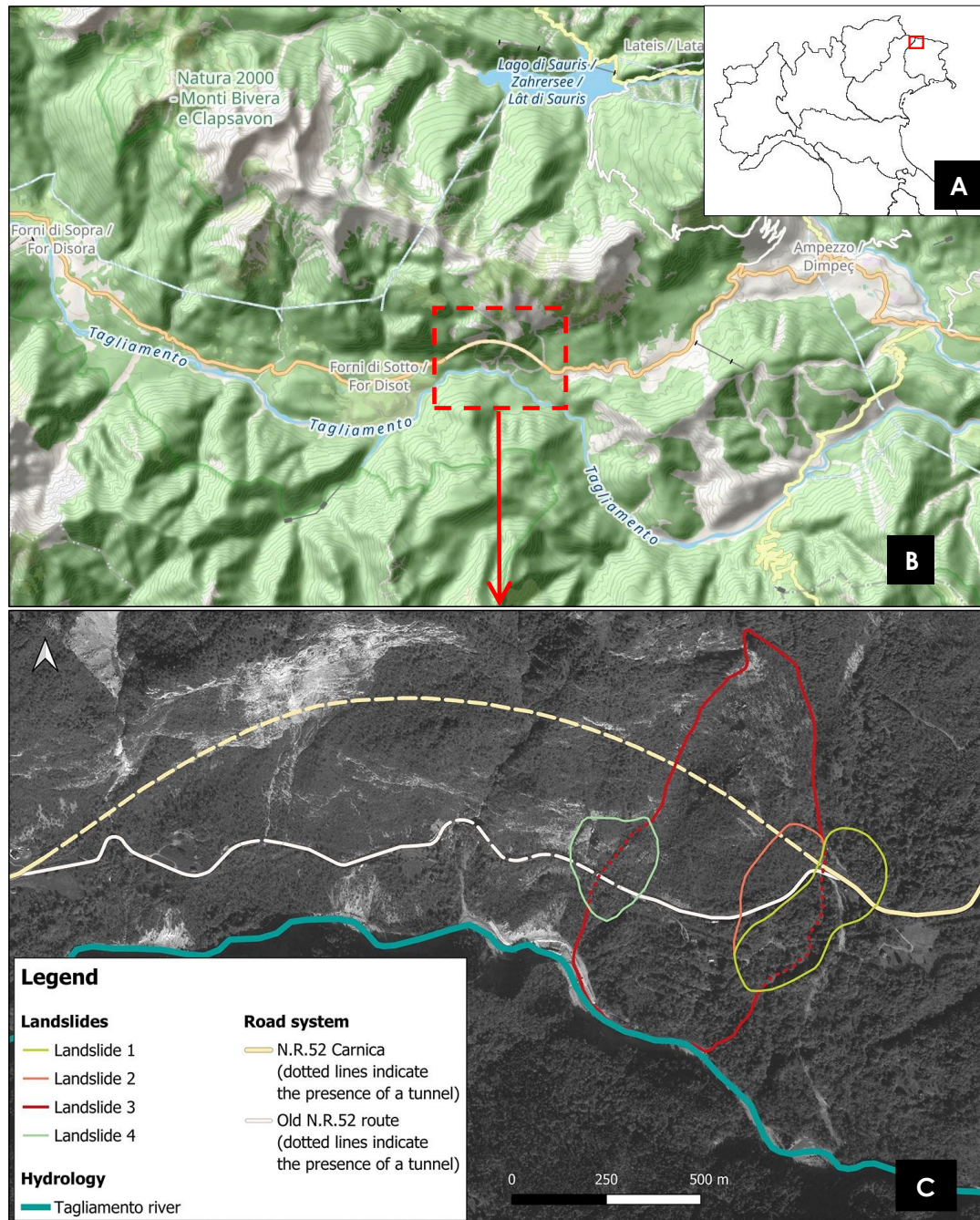


Figure 13 - (A) Geographical framework, with study area outlined by the small red rectangle; (B) Major transportation routes in the area; (C) case study area and the four landslides forming the Passo della Morte landslide system (Ballaera et al. 2024)

3.2.1. Geographic and climatic context

The study area is located in the Upper Tagliamento Valley in the Friuli Venezia Giulia (FVG) region, north-eastern part of Italy, approximately 70 km from national border with

Austria and 80 km from national border with Slovenia. The area of interest of this study is specifically located within the municipality of Forni di Sotto and Ampezzo, respectively between 777 m and 560 m a.s.l. The area presents several challenges for urban development and infrastructure construction, as 43% of its territory is mountainous and it has one of the highest levels of rainfall in Europe, with historical data from 1961 to 2000 showing annual mean precipitation of 1700 mm, varying between 1200 and 2400 mm (ARPA FVG 2023).

3.2.2. *Geological framework and structural overview*

The study area is situated within the Alpi Tolmezzine Occidentali—Bivera group according to the International Standardized Mountain Subdivision of the Alps (ISMSA) (Marazzi 2005). The stratigraphic sequence, developed through integration of fundamental geological studies (Pisa 1972) with extensive borehole data, reveals a complex succession of geological units (Figure 14). This includes the Schlern dolomite unit, dating back to the Upper Ladinian (Triassic period), composed by dolomite, dolomitic limestone, and calcareous dolomite. This unit is overlain by stratified dark limestone, which alternates layers of micritic limestone between 0.1 m and 1 m thick and layers of dark marls up to 0.2 m thick. Subsequent units include stratified limestone and dolomite, which comprise a succession of dolomite, limestone and calcarenite with thin gray marly intercalations with a total thickness of 25 m. On top of these units is the massive crystalline dolomite, consisting of a 10 m thick layer of compact light grey doloarenite. The overlying unit is composed of chaotic silty clay, a characteristic reddish claystone with arenaceous layers less than 1 m thick with some intercalations, up to 10 cm, of massive whitish-gray marly dolomite. Further up in the succession, there are two Upper Carnian units, the gypsum, with clayey dark layers or inclusions, and the pitted dolomite, made of gray marly dolomite and light-tone dolomite and dolomitic marl.

Finally, the uppermost unit, the Forni dolomite, consists of dolomite and dark marly dolomite in thin layers up to 0.1 m thick, dating back to the Norian age. Quaternary deposits locally cover the Triassic basement and are a result of complex regional geomorphological processes dating back to the Pleistocene and the Holocene. These deposits mapped in the Passo della Morte area include alluvial deposits, glacial moraines, polygenic conglomerates, slope debris and the chaotic deposits of a late-glacial landslide, i.e., the Marocca di Sacrovint, a landslide deposit, characterized by various degrees of cementation, that caused the blockage of the Tagliamento River. This ancient landslide demonstrates the long-term geomorphological impact of large-scale slope instabilities in this region.

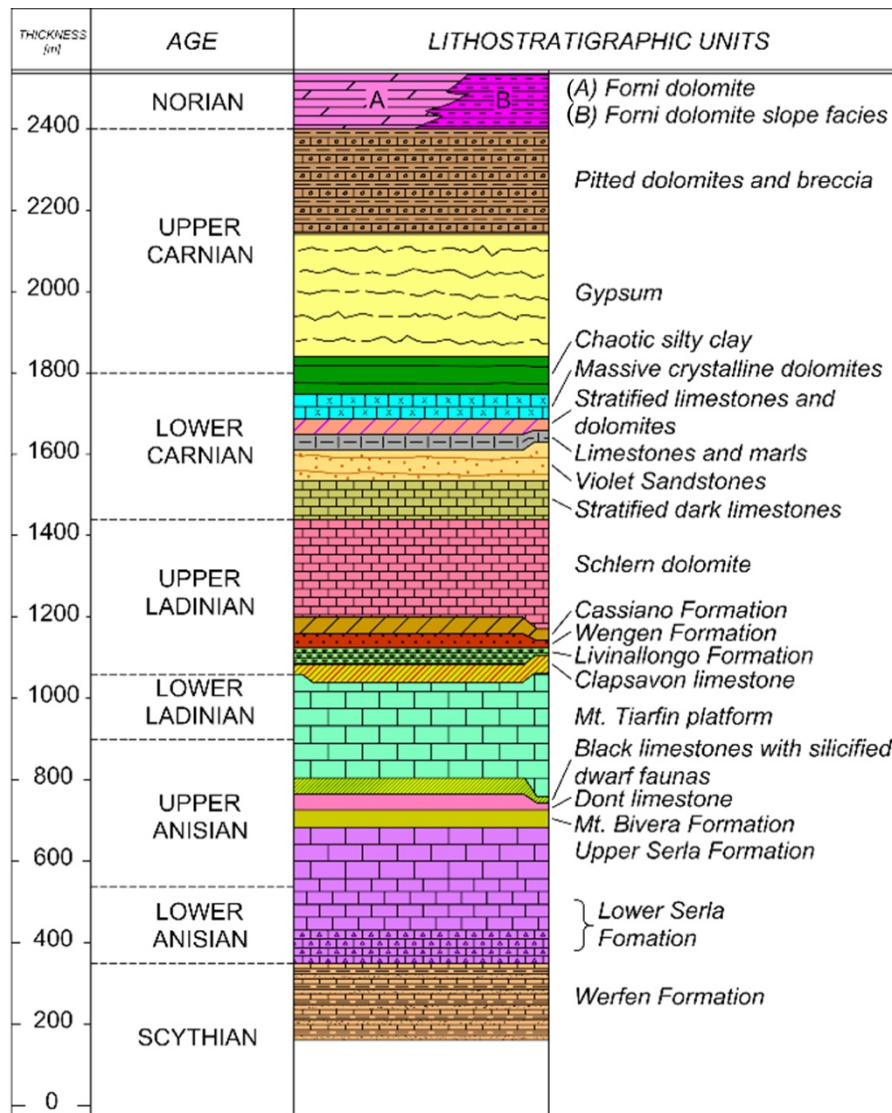


Figure 14 - Chronostratigraphic chart of Passo della Morte area from Pisa (1972), revised by Marcato (2007) (Ballaera et al. 2024)

The regional tectonic framework further completes this geological setting. In fact, the most significant tectonic structures in the Upper Tagliamento valley include the Sauris thrust front to the north and the Alto Tagliamento line to the south (Carulli e Polonia 1992). The Sauris thrust front is characterized by extensive conjugated east–west tectonic structures. This low angle overthrust is a particularly significant regional structure that led to Upper Ladinian and Carnian units (Schlern dolomite and stratified dark limestone) lying above the most recent Upper Carnian units (gypsum and chaotic silty clay). The visible change in direction of the Sauris thrust front at the Passo della Morte may be due to its intersection with a conjugate north–south oriented strike fault system (Figure 15).

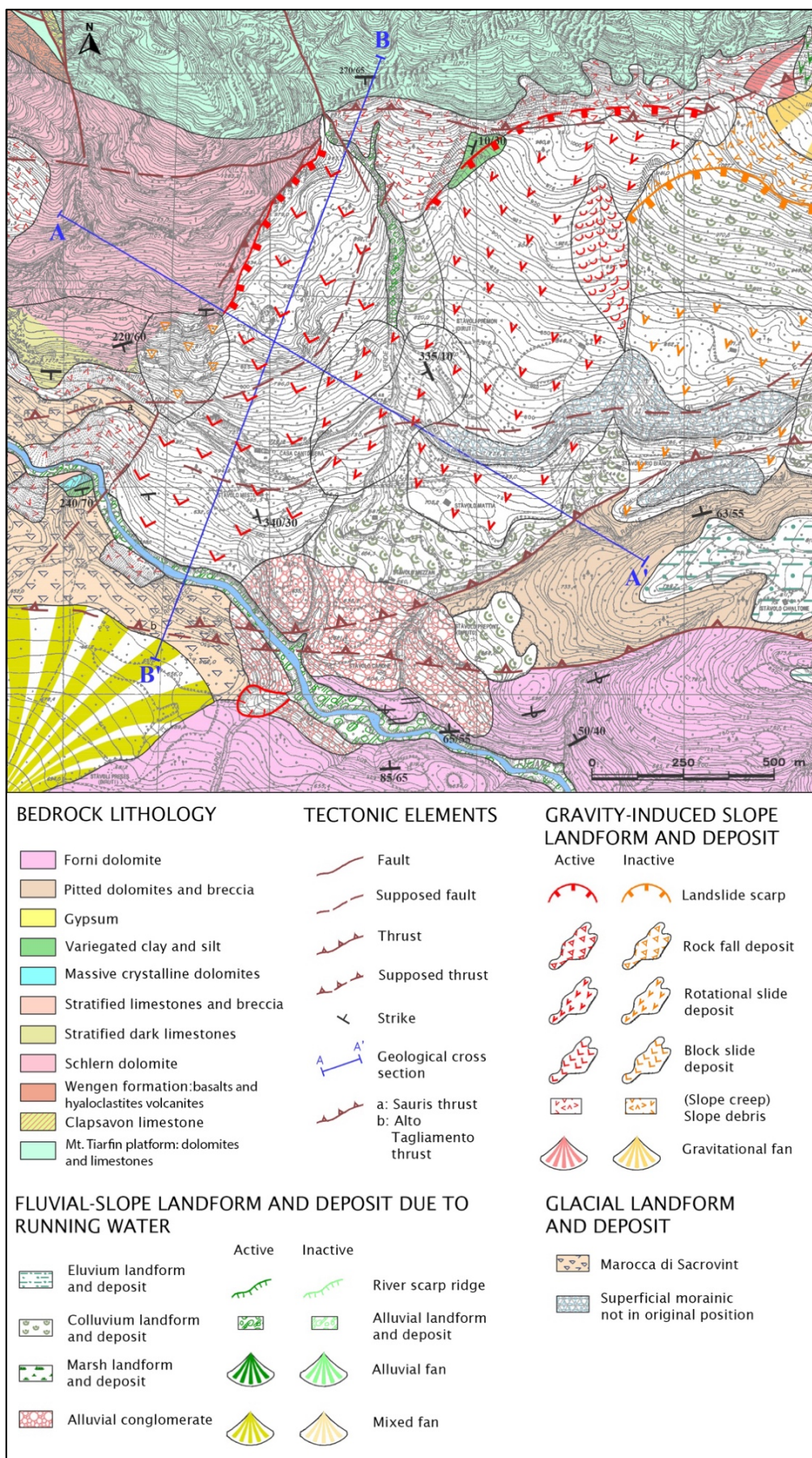


Figure 15 - Geological map of the Passo della Morte area (Ballaera et al. 2024)

The gradual reshaping of the upper Tagliamento valley slopes after the Last Glacial Maximum (LGM) has represented a crucial geomorphologic factor driving slope instability. During the Pleistocene glaciations, the glacier ice in the Tagliamento basin reached an altitude of up to 1600 m a.s.l., with only a few peaks emerging from the ice cap. The area has experienced slope instabilities, resulting in the Tagliamento river changing its course from a westward direction to a southward flow (Monegato and Stefani 2011). The main cause of these instabilities is believed to be the removal of support as a consequence of glacier retreat and down-wasting (Ballaera et al. 2024).

The release of energy following the LGM, together with the tectonic deformation revealed by the presence of the Sauris thrust, eventually contributed to creating conditions favorable to triggering the Passo della Morte landslide. The lack of lateral support due to the presence of ice likely influenced the onset of the slope instability phenomenon in the form of a DsGSD/rock-block slide.

3.2.3. *Landslide system*

The four landslides composing the Passo della Morte landslide system (Landslides 1–4 in Figure 13) are part of a larger, possibly late-glacial, DsGSD, making them secondary slope instability processes (Ballaera et al. 2024). Among these four landslides, Landslide 3, known as Passo della Morte landslide, represents the primary focus of this research. Within the landslide system, this landslide is the most relevant slope instability process in terms of state of activity, area, depth and volume, and it is also the one that most affects the San Lorenzo tunnel. It can be classified as an active rock-block slide (Hungre et al. 2014) extending between 970 m and 640 m a.s.l., with an area of 0.45 km², a sliding surface approximately 60 m deep and a volume of 24×10^6 m³ (Bossi et al. 2017) (Figure 16).

The slope movements initiated with a subvertical displacement of the DsGSD conditioned by the tectonic lineaments conjugate to the main overthrust lineaments (post LGM), which then evolved into a rock-block slide, that is currently slowly moving in a south–southwest direction with an average of 2/3 cm/year (3.5 cm/year at surface and 2 cm/year along the basal surface) (Marcato 2007).

The landslide body consists of a highly fractured and permeable dolomitic rock mass overlying plastic and less permeable clay-rich units. This contrast in competence and permeability between lithotypes governs the dynamics of the landslide. In fact, the weight of the fractured dolomite unit bears directly on the clay-rich units, causing, especially in the presence of water, a loss of resistance and the consequent triggering of landslide movements. The geological context also contributes to complicating the landslide hydrogeological behavior, as progressive fracturing of the carbonate portion

facilitates rapid meteoric water infiltration, eventually reaching clay-rich units where the main sliding surface is located.

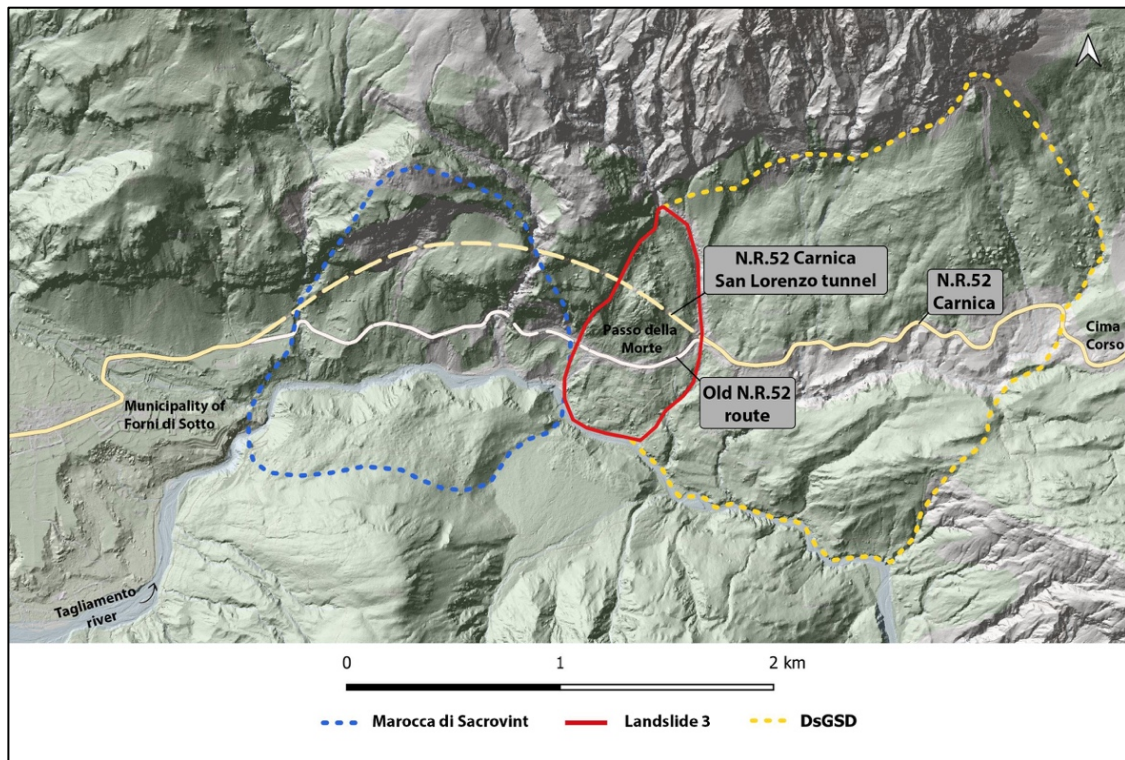


Figure 16 - Paleo-landslides recorded in the Passo della Morte area with Landslide 3, the commonly known Passo della Morte landslide, outlined in red (Ballaera et al. 2024)

3.2.4. San Lorenzo road tunnel

The Passo della Morte section represents a critical infrastructure bottleneck, where the valley narrows, creating a steep gorge above the Tagliamento River. The National Road 52 Carnica serves as the only route connecting the Upper Friuli-Venezia Giulia region with the neighboring dolomitic area of Cadore. To bypass a section of National Road 52 that was exposed to frequent rock falls, shallow landslides, and snow avalanches, the San Lorenzo road tunnel was built. The peculiar geographic position and context of the Passo della Morte area makes the San Lorenzo tunnel not merely an infrastructure element, but a critical lifeline for regional connectivity. Should this section experience closure or significant problems, the required detour would extend travel time by more than two hours, emphasizing the critical importance of maintaining this infrastructure's structural integrity and operational capacity.

This road tunnel represents a classic example of infrastructure development in landslide-prone mountainous terrain, where engineering solutions must balance safety, functionality, and economic constraints within a geologically challenging environment.

The 2200 m long tunnel was excavated using drill and blast between 1994 and 1996 to connect the municipalities of Ampezzo (to the East) and Forni di Sotto (to the West). 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 depending on the section type. The tunnel has a humpback profile, with its highest point approximately halfway along its length, thus achieving natural drainage towards the entrances.

The tunnel construction encountered the geological complexity of the Passo della Morte area, especially the lithological succession between clay-rich units and carbonate units. Indeed, the clay-rich units are characterized by very poor mechanical quality, which compromises their ability to support the tunnel excavation process. The dolomitic unit, on the other hand, while being more competent, is defined by an extensive pattern of fractures that allow water to infiltrate and percolate, eventually reaching the tunnel.

This overall scenario required adaptive design measures as excavation progressed through geological units with different rock mass behavior. The first 500 m of the excavation on the Ampezzo side involved an initial section of approximately 100 m of Quaternary detrital deposits, before entering the rock mass. The first rock unit encountered by the excavation front were varicolored siltstones and claystones, with the Schlern dolomites being encountered at about 400 m along the tunnel. This succession required the adoption of different tailor-made section types based on the geological units, which differed in terms of:

- *Method required to stabilize the surrounding ground:* micropiles were used in sections starting from the eastern entrance (Ampezzo side) up to 160 m, i.e., for the entire section in Quaternary deposits and for the first portion within the varicolored claystones and siltstones; in contrast, tie rods around the perimeter were used for the remaining tunnel portion.
- *Lining and reinforcement:* double IPE160 ribs anchored with micropiles at ground level, 20 cm of shotcrete, and final unreinforced cast-in-place lining, with a thickness of 60 cm in the crown and 90 cm in the invert were defined in the portion from the eastern entrance (Ampezzo side) up to 400 m, i.e., until the Schlern dolomite unit; 10 cm of shotcrete, and a final unreinforced coating cast in situ, with a thickness of 40 cm in the dome and 60 cm in the inverted arch for the remaining tunnel portion.

The tunnel included a built-in drainage system consisting of a layer of geotextile extending across the entire dome, placed on the underside of the pre-lining. The geotextile conveys the water to two micro-perforated pipes that run parallel to the tunnel, positioned at the point of contact between the crown and the walls and connected every 30 m to a main drainage pipe located between the invert and the ground level (below the road surface).

Despite comprehensive design precautions, within construction works in 1996, in the wake of a heavy rainfall event that triggered a partial reactivation of the DsGSD, the tunnel suffered widespread structural damage, such as lining cracks and detachment of concrete flakes. Structural damage forced a halt in construction from 1997 to 2006, while investigations and mitigation measures were carried out.

From the very first monitoring campaigns and observations, the tunnel seemed to be located within a large slope instability, i.e. the Passo della Morte landslide, whose movement had caused the serious structural damage reported. This condition was not properly assessed during the design phase, likely due to the low velocity and limited visible evidence of landslide displacement at the slope surface. Following this discovery, structural countermeasures were taken to mitigate the impacts (Figure 17).

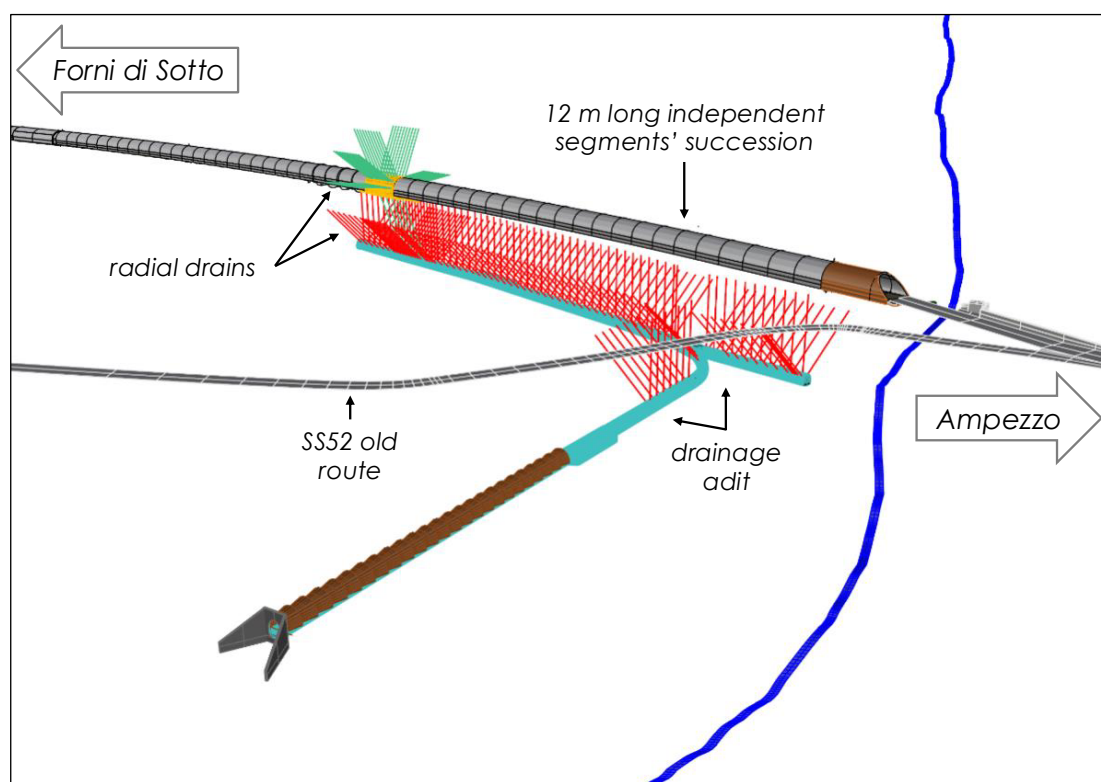


Figure 17 - Countermeasures adopted in the aftermath of 1996 landslide acceleration

In the first 400 m from the Ampezzo tunnel entrance, the final lining has been removed and replaced with a new cast-in reinforced concrete. This operation was preceded by a campaign of radial consolidation around the tunnel perimeter, aimed at improving the mechanical strength of the rock mass for the successful replacement of the linings. Then, a new coating was installed, consisting of IPE180 coupled ribs with a center distance of 0.75 m and a 20 cm thick layer of fiber-reinforced shotcrete. Subsequently, the new final lining was cast in situ, fully reinforced with a thickness of 60 cm in the shell and 90 cm in the inverted arch.

The entire 400-m tunnel portion was rebuilt as succession of 12-m-long independent tunnel segments, purposely built without continuous reinforcement and specifically designed in this manner to accommodate ongoing landslide-induced deformation. Additionally, a drainage tunnel was constructed approximately 30 m below the road tunnel to decrease groundwater pressures withstand by the structure. It was excavated with a horseshoe section, 4 m in width and 5.50 m in height, and lined with unreinforced shotcrete. This drainage tunnel features a T-shape in plan, with both T-arms nearly parallel to the San Lorenzo tunnel for a total length of 300 m, and a perpendicular T-stem extending downslope towards the Tagliamento river for a length of 250 m. After the completion of these countermeasures, the tunnel was reopened to traffic in 2008.

To highlight the spatial relationship between the landslide body and the road infrastructure, i.e., the road and the new drainage tunnel, several geological cross-sections were drawn, two of which are reported hereafter (Marcato 2007): the geological section AA' runs in the direction of the tunnel, whereas BB' follows the slope, both illustrating the scarp, the body and the sliding surface of Passo della Morte landslide (Figure 18).

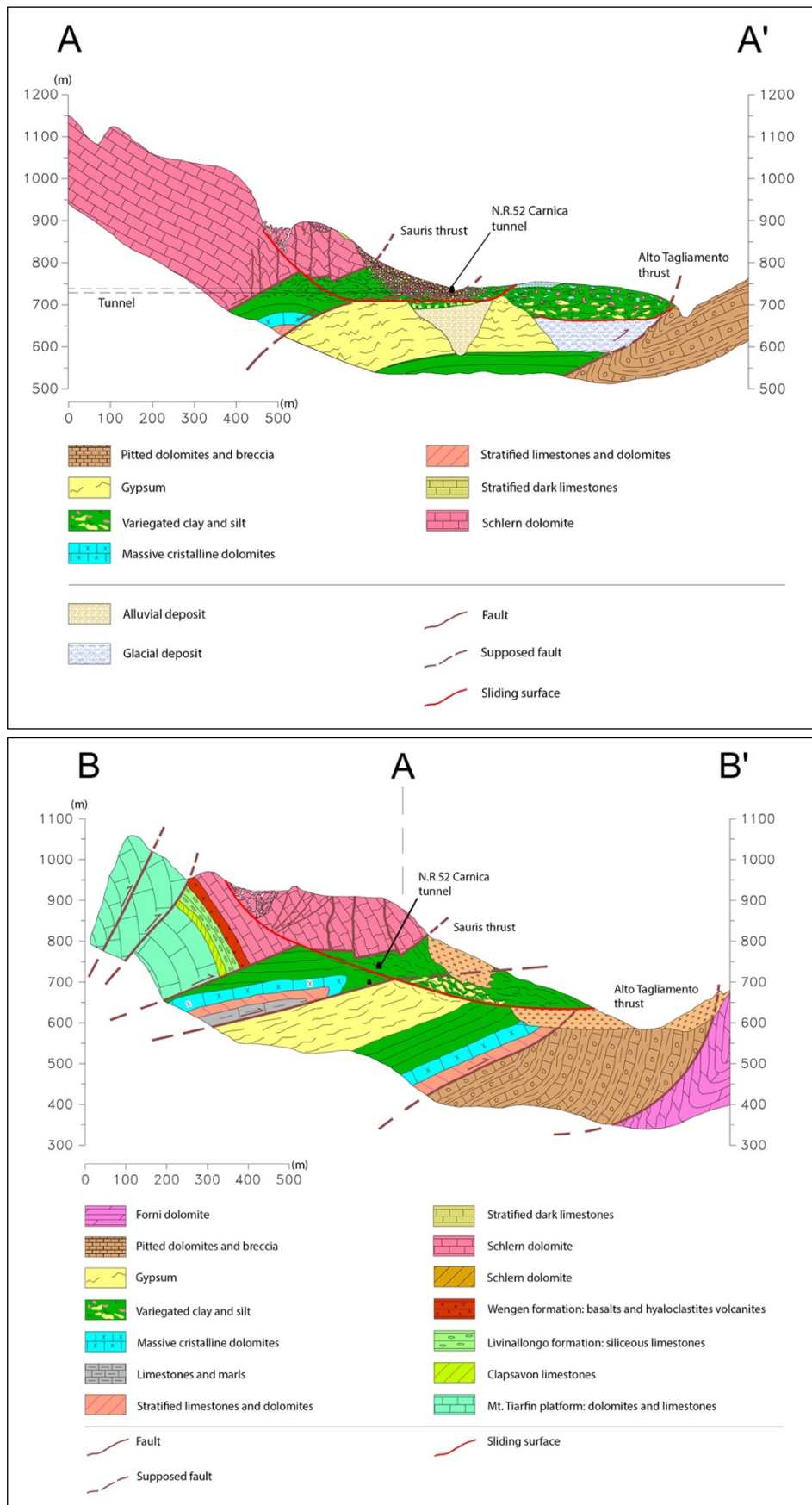


Figure 18 - Earlier geological cross sections AA' and BB' (cfr Figure 15) (Ballaera et al. 2024 after Marcato 2007)

3.2.5. *Landslide Monitoring System*

Within the Passo della Morte area, an initial monitoring system was set up in the aftermath of the 1996 heavy rainfall event, when tunnel construction had to be halted due to slope movements. The first investigations carried out by the stakeholders were primarily focused on resuming tunnel construction, preventing further unforeseen events or interruptions. In contrast, a site-customized monitoring plan deployed by the Research Institute for Geo-Hydrological Protection (IRPI) of the Italian National Research Council (CNR) was developed, and expanded yearly ever since, to obtain a comprehensive understanding of the phenomena at the slope scale and of the geomorphological evolution of the area.

The CNR-IRPI monitoring system, operational since 2012, has effectively characterized the kinematic behavior of all four landslides through both periodic and continuous measurements. This monitoring system consists primarily of: inclinometers, either in-place (IPI) or in-hole ones, strategically located to measure the depth and rate of landslide movements; piezometers deployed to monitor changes in groundwater within the slope in response to precipitation and snowmelt events; a GNSS (Global Navigation Satellite System) control network composed of eleven benchmarks (five still active), installed to monitor superficial slope movements.

Figure 19 illustrates the spatial distribution and temporal coverage of the monitoring network, including surveys and instrumentation deployed by both stakeholders and CNR-IRPI, while also distinguishing between operational and non-operational instruments. However, not all acquired data were available or suitable for analysis due to instrument malfunctions, data gaps, or accessibility issues.

Data quality, continuity, and accessibility, in addition to monitoring network extent, are of critical importance for robust landslide analysis. Consequently, the analyses presented in this thesis are based exclusively on data from currently operational instruments. The interpretations explicitly account for the spatial limitations of the monitoring network relative to landslide dimensions, recognizing that incomplete instrumental coverage introduces inherent uncertainties in the characterization of slope behavior and failure mechanisms.

These limitations were deemed acceptable within the scope of this research, which prioritizes methodological demonstration over detailed site-specific modelling. Furthermore, the data constraints encountered here reflect typical conditions in landslide monitoring and studying practice, where comprehensive, high-quality datasets are rarely available. This representativeness strengthens the relevance of the proposed methodology for practical applications in data-limited environments.

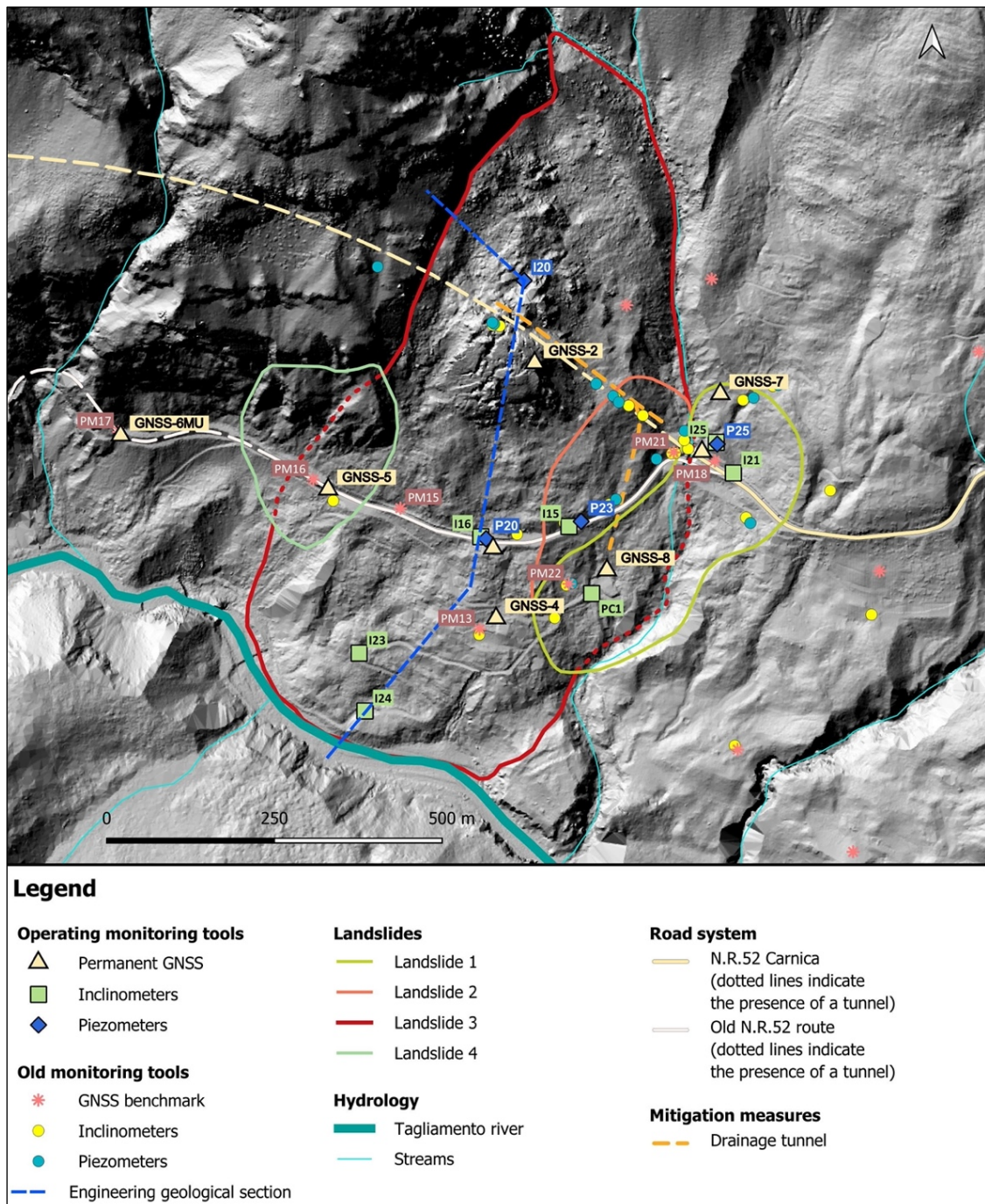


Figure 19 - Slope-scale monitoring system, with instrumentation both operating and decommissioned; Passo della Morte landslide labelled as Landslide 3 (Ballaera et al. 2024)

In March 2023, eight permanent GNSS stations (five of them are monitoring Passo della Morte landslide) were installed, with one station located in a stable area serving as the master station (GNSS-MU in Figure 22). This network provides continuous, near-real-time monitoring of surface deformations caused by landslides activity.

The inclinometer I-16, installed in 2012 and consistently operational until 2024, delineated effectively the displacement along the sliding surface situated at a depth of

–59 m below the ground level. Two additional in-place inclinometers, I-23 and I-24, were drilled and instrumented, enabling a further definition of Passo della Morte landslide perimeter lower boundary. The sliding surface is indicated by deformation at a depth of approximately -22 m for I-23 and -16 m for I-24 (Figure 20), highlighting a significant difference compared to the readings recorded by inclinometer I-16. This variation is attributed to the post-failure behavior of the clayey units in the lower landslide body, which experience a reduction in mechanical competence and tend to spread toward both the landslide boundaries and the Tagliamento River.

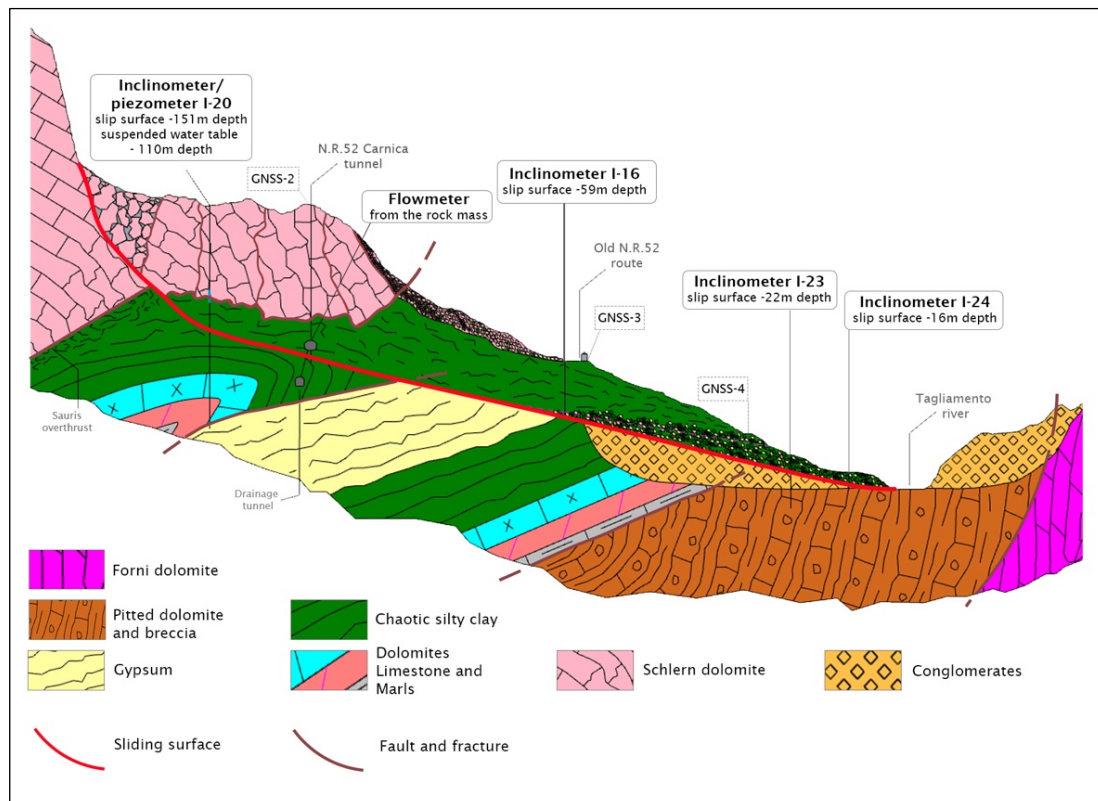


Figure 20 - Engineering-geological cross-section indicating borehole locations and depth and shape of the sliding surface of the Passo della Morte landslide (cfr Figure 19 for location) (Ballaera et al. 2024)

Both inclinometers I-23 and I-24 recorded displacements of almost identical magnitude in the months between measurements, stabilizing at 4 cm for I-23 and 3 cm for I-24 (Figure 21). These displacement rates are consistent with observations derived from GNSS periodic measurement, ranging from approximately 2 cm/year for the uphill benchmark (i.e., GNSS2) and 3.5 cm/year for the downhill benchmark (i.e., GNSS4, GNSS5). These GNSS data, considering that they are influenced by possible surface deformations, still provide evidence of the differential displacement rate of the Passo della Morte landslide. In fact, GNSS2 data show a clear movement towards south-southeast, while GNSS4, on the contrary, shows a movement towards south-southwest (Figure 22).

Periodic inclinometric measurements - I23 (left) and I24 (right)

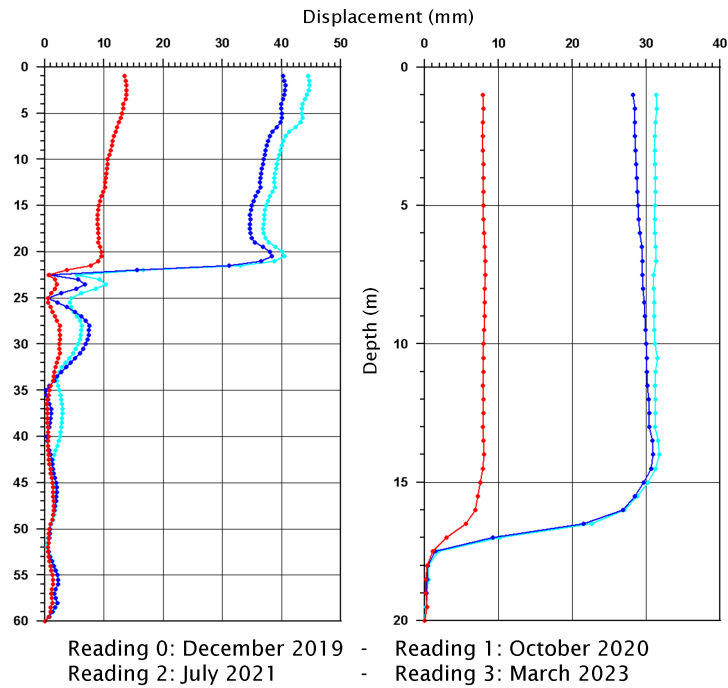


Figure 21 - Inclinometers I-23 and I-24 data

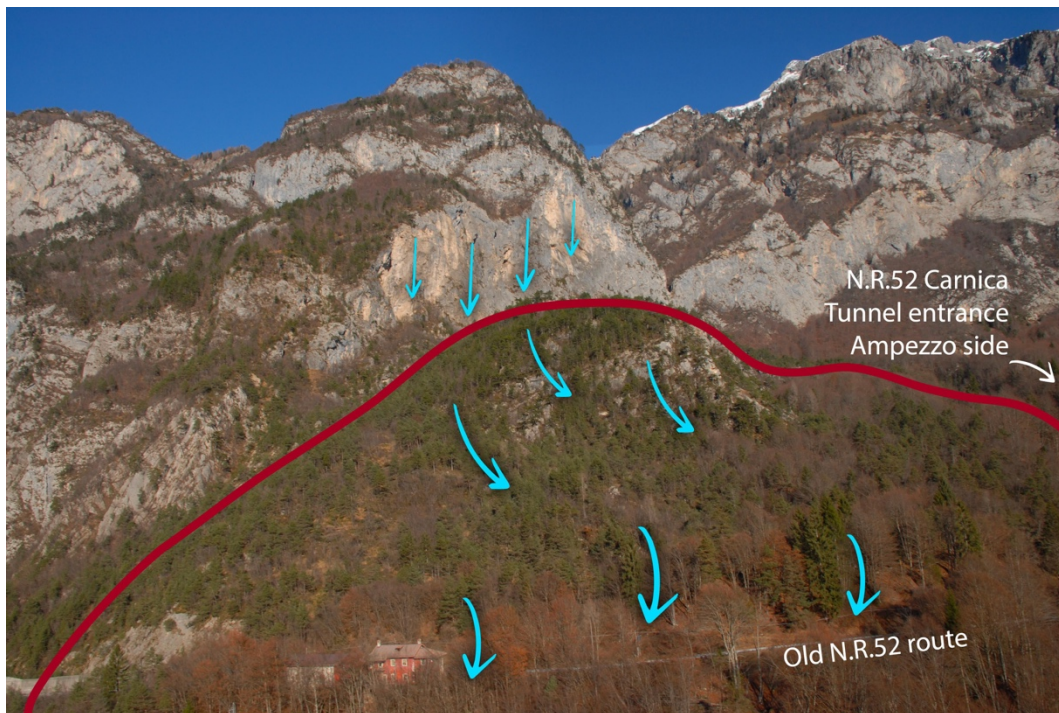


Figure 22 - Passo della Morte landslide evolution stages and directions (Ballaera et al. 2024)

This uneven spatial displacement rate is evidently not only related to the significant behavioral difference between the two lithologies governing the landslide movement, but is also confirmed by the magnitude of damage in the tunnel visible to date (Figure

23). In fact, the accumulated displacement from the reopening of the tunnel to the date of the photograph (i.e., 3 cm as of June 2024) differs consistently from the expected landslide-induced displacement considering the recorded annual velocity rates (i.e., 30 cm).



Figure 23 - Photographs of the resulting gap in sidewalks in different adjacent segment connection points

3.2.6. Tunnel Monitoring System

Despite the effectiveness of the solutions adopted, new damages on the concrete lining corresponding to segments from the number 26 to the number 29 (numeration starting from the eastern entrance, Ampezzo side) reappeared shortly after reopening the road to traffic (Figure 24).

This highlighted the possibility that the sliding surface of the Passo della Morte landslide intersects the infrastructure structure within these damaged segments (Tedesco et al. 2020) (Figure 25). For this reason, starting in 2014, a dedicated monitoring system was also installed inside the tunnel, alongside the existing slope-scale one, to document the temporal evolution of cracks in the most damaged segments. This system is composed of 24 crackmeters and 4 bi-axial clinometers (Figure 26). The crackmeter used is a standard resistive bar displacement transducer made of stainless steel, operating from -20°C to $+80^{\circ}\text{C}$. The bi-axial clinometer, on the other hand, is made of aluminum with a resolution of $0,001^{\circ}$, operating from -20°C to $+60^{\circ}\text{C}$ and measuring the tilting along the tunnel axis and cross section. The measurement data of these instruments are collected in real time via the optical fibers connected to them, and stored on a web-based platform, making them immediately accessible (Festi et al. 2023).

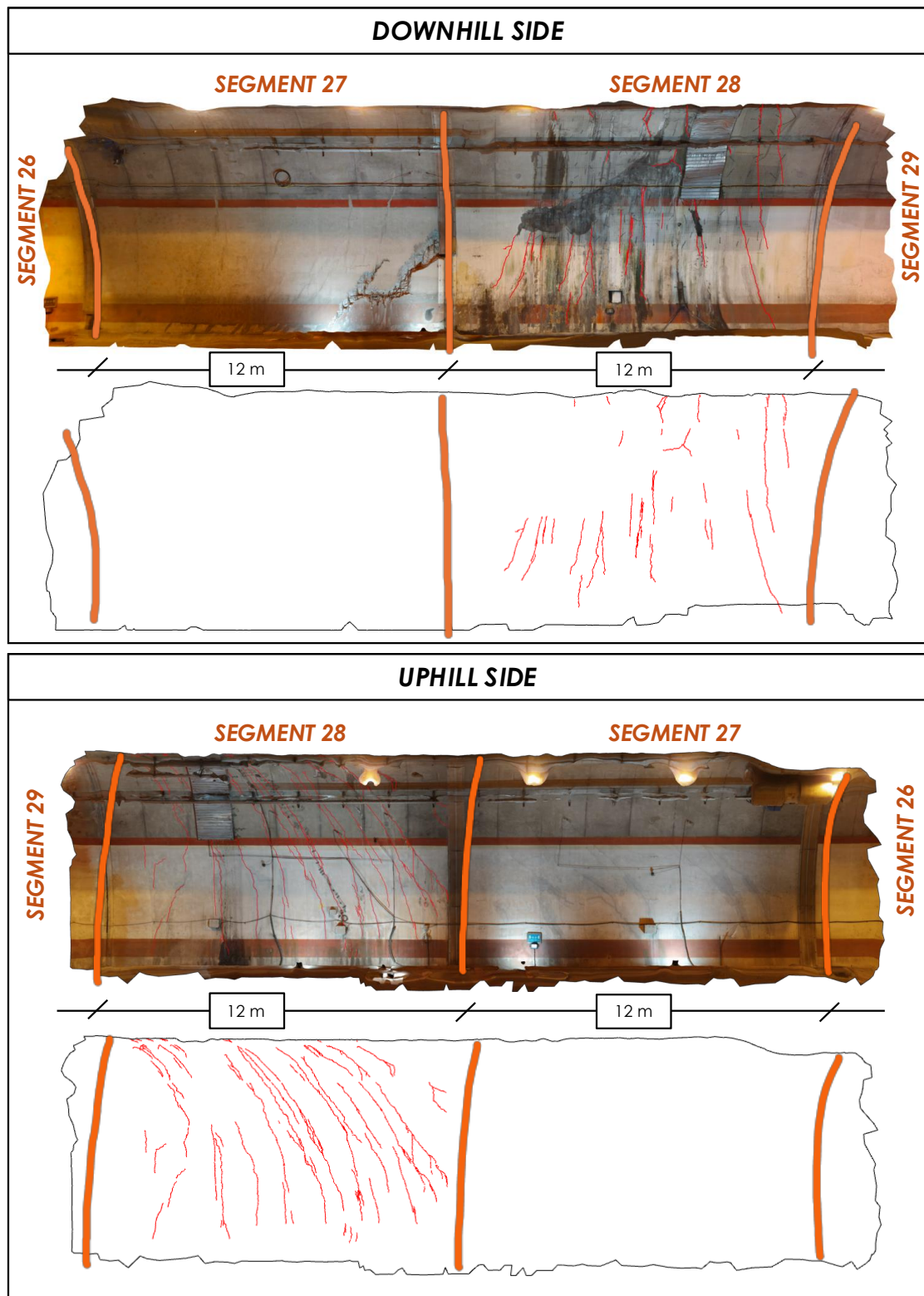


Figure 24 - Concrete crack pattern appeared after reopening to traffic in 2008; photos taken in late 2018

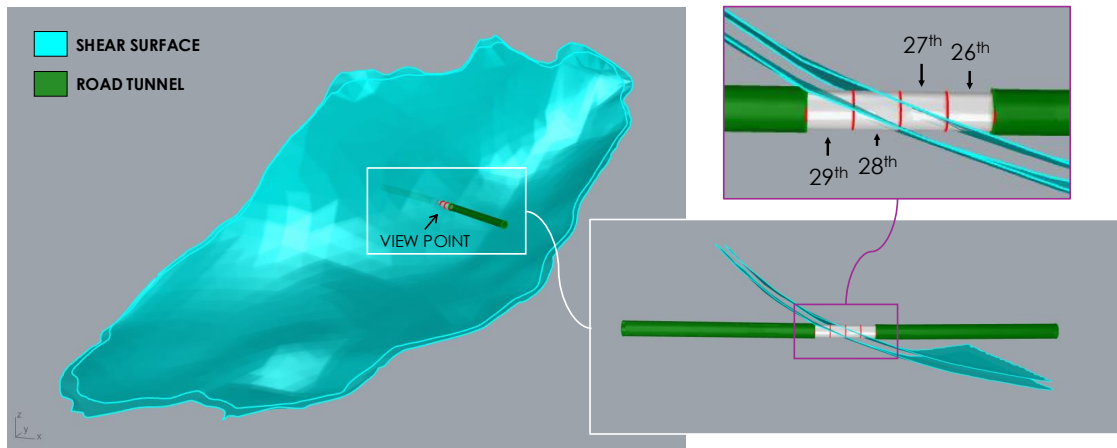
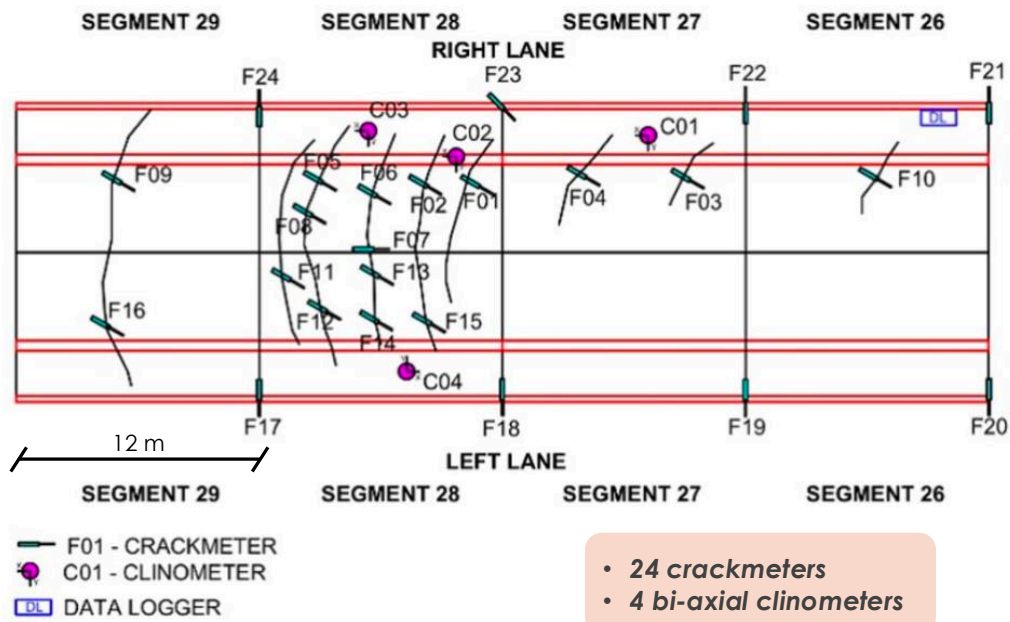


Figure 25 - San Lorenzo road tunnel positioning, with details on the shear surface segments crossing



CRACKMETER F23



CLINOMETER C03

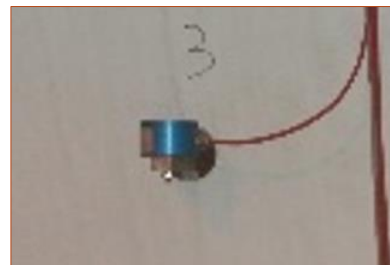


Figure 26 - Overview of the San Lorenzo infrastructure-scale monitoring system

4. Numerical modelling of the Passo della Morte LIS

4.1. Application of the multi-scale approach

The parallel operation of landslide-scale and infrastructure-scale monitoring systems provides opportunities for multi-scale framework validation while highlighting the integration challenges that motivate this research. On the one hand the landslide monitoring system operates at spatial scales of hundreds of meters, on the other hand tunnel monitoring focuses on millimeter-scale crack propagation within specific structural elements.

Current analysis approaches treat these monitoring datasets separately, limiting understanding of the quantitative relationships between slope processes and infrastructure response. The multi-scale approach developed in this thesis specifically aims to bridge this gap by establishing numerical frameworks that can integrate information across these disparate scales and measurement types.

The comprehensive characterization and monitoring data available from the Passo della Morte case study provides the foundation for implementing and validating the multi-scale approach. Recalling the essential criteria to be satisfied by the selected site:

- Passo della Morte landslide, which directly affected the San Lorenzo tunnel, proved to be a large and active landslide, and was properly characterized using various techniques and tools
- San Lorenzo road tunnel shows clear signs of damage accumulated since its construction, including lining cracks corresponding to the location of the expected landslide sliding surface position, evidence of the interaction between the tunnel and the landslide
- Geological, geomechanical, and monitoring data was collected over a significant period at both the slope-scale and tunnel-scale monitoring systems

Effective multi-scale modelling demands systematic integration of models operating at different spatial scales through purposefully designed data transfer procedures, utilizing advanced numerical tools while maintaining computational efficiency and physical accuracy. Based on the case study characteristics and the challenges identified in the state-of-the-art review, the following general workflow has been designed to obtain an effective multi-scale framework:

1. Comprehensive understanding of the site
2. Identification of the most suited modelling technique
3. Large-scale model definition and objectives
4. Data transfer procedure development
5. Small-scale model definition and objectives

4.1.1. *Identification of the most suited modelling technique*

The selection of appropriate numerical modelling tools represents a critical aspect for the multi-scale approach to succeed. In order to establish which numerical model suits better the case study under consideration, both the ultimate objective of the modelling activity and the type of data available need to be decided (Donati et al. 2017). The goal of this work was to study within the multi-scale framework both a large landslide with a heterogeneous composition, and a damaged road tunnel, with a localized crack pattern, to validate the proposed multi-scale framework.

After comprehensive evaluation of available options (Stead and Coggan 2012), considering case study characteristics and modelling requirements, FLAC3D and 3DEC software packages were selected for large-scale and small-scale modelling respectively. In this case, the selection of software from the same developer (Itasca Consulting Group Inc.) is expected to provide practical advantages for data transfer procedure development, since both packages offer extensive customization capabilities through the FISH programming language and Python integration essential for implementing the multi-scale data transfer.

FLAC3D selection for landslide modelling was based on the software's FDM implementation, which provides optimal capabilities for modelling large-scale slope behavior while maintaining computational efficiency. The continuum-based approach suits the objective of capturing overall landslide dynamics rather than discrete discontinuity behavior, while the software's extensive constitutive model library enables representation of the complex geological materials encountered at Passo della Morte.

3DEC selection for tunnel modelling leveraged the software's DEM capabilities, essential for modeling independent segments relative movements. The discontinuum approach also enables explicit representation of damage in concrete observed in the San Lorenzo tunnel.

The selection of two different numerical methods constitutes a deliberate methodological enhancement of the multi-scale framework. This approach demonstrates the framework's capability to integrate heterogeneous modelling

paradigms when the physics of the problem at different scales unequivocally requires distinct numerical representations. Such flexibility represents a critical advancement for cases where landslide behavior and structural response cannot be adequately captured within a single modelling approach, thereby broadening the methodology's practical applicability.

4.1.2. *Large-scale model definition and objectives*

The large-scale model must encompass the landslide within its broader geological and geomorphological context, with the primary objectives of realistically reproducing global landslide dynamics and extracting relevant data in the vicinity of the infrastructure. This will enable a precise transfer of the landslide movement and related forces to the infrastructure in the small-scale model, thus triggering the corresponding tunnel structural response. To provide meaningful boundary conditions for the small-scale tunnel model, the large-scale model must balance computational efficiency with sufficient resolution at least locally within the volume of interest.

The model geometry includes the entire Passo della Morte landslide body and extends sufficiently beyond the landslide area to avoid boundary effects, while maintaining computational efficiency. A mesh refinement strategy with spatially variable resolution was adopted, with the finest discretization applied in the tunnel vicinity. This enables an accurate representation of stress and deformation gradients that will be transferred to the small-scale model, while simultaneously optimizing computational resources and ensuring adequate detail where landslide-infrastructure interaction occurs.

Lithological and geomechanical characterization through geological mapping, borehole logging, and geotechnical laboratory testing data provided by CNR-IRPI informed the choice of constitutive models and parameters, accounting for the complex stratigraphic sequence encountered. Particular attention was given to the competence contrast between carbonate and clay-rich units, which is considered to strongly control landslide behavior (Ballaera et al. 2024; Bossi et al. 2017). Large-scale model predictions must be compared with inclinometer displacement data, GNSS surface measurements, and global movement patterns in order to validate the model's performance.

4.1.3. *Data transfer procedure development*

The critical challenge in multi-scale modelling lies in the development of effective and efficient data transfer procedures that enable seamless information exchange between large- and small-scale models minimizing information loss and maintaining physical consistency.

Therefore, variable selection criteria focused on parameters that most effectively represent landslide-induced stress on tunnel infrastructure while being physically meaningful within the small-scale model context. For the Passo della Morte case study, velocity fields and stress tensors have been selected as primary variables. The transfer procedure was necessarily developed as a mix of Python code, FISH scripts, and standard Itasca program commands.

4.1.4. *Small-scale model definition and objectives*

The small-scale model has the objective to investigate the behavior of the infrastructure, in relation to the landslide-induced stress, implementing data from the large-scale model. Thereby, the small-scale model focuses on detailed representation of the San Lorenzo tunnel structure and its immediate geological environment, with the primary objective of simulating infrastructure response to landslide displacement, using data transferred from the large-scale model. This allows significantly finer resolutions to be used in the model, potentially allowing damage and deformation mechanisms observed in the tunnel monitoring data to be replicated.

Structural modelling strategy employed discrete element methods to enable explicit representation of failure mechanisms, joint opening, and potential concrete cracking. Boundary condition implementation utilized data transferred from the large-scale model to impose realistic loading conditions representing landslide-induced deformation, in the attempt of replacing simplified loading assumptions typically used in tunnel analysis. Additionally, the model domain encompasses sufficient surrounding rock mass to accommodate stress redistribution while maintaining focus on infrastructure behavior.

Damage mechanism simulation focused on reproducing structural deformation and deterioration observed on the tunnel lining surface and with monitoring data, enabling validation of the multi-scale approach through direct comparison with field observations.

The multi-scale workflow presented establishes the methodological framework that will be detailed in subsequent sections. The approach recognizes that effective integration of models operating at disparate spatial scales requires careful attention to data transfer protocols, boundary condition implementation, and validation procedures that ensure physical consistency across scale transitions. Through this systematic process, the research will demonstrate that the multi-scale challenge in landslide-infrastructure interaction can be effectively addressed through carefully designed numerical modelling strategies that maintain both computational efficiency and physical accuracy while achieving comprehensive understanding of these complex systems.

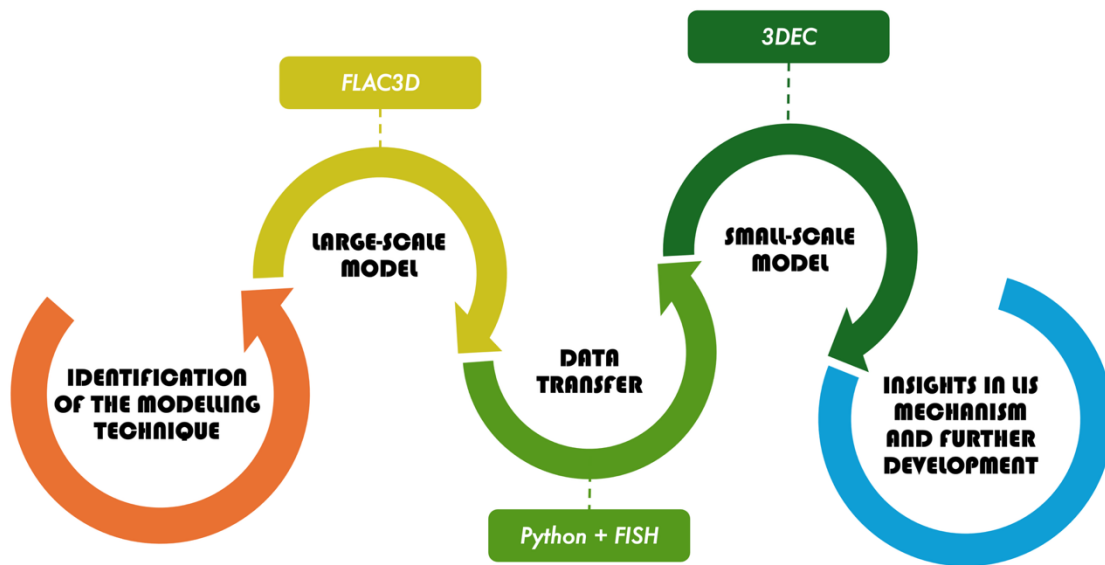


Figure 27 - Multi-scale framework applied to the Passo della Morte case study

4.2. Landslide-scale model

Successful large-scale landslide modelling demands comprehensive geological characterization, robust integration of monitoring data for model calibration and validation, selection of appropriate numerical methods for investigating the physical processes of interest, and attention to boundary conditions and their influence on model behavior. The multi-scale approach applied to the Passo della Morte case study specifically addresses these challenges through systematic integration of geological mapping, field data, geotechnical testing, and extensive monitoring records within a structured numerical framework.

The modelling workflow presented in this section exploits the geological and geotechnical characterization of Passo della Morte to develop a quantitative numerical representation capable of reproducing observed landslide behavior and providing reliable input for tunnel-scale analysis. The section follows a logical progression from geological reconstruction through model validation:

1. *Data collection*: gathering relevant information from field and monitoring data, and previous interpretations.
2. *General model construction*: definition of the shear surface, followed by topographic model development, incorporating all relevant geological elements (faults, dolomitic pillars, and lithological boundaries).
3. *Mesh discretization and meshing*: implementation of intelligent mesh sizing strategies that balance computational efficiency with resolution requirements.

4. *Continuum modelling*: appropriate material property assignment based on geology and global assumptions, and related rationale (groundwater, shear surface, geomorphological features).
5. *Comparison of the results with monitoring data and previous analyses*: comprehensive comparison of model predictions with available monitoring data (GNSS measurements, inclinometric data) and observed landslide displacement distribution, to establish model reliability.
6. *Data extraction for multi-scale transfer*: systematic extraction of selected information (stress conditions and velocity fields) in the tunnel vicinity, defining the spatial domain and data format requirements for subsequent tunnel-scale analysis.

4.2.1. Data collection

Slope instability is linked to a change in stress-strain behavior in a volume that crosses different regions, i.e., shear surfaces or zones (Nitzsche and Herle 2020). To infer the location and geometry of a shear zone, borehole-based geotechnical tools such as inclinometers are conventionally used, since they can determine subsurface displacement magnitude, rate, and direction (Stark and Choi 2008; Wang et al. 2023). Within the slope-scale monitoring system deployed at Passo della Morte, inclinometric surveys were carried out over the years of investigation, identifying both the depth and the thickness of the shear zone within the Passo della Morte landslide body (see Figure 19). To properly reconstruct the landslide shear surface, thirteen points have been either selected from the mentioned boreholes dataset or recovered from the engineering–geological cross-section (see Figure 21). To improve constraint on the shear zone reconstruction, the perimeter of the landslide was considered by integrating both evidence from the literature (Ballaera et al. 2024) and morphological elements of the area that clearly indicate the boundaries of the landslide body (i.e., Rio Verde stream valley). Eventually, the data reported in Table 1 have been used.

Table 1 - Points for the shear surface reconstruction where: B=Borehole, DES=Digitalized Engineering-Geological Section, DLP=Digitalized Landslide Perimeter

ID	X	Y	Z	Source
1	2343960	5140460	644	B
2	2343890	5140470	623	DES
3	2343780	5140440	611	I-23
4	2343800	5140300	582	I-24
5	2343960	5140590	660	DES
6	2343760	5140670	684	B
7	2344130	5140510	661	B
8	2344010	5140750	683	DES

ID	X	Y	Z	Source
9	2344010	5140780	703	DES
10	2344040	5140900	734	DES
11	2344060	5140980	754	DES
12	2344030	5141010	789	DES
13	2344000	5141050	838	DES
14	2344147	5141341	960	DLP
15	2344184	5141326	947	DLP
16	2344207	5141311	939	DLP

ID	X	Y	Z	Source
17	2344236	5141268	925	DLP
18	2344268	5141224	907	DLP
19	2344286	5141171	886	DLP
20	2344302	5141120	870	DLP
21	2344309	5141060	847	DLP
22	2344305	5141015	838	DLP
23	2344306	5140980	830	DLP
24	2344304	5140950	824	DLP
25	2344300	5140919	813	DLP
26	2344301	5140888	801	DLP
27	2344287	5140851	784	DLP
28	2344287	5140824	773	DLP
29	2344297	5140791	760	DLP
30	2344307	5140740	749	DLP
31	2344296	5140673	734	DLP
32	2344286	5140625	711	DLP
33	2344289	5140579	700	DLP
34	2344254	5140514	681	DLP
35	2344233	5140478	668	DLP
36	2344203	5140435	666	DLP
37	2344121	5140391	637	DLP
38	2344100	5140360	627	DLP
39	2344069	5140331	628	DLP
40	2343995	5140278	619	DLP
41	2343967	5140244	593	DLP
42	2343936	5140205	580	DLP
43	2343894	5140195	588	DLP
44	2343829	5140225	589	DLP
45	2343782	5140276	582	DLP
46	2343738	5140298	582	DLP
47	2343694	5140329	584	DLP
48	2343641	5140388	584	DLP
49	2343620	5140417	585	DLP
50	2343613	5140482	588	DLP
51	2343618	5140532	598	DLP
52	2343633	5140561	618	DLP
53	2343642	5140608	644	DLP

ID	X	Y	Z	Source
54	2343635	5140635	655	DLP
55	2343669	5140713	694	DLP
56	2343734	5140787	768	DLP
57	2343770	5140807	828	DLP
58	2343807	5140838	872	DLP
59	2343709	5140756	731	DLP
60	2343844	5140875	898	DLP
61	2343940	5141057	1004	DLP
62	2343934	5141045	993	DLP
63	2343926	5141025	962	DLP
64	2343967	5141127	1106	DLP
65	2343948	5141091	1075	DLP
66	2344005	5141183	1123	DLP
67	2343950	5141089	1064	DLP
68	2344039	5141231	1126	DLP
69	2343897	5140979	943	DLP
70	2343906	5140973	883	DLP
71	2343940	5141069	1043	DLP
72	2344017	5141199	1121	DLP
73	2344035	5141226	1128	DLP
74	2344000	5141171	1106	DLP
75	2343941	5141065	1024	DLP
76	2343964	5141114	1079	DLP
77	2343961	5141115	1096	DLP
78	2343928	5141027	962	DLP
79	2343911	5141001	952	DLP
80	2343985	5141150	1105	DLP
81	2344087	5141287	1098	DLP
82	2344126	5141305	987	DLP
83	2344056	5141260	1145	DLP
84	2344097	5141290	1060	DLP
85	2344075	5141286	1146	DLP
86	2344120	5141302	1000	DLP
87	2344096	5141292	1075	DLP
88	2344168	5140412	680	DLP
89	2344135	5140391	663	DLP
90	2344135	5140391	663	DLP

Material parameters derived from geotechnical tests and boreholes logging analyses presented in the work of Tedesco (2018) were used for the landslide-scale model, and the corresponding values are reported in Table 2.

Table 2 - Material properties for the landslide-scale model

	<i>Density (kg/m³)</i>	<i>Young modulus (GPa)</i>	<i>Poisson coefficient</i>	<i>Internal friction angle (°)</i>	<i>Cohesion (kPa)</i>	<i>Constitutive model</i>
Stable	2600	30	0.2	-	-	Elastic
Clay	2500	3	0.3	39	660	Mohr – Coulomb (elastic – perfectly plastic)
Dolomite	2500	7.7	0.25	46	990	
Shear zone	2500	0.7	0.35	14	100	

4.2.2. General model construction

A 1-m LiDAR dataset, provided by Friuli-Venezia Giulia region, was sampled to create a 3D point cloud, which was interpolated in CloudCompare (CloudCompare 2021), an open-source software application for processing and analyzing 3D point clouds and triangular meshes. The surface was reconstructed using a Poisson surface reconstruction approach, which allows the reconstruction of a surface to be expressed as a solution of a Poisson equation (Kazhdan et al. 2006), to turn the point cloud into vector data. The obtained surface was then imported into Rhinoceros3D (Robert McNeel & Associates 2020), a computer-aided design platform widely employed in engineering applications for 3D processing.

For the geometric refinement, Griddle 2 plugin (Itasca Consulting Group, Inc. 2020) was used. Griddle generates conforming tetrahedral meshes compatible with Itasca 3D numerical modelling software such as 3DEC and FLAC3D. The model domain was defined by a bounding box approximately 3 km × 2 km × 2 km, that comprised the landslide body and sufficient surrounding material on the sides and below the landslide to minimize boundary effects.

The first feature to be implemented in the Rhino model was the shear zone. Starting from the collected field measurements and observations (details of the location of the points are reported in Table 1), the entire basal surface of the shear zone was reconstructed using Poisson surface reconstruction algorithms (i.e., PoissonRecon command) within CloudCompare.

Following import into Rhino, the basal slip surface was duplicated with a 6-meter uniform upward offset, creating a three-dimensional representation of the shear zone (Figure 28).

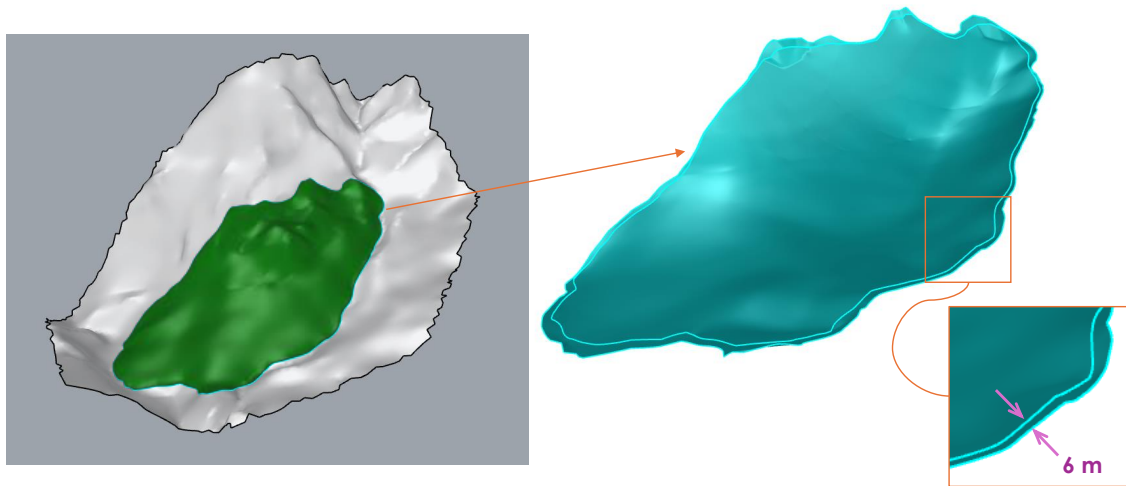


Figure 28 - Surfaces bounding the shear zone, showing the duplication and offset of the surface to create the 3D volume of the shear zone

This approach reflects inclinometric evidence indicating that displacement occurs within a zone of sheared and damaged material rather than along a discrete surface. The thickness of the shear zone volume may vary substantially, ranging from very thin layers, that can be approximated as a surface, to several meters, resulting in a deformation zone. Individual measurements show spatial variability in shear zone thickness, ranging from approximately 3 to 25 m across measurement locations, with thickness values decreasing as reaching the landslide toe. Considering the spatial uncertainty related to the shear surface data and the model's focus on tunnel-landslide interaction rather than detailed failure surface characterization, a uniform 6-meter thickness was therefore adopted. This value represents a conservative estimate within the measured shear zone thickness range while providing adequate numerical resolution. In fact, in this way the selected thickness ensures that the intersection with tunnel segment 28 occurs within a single 12-meter tunnel segment itself. The resulting shear zone was then integrated with the topographic surface to define the 3D geometry of the landslide body.

4.2.3. Geological model construction and refinement

Following initial geometric reconstruction, additional geological features were incorporated, and mesh refinement was applied to prepare the model for FLAC3D import. The complex stratigraphic sequence described in the Passo della Morte chapter was simplified into two primary lithological units: dolomite and clay-rich formations (referred to as clay in Table 2). This simplification reflects both units' abundance and mechanical significance in controlling landslide behavior, as these lithologies exhibit the critical competence contrast responsible for shear zone development and thus evolution of Passo della Morte landslide (Marcato 2007).

As detailed in the previous chapter of this work, a regional thrust structure controls the contact between dolomite and clay-rich units. To represent this tectonic contact and maintain lithological distinction in the numerical model, a segmented surface was digitized and implemented from the geological cross-section and related indications included in Marcato (2007) and Ballaera et al. (2024) [see Figure 20].

Following the definition of this lithological contact in the Rhino model, the dolomite unit was internally subdivided using a rectilinear grid to geometrically represent the characteristic fracture patterns. Such fracture network was included in the geometry to ready the model for future analyses, but it was not activated within this work, thus maintaining the dolomite behaves as a single, competent block. This simplification reflects scale-dependent prioritization inherent to the multi-scale approach: the landslide model's primary objective is capturing bulk deformation and stress distribution patterns in the surrounding of the tunnel, rather than detailed discontinuity mechanics. This decision enables satisfactory reproduction of overall kinematic behavior, meaning agreement with landslide monitoring and distribution of damage in the tunnel, while maintaining computational efficiency (Figure 29).

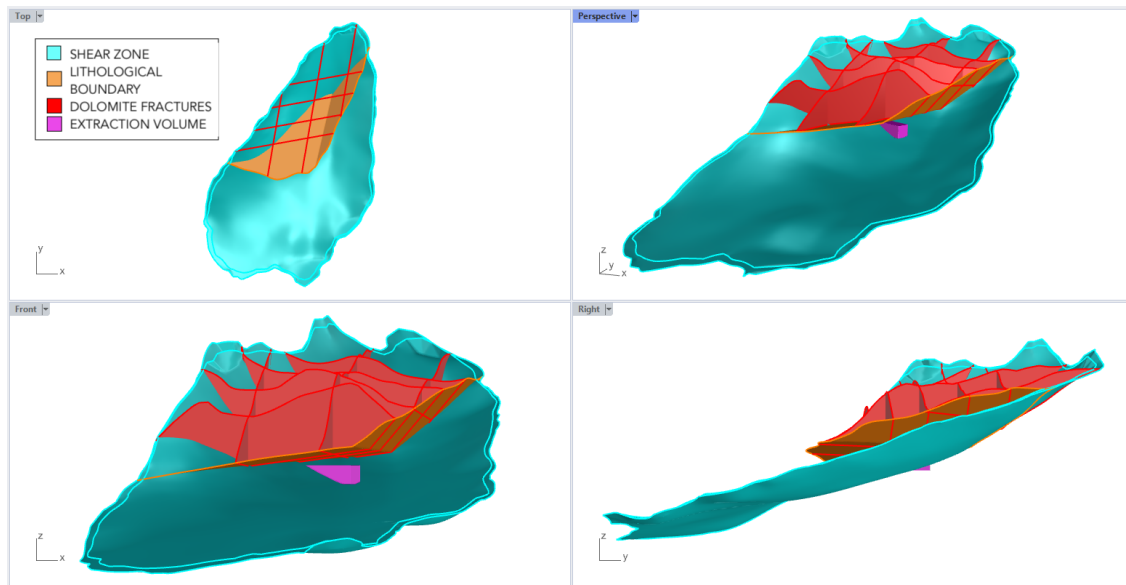


Figure 29 - Passo della Morte landslide model relevant geological features; dolomite fractures are not activated within this work

4.2.4. Mesh discretization and meshing

To optimize computational efficiency while maintaining adequate resolution in regions of interest, variable mesh refinement strategies were implemented. This approach concentrates numerical resources on the landslide body and tunnel vicinity while employing coarser discretization in peripheral regions. These multiple mesh refinement stages were applied progressively. The initial refinement targeted the topographic

surface, manually subdividing the domain into a central region, centered on the landslide body, and a peripheral region extending towards the boundaries of the model. Within the central region, tetrahedral element size was fixed at 15 m, while in the peripheral domain, element size was allowed to vary freely, generating progressively coarser mesh away from the region of interest. This strategy reduced computational burden while preserving resolution where deformation was anticipated (Figure 30).

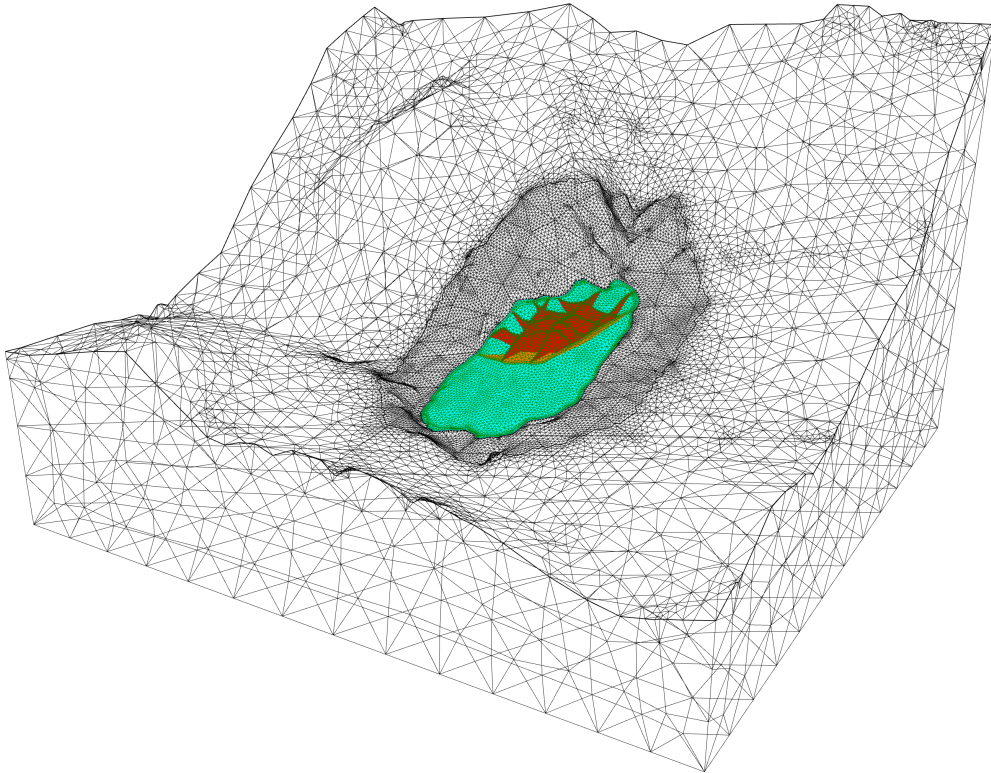


Figure 30 - Passo della Morte model geometry after importing and group definition

Additional refinement was applied to the surfaces defining the shear zone, where element size was reduced to 3 m to enhance representation of deformation gradients. The finest discretization was implemented within a 108 m × 30 m × 30 m volume, corresponding to the tunnel portion intersecting the shear zone, where element size was further reduced to 0.5 m. This volume encompasses exactly nine 12-meter tunnel segments, with segment number 28, i.e., the most severely damaged, located at its center. This refinement strategy was specifically designed for multi-scale transfer: finer discretization directly facilitates geometry matching between the large-scale and small-scale models and increases data resolution for boundary condition specification in the small-scale model.

At this stage of the modelling process, the road tunnel itself was not included. This choice was made because the landslide simulation was intended to reproduce the conditions prior to tunnel excavation, so that the tunnel could be introduced directly

into the small-scale model. The exclusion of the tunnel reinforces two concepts already outlined: first, the multi-scale approach inherently involves careful optimization to achieve the desired level of characterization of the tunnel–landslide interaction; second, the aim of the landslide-scale model was explicitly a coherent reproduction of slope instability phenomenon global kinematic behavior.

Furthermore, geomorphological evidence and previous studies indicate that Passo della Morte landslide was already active prior to tunnel construction, as evidenced by its classification as a reactivation of the larger DsGSD.

4.2.5. Continuum modelling

Following mesh refinement, the final discretization, comprising approximately 9.7 million zones and 1.6 million gridpoints, was exported from Rhino and imported into FLAC3D for the assignment of boundary conditions and mechanical parameters and the execution of numerical simulations. The mesh design strategy, supported by the use of the Griddle plug-in, streamlined this process by enabling a precise and structured mesh construction, thereby eliminating the need for geometry configuration within FLAC3D and significantly reducing the overall modelling effort. Thus, as the Rhino final mesh was imported into FLAC3D, the relative model domain was divided into the different units useful for modelling purposes, mirroring the subdivision carried out in Rhino: dolomite, clay, shear zone, and the area external to the landslide body, i.e., the so-called stable zone, as it has been constrained to be fixed in order to focus the modeling on the landslide movement (Figure 31).

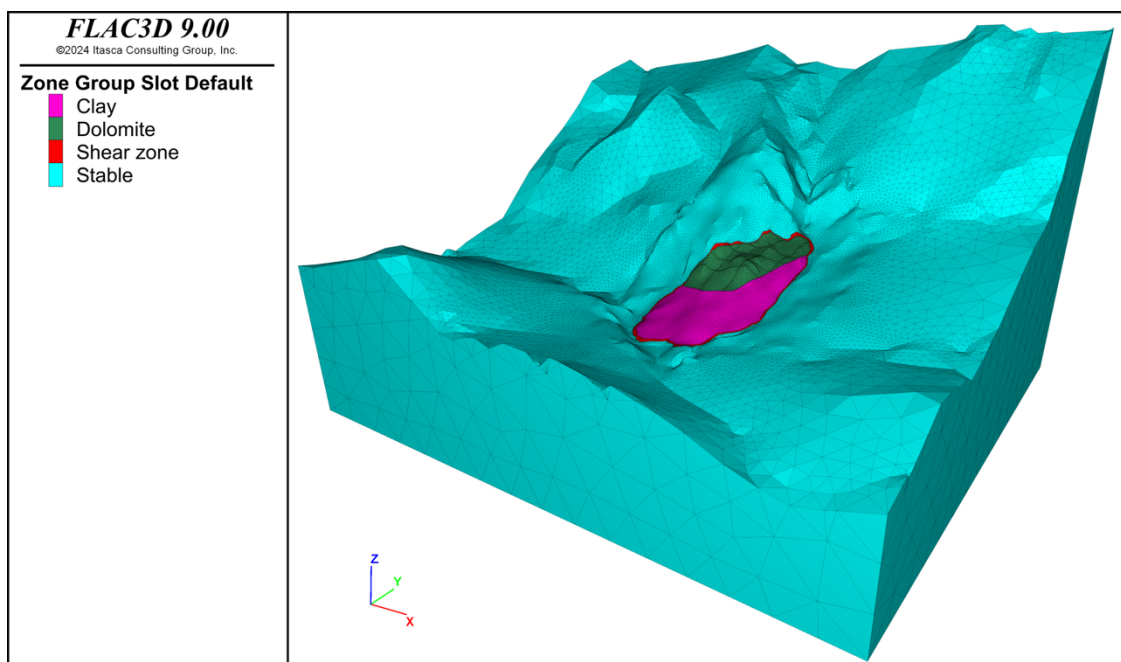


Figure 31 - Passo della Morte landslide FLAC3D model group definition

FLAC3D, like many other numerical modelling codes, requires a series of steps to correctly frame and define the imported geometric mesh and proceed with the simulations. The first of these steps was therefore to select and assign the appropriate constitutive model to all the newly defined units, thus physically and mechanically characterizing all volumes of the model. The Mohr-Coulomb model was assigned to dolomite, clay, and shear zone units, while the stable zone was modeled as a fully elastic medium. This configuration ensures deformability within the landslide domain while constraining unnecessary plastic deformation in peripheral regions.

The Mohr-Coulomb model was deemed appropriate for this purpose, given its simplicity of implementation, the limited number of required parameters, and the level of detail adopted in the large-scale model. As an elastic–perfectly plastic constitutive model, it provides an effective and physically meaningful representation of the shear failure behavior in landslide analyses, offering a balanced compromise between model simplicity, parameter availability, and the ability to capture the key mechanical processes governing slope instability. The model’s strength lies in combining computational efficiency with a realistic representation of failure mechanisms, especially in modelling large, heterogeneous rock masses where deformation is controlled by shear-dominated processes.

The parameters required by the constitutive models are density, Young’s modulus, Poisson’s ratio for both elastic and plastic models, and internal friction angle, dilation angle, and cohesion only for the Mohr-Coulomb model. Material parameters were derived from laboratory testing reported by Tedesco (2018), except for the dilation angle, for which the default value (i.e., 0.0) was used. These rock sample properties were converted to rock mass equivalents using ORMAS v2.0 (Mikola 2022), an online tool implementing established rock mass classification systems to account for discontinuities, weathering, and scale effects. Table 2 presents the material properties assigned to each unit in the FLAC3D model.

The seemingly low values assigned to the materials are representative of the fracturing state of the dolomite, as well as the poor mechanical quality and low durability of the clayey materials (Tedesco 2018). In the absence of direct sample data, the shear zone unit was characterized by applying a generalized reduction of key mechanical parameters, aimed at representing a realistic material degradation capable of triggering the observed landslide movements and deformations. The values of deformation modulus, cohesion and internal friction angle adopted as input for ORMAS v2.0 to characterize the shear zone were selected based on literature references for poor-quality rocks (Hoek and Brown 1997). The resulting parameters are reported in Table 2. The effects of this choice were almost immediately visible from the start of the simulation process.

To minimize boundary effects on landslide deformation, a high stiffness value was assigned to the stable zone. Such an approach is widely employed in numerical modelling of instability phenomena, especially in slope stability analyses, where the peripheral rock mass is assumed not to be affected by the investigated instability.

Boundary conditions were then assigned to the model. Zero-velocity conditions were prescribed on the basal boundary and all four lateral boundaries, preventing translation while permitting stress redistribution. The upper boundary (topographic surface) remained free to deform. A gravitational acceleration of 9.81 m/s^2 was applied before automatically computing in-situ stress conditions, based on the actual topographic surface.

Once this setup was completed, the model was run to equilibrium, preventing failure during this procedure by considering all materials in the model as elastic. Hence, FLAC3D's '*elastic only*' solve criterion was employed, which enforces purely elastic constitutive behavior across all zones. The model was executed until static equilibrium was achieved, defined as the state where residual forces fall below convergence thresholds and no further deformation occurs. This condition represents the pre-failure stress state prior to shear zone weakening. Starting from this condition, the next phase of the modelling structure addressed the initiation of the landslide displacement. This was achieved by assigning plastic (i.e., Mohr-Coulomb) parameters to the landslide and the shear zone volume and, for the latter, further reducing the internal friction angle and cohesion (as shown in Table 2). This allowed plastic deformations to form and initiate landslide displacement.

Following the attainment of elastic equilibrium, landslide initiation was simulated through progressive plasticity: rather than solving to full convergence, a sequential cycling procedure was implemented to capture intermediate deformation states. This approach was not intended to reach the final equilibrium condition (i.e., when the landslide becomes stable), but rather to identify a deformation-rate distribution representative of a realistic stage of instability corresponding to the actual landslide conditions. Progressive running of the model allows the observation of displacement rates and stress redistribution at different stages of landslide evolution, thereby enabling the identification of the stage characterized by the highest degree of progressive deformation. Accordingly, the model state was saved after 3000, 6000 (additional 3000), and 10000 cycles (additional 4000), prior to final convergence. These cycle increments were selected taking as a rough reference the elastic run, which converged after 1287 cycles.

The first save state at 3000 cycles (approximately twice the elastic convergence time) was assumed to capture early plastic deformation, while subsequent saved states documented progressive evolution toward equilibrium. Comparison of displacement

and velocity distributions among the three intermediate states (Figure 32) indicated that the model after 3000 cycles exhibited the most pronounced deformation gradients and was therefore selected as the most representative state for data extraction.

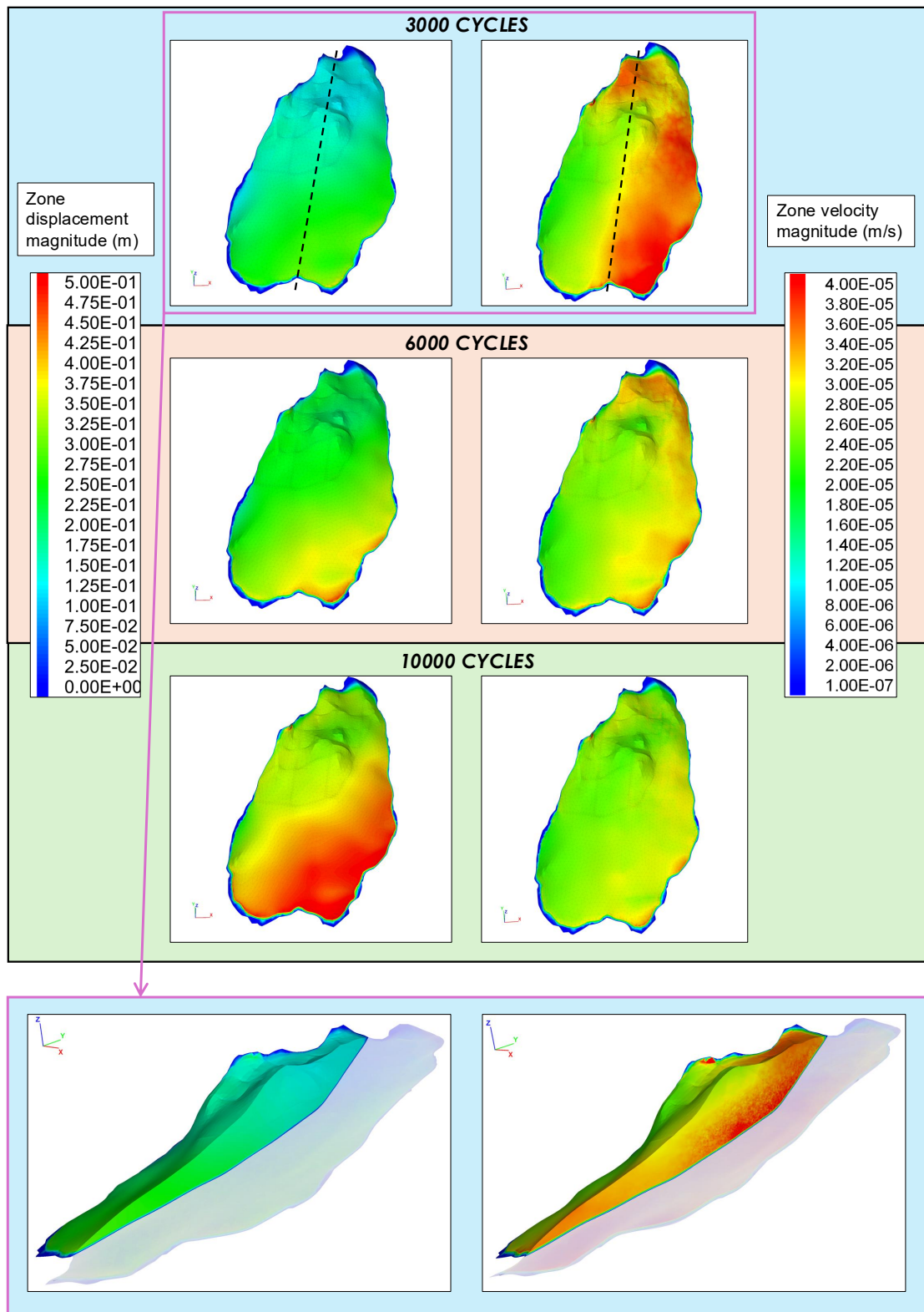


Figure 32 - Comparison between displacement and velocity distributions of each sequential step, namely 3000, 6000, and 10000 cycles after equilibrium

Although displacement rates in this type of numerical modelling environment are governed by numerical time-step convergence rather than physical time, this condition effectively captures active stress redistribution during the early stages of landslide movement, providing boundary conditions representative of landslide-induced loading on the infrastructure.

4.2.6. *Comparison of the results with monitoring data and previous analyses*

Model results were compared with and validated against previous numerical modelling work (Tedesco 2018) and selected monitoring data. To enable comparison with real GNSS monitoring data, history points were implemented within the numerical model at the exact coordinates of GNSS stations GNSS2 and GNSS4, thus creating a surface virtual monitoring system. These stations were selected as representative of the upper (dolomitic) and lower (clay-rich) landslide domains, respectively. Model predictions reproduce the observed displacement pattern: GNSS2 (upper landslide portion) exhibits lower displacement magnitude than GNSS4 (lower landslide portion), confirming the displacement spatial gradient evident in field measurements (Figure 33).

This configuration is consistent with the classification of the landslide as a rock-block slide, where the dolomite unit overlies weaker clay formations that accommodate most of the displacement. The observed displacement gradient reflects fundamental mechanical behavior: although extensively fractured, the dolomitic rock mass maintains higher strength than underlying clay units, which yield progressively under gravitational loading.

In the same context, the inclinometer I-16 was also simulated within the landslide-scale model. The real inclinometer actively collected displacement data between 2012 and 2024 in correspondence of the shear zone, whereas the inclinometer simulated in FLAC3D recorded displacements at the end of the 3000 cycles run, corresponding to the stage of peak plastic deformation. Comparison between the monitored and simulated inclinometers shows good agreement in both displacement magnitude and direction, thereby providing additional validation of the Passo della Morte landslide model (Figure 34).

Qualitative comparison with Tedesco's model (Figure 35) further demonstrates consistent spatial distribution of displacement magnitudes across the landslide body, despite differences in mesh design, landslide perimeter and material parameterization. This consistency indicates once more that the current model captures fundamental mechanical behavior controlled by geological structure and material properties.

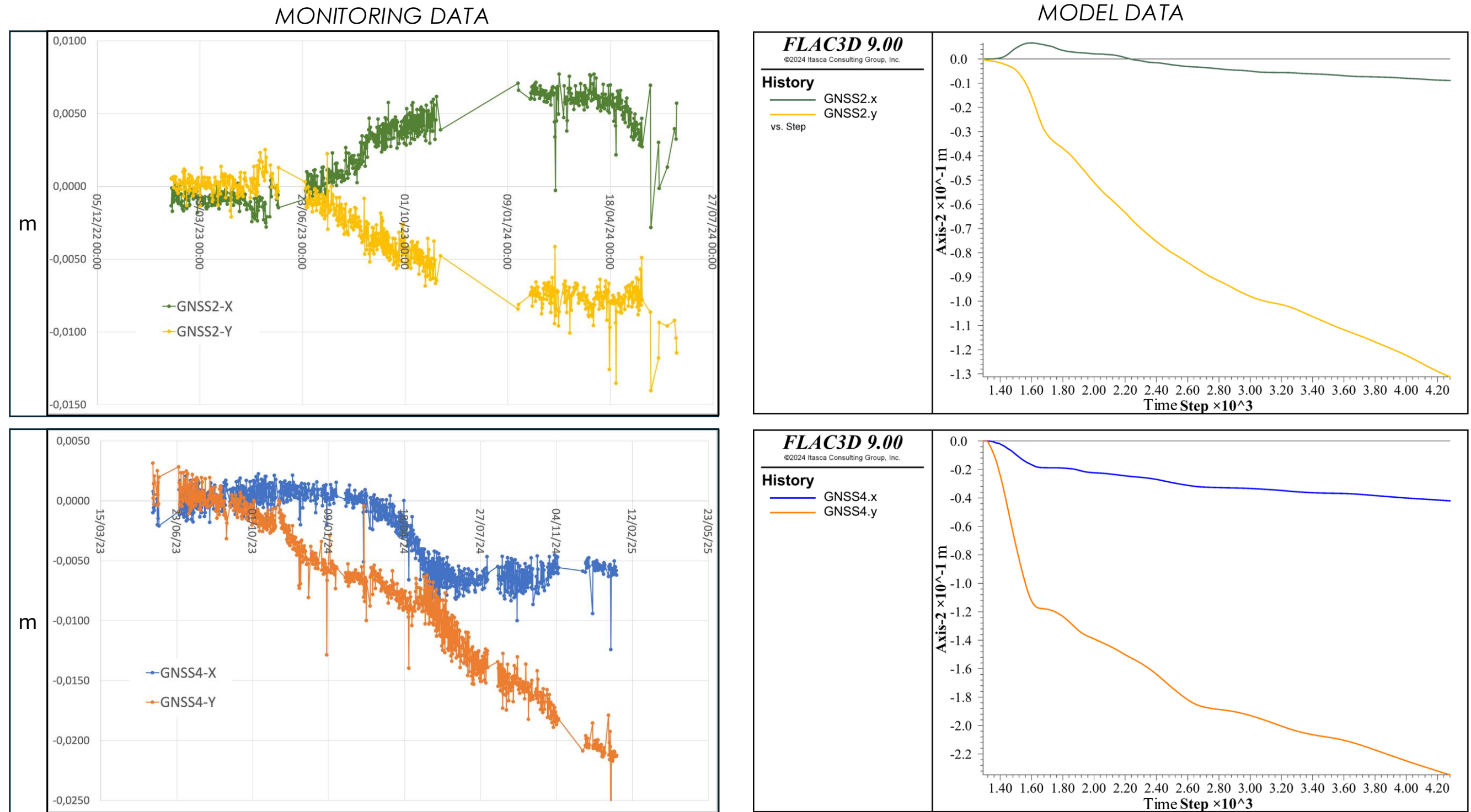


Figure 33 - Comparison between GNSS monitoring data and model outcome: it can be noticed that a good comparison can be made for GNSS4, while for GNSS2 the data show possibly differences related to aleatory component given by superficial movements and to continuum

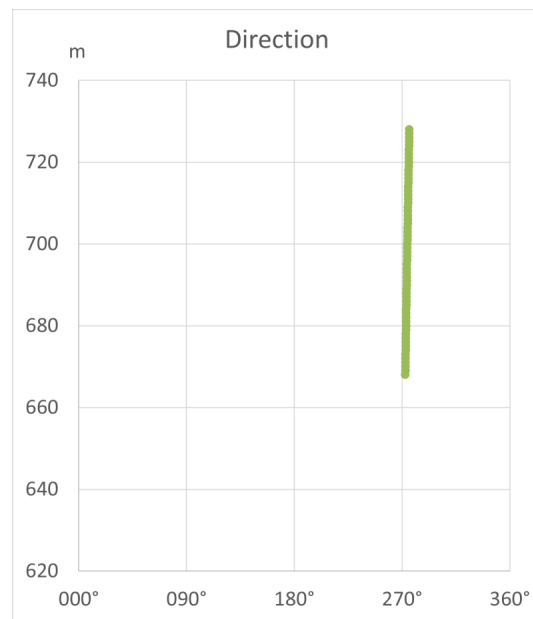
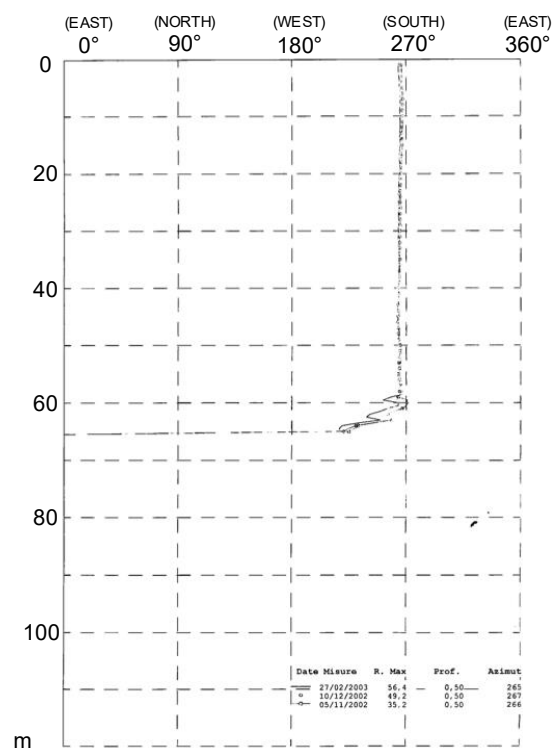
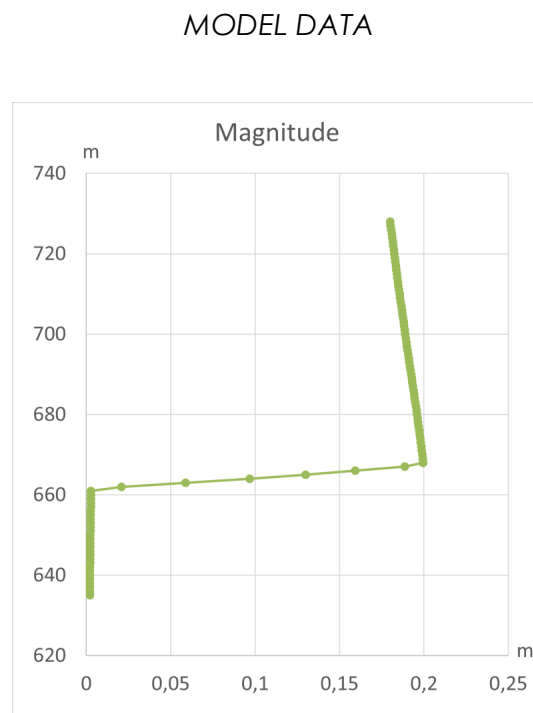
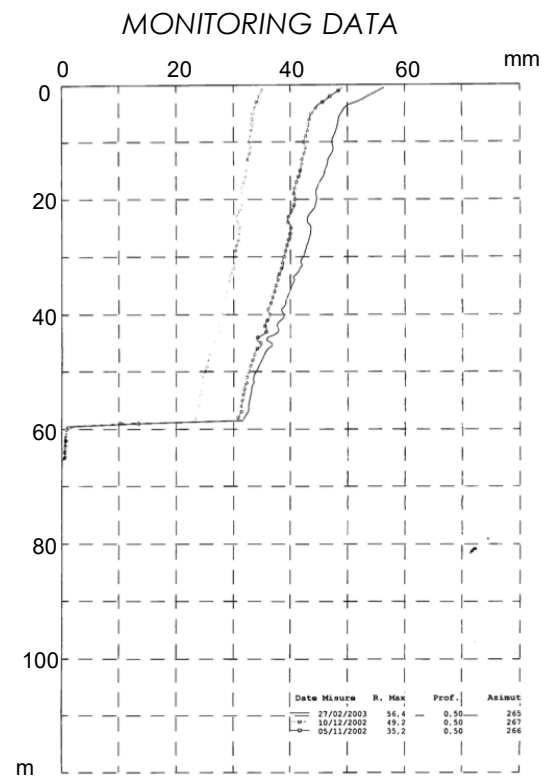


Figure 34 - Comparison between inclinometer I-16 monitoring data and model outcome

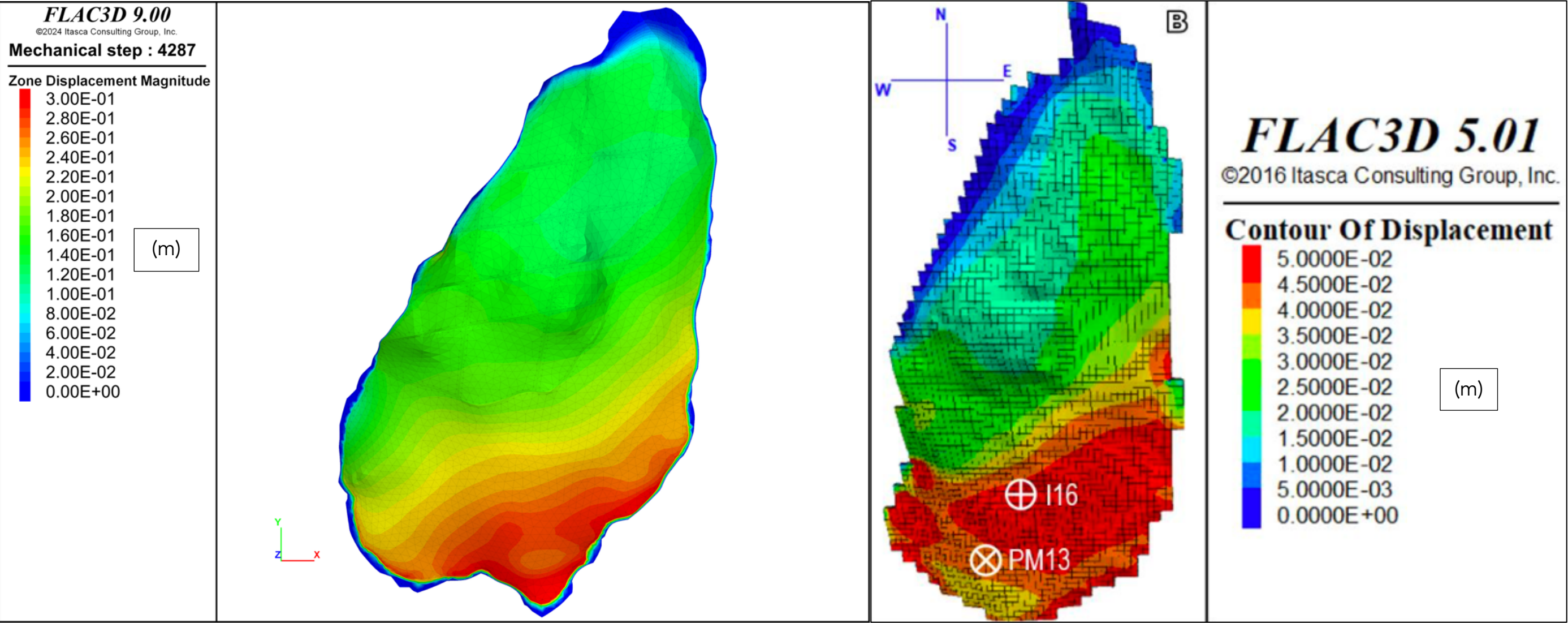


Figure 35 - Comparison between displacements distributions of present work and Tedesco (2018) models

The model successfully reproduces first-order landslide characteristics required for multi-scale analysis: (1) spatial distribution of displacement magnitudes consistent with independent numerical modelling (Tedesco 2018); (2) qualitative agreement with monitored displacement patterns maintaining the observed gradient from upper to lower landslide sectors; and (3) mechanical behavior consistent with rock-block slide classification (Hung et al. 2014).

While more extensive validation would strengthen confidence in model results, in its present form the model adequately captures stress and deformation field patterns required for extracting boundary conditions for tunnel-scale analysis. Primary limitations include uniform shear zone thickness (whereas actual thickness varies spatially), excluded hydrogeology (explicit fracture flow and pore pressure evolution are not presently included explicitly), and elastic-perfectly plastic constitutive behavior. These simplifications may affect temporal evolution patterns and absolute displacement magnitudes but are expected not to compromise the model's utility for extracting representative stress fields for infrastructure-scale analysis

4.3. Multi-scale data transfer procedure

Data transfer between numerical models operating at different scales represents the most critical challenge in multi-scale modelling. The challenge extends beyond simple format conversion and includes fundamental differences in numerical formulation, spatial discretization, and mechanical representation. In this research, the transition from FLAC3D zone-based finite difference approach to 3DEC block-based discrete element method required development of custom procedures to preserve mechanical information while accommodating software-specific constraints. The selected transfer variables, velocity and stress, represent the mechanical state extracted from the landslide model. Velocity fields represent kinematic boundary conditions describing landslide movement patterns, while stress tensors represent the load distribution induced by slope deformation within the model. Together, these variables allow the current state of the investigated volume to be transferred between different models.

The methodology presented demonstrated how careful procedure design can bridge fundamental software incompatibilities while maintaining physical consistency required for reliable multi-scale analysis. This section has been structured as follows:

- *Fundamental requirements for data transfer:* general principles and variables selection rationale.
- *Software architecture and compatibility challenges:* FLAC3D zone-based vs. 3DEC block-based approaches.

- *Data extraction from FLAC3D*: extraction methodology for velocity and stress fields.
- *Data import strategy for 3DEC*: volume specification and data redundancy approach.
- *Stress transfer implementation*: proximity-based assignment using Python scripting.
- *Velocity transfer implementation*: FISH-based surface application strategy.
- *Procedure validation and verification*: completeness and physical consistency checks.
- *Limitations and assumptions*: spatial discretization effects and temporal considerations.

4.3.1. Fundamental requirements for data transfer

Effective data transfer between models operating at different scales needs several fundamental requirements to be satisfied, to ensure both technical feasibility and physical validity of the target model. These requirements emerge from a two-fold objective: first, preserving mechanical information extracted from the source model, and second, conforming to the structural and computational constraints of the target model. Thus, the selection of variables to be transferred represents the first critical decision that determines which aspects of the large-scale mechanical state will influence small-scale behavior.

For landslide-infrastructure interaction, two variable types capable of capturing essential mechanical characteristics can be considered: kinematic fields, describing displacement patterns, and stress fields, representing force distributions. Velocity, in its three components v_x , v_y , v_z , was selected as the primary kinematic variable rather than displacement for several technical and physical reasons.

First, velocity functions as a valid boundary condition, whereas displacement cannot be one. Second, stress boundary conditions, while theoretically applicable, are unsuitable for scenarios involving mass redistribution, such as tunnel excavation. When excavation occurs within a stress-controlled boundary model, the removal of material disrupts stress equilibrium, causing unphysical upward motion of the model domain (Itasca Consulting Group, Inc. 2023). Velocity boundary conditions circumvent this limitation by kinematically constraining the model, effectively transforming the tunnel model into a sort of large-scale direct shear configuration where imposed displacement rates govern mechanical response independently of mass changes. Third, although the velocity magnitudes applied at boundaries do not directly correspond to real displacement rates, since numerical time differs from physical time in the absence of creep

formulations, this limitation aligns with the research objectives. The primary goal is to assess damage distribution patterns and mechanisms rather than to reproduce precise temporal evolution of deformation or accurate landslide displacement rates. Implementation of time-dependent creep constitutive models would enable direct simulation of real time; however, such refinement, while beneficial, is not essential for demonstrating the validity of the multi-scale framework and remains a potential avenue for future methodological enhancement. Finally, FLAC3D computes velocities directly at gridpoints, providing native extraction locations without requiring interpolation, thereby minimizing numerical artifacts during data extraction.

Stress was selected to represent the force state induced by landslide deformation. The complete stress tensor (σ_{xx} , σ_{yy} , σ_{zz} , σ_{xy} , σ_{xz} , σ_{yz}) captures both normal and shear stress components, enabling full specification of the three-dimensional stress state within the volume surrounding the tunnel. This representation preserves directional information critical for assessing tunnel lining response, where stress orientation significantly influences structural loading patterns.

Data transfer procedures must balance precision requirements against computational constraints. Perfect preservation of all mechanical information extracted from the source model would require spatial resolution matching or exceeding the source discretization, potentially creating computationally prohibitive target models. Conversely, excessive simplification may compromise the physical validity of transferred conditions. Computational efficiency considerations necessarily influenced multiple design decisions, including extraction volume sizing, spatial sampling strategies, and velocity application approaches. While computational cost represents a non-negligible constraint, for the Passo della Morte landslide application, precision requirements were established considering the overall validation of the multi-scale approach as the fundamental objective of this work. Therefore, it was decided to focus on reproducing stress distributions and first-order deformation patterns, such as segment-scale deformation patterns and inter-segment joint behavior, rather than predicting crack propagation at millimeter scales. As it will be discussed in the following, this decision permitted reasonable approximations in the transfer procedure while maintaining sufficient accuracy for infrastructure-scale analysis.

Throughout procedure development, data integrity preservation remained the paramount concern. Data integrity encompasses multiple aspects: completeness (all regions of the target model receive boundary conditions), consistency (transferred values maintain physical relationships present in the source model), and accuracy (numerical values are not corrupted during transfer operations). To ensure data integrity, the procedure incorporated several verification stages, including redundancy strategies to prevent data loss, proximity-based mapping algorithms to maintain spatial

relationships, and validation procedures to confirm that transferred fields reproduce the expected mechanical state.

4.3.2. *Software architecture and compatibility challenges*

The fundamental challenge in transferring data between FLAC3D and 3DEC stems from their divergent numerical formulations and spatial discretization strategies. Understanding these differences was essential for developing transfer procedures that preserve mechanical information while conforming to each software's structural requirements.

FLAC3D employs the finite difference method, discretizing the computational domain into contiguous polyhedral zones. The software solves equations of motion at gridpoints (vertices of zones), while computing stresses within zone volumes. This zone-based structure treats material as a continuum, with deformation occurring through gradual strain accumulation within zones according to assigned constitutive models (Itasca Consulting Group Inc., 2023). In this framework, velocities are primary variables computed at gridpoints, while stresses are secondary variables computed and stored at zone centroids. This computational structure makes gridpoints the natural extraction location for velocities, while zone centroids provide the reference for stress extraction. The zone-based continuum approach excels at representing large-scale deformation of homogeneous geological materials where discontinuities can be implicitly accounted for by choosing appropriate equivalent continuum properties. For the landslide model, this representation was deemed to be suitable given the scale of analysis and the focus on deformation patterns rather than discrete fracture mechanics.

3DEC employs the discrete element method, which allows the model domain to be represented as an assemblage of discrete blocks that may deform internally but interact through contact surfaces (Itasca Consulting Group Inc., 2023). In 3DEC, mechanical behavior emerges from block-block interactions, as well as internal deformation, rather than continuum constitutive relationships alone. Blocks may translate, rotate, and separate, enabling representation of discontinuous deformation that is not generally permitted in continuum frameworks. This capability makes 3DEC particularly suitable for tunnel modelling where discrete cracking and joint opening represent the primary failure mechanisms. However, the block-based structure creates compatibility challenges for data transfer.

In fact, the main challenge lies in the fact that data assigned to zone centroids in FLAC3D cannot be transferred directly to an equivalent entity, since in 3DEC the centroids are not assigned to zones but rather to blocks. To address this divergent spatial discretization, the transfer procedure employed a proximity-based mapping strategy. Rather than attempting direct structural correspondence, the procedure

identified geometric relationships between source and target locations through coordinate comparison and distance calculation, using a nearest-neighbor approach. For each target location in 3DEC (block centroid or gridpoint), the protocol identified the nearest corresponding location in FLAC3D (zone centroid or gridpoint) and applies the required variable value.

4.3.3. Data extraction from FLAC3D

Data extraction from the FLAC3D landslide model employed custom Python scripts to systematically collect both velocity and stress information from the refined extraction volume. The extraction procedures differed for velocity and stress fields due to their different computational representations within FLAC3D but was performed on the same extraction volume (dimensions 108 m × 30 m × 30 m; Figure 36) established during mesh development as documented in the previous section.

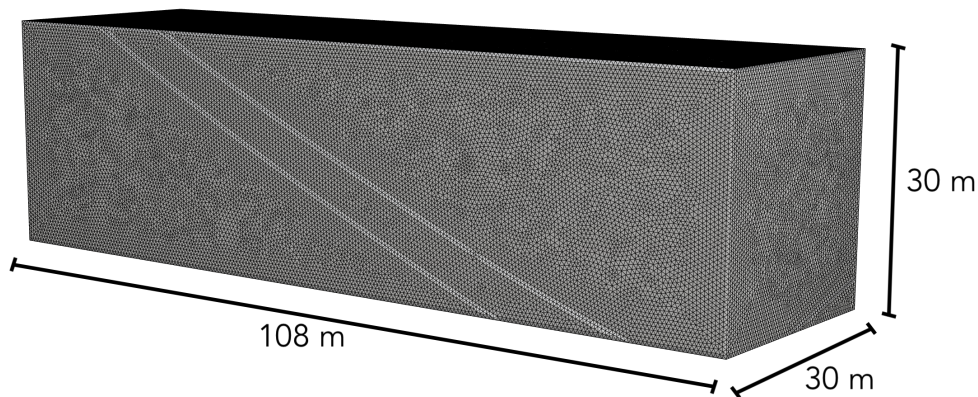


Figure 36 - FLAC3D extraction volume

This volume encompasses nine 12-meter tunnel segments centered on segment 28, with 30 m height and depth thus providing sufficient buffer around the tunnel volume to ensure all blocks in 3DEC will be assigned the correct stress values, avoiding possible boundary effects. The refined mesh within this volume employs 0.5 m tetrahedral elements, generating approximately 719360 gridpoints and 4098857 zones from which data would be extracted.

The extraction was performed at the model state corresponding to 3000 calculation cycles, previously identified as the stage exhibiting the highest deformation rates (to avoid unnecessarily long runtime in the small-scale model) with a realistic spatial distribution. This non-equilibrium state captured stress redistribution during early plastic yielding, providing boundary conditions representative of landslide-induced loading on infrastructure rather than relaxed, near equilibrium, steady-state conditions.

Velocity extraction employs a Python script accessing native FLAC3D data structures through the internal Python interface of Itasca software. The extraction process proceeded as follows:

1. The script first identified all gridpoints within the extraction volume using group reference filtering, selecting them if they belonged to the group related to the extraction volume (previously defined within mesh construction in Rhino).
2. For each identified gridpoint, the script extracts the gridpoint ID, the coordinates and the three components of the velocity vector (v_x , v_y , v_z).
3. Extracted data are organized into a structured format suitable for file import/export, with each row representing a single gridpoint and columns containing gridpoint ID, position (x-coordinate, y-coordinate, z-coordinate), and velocity data (v_x , v_y , v_z).
4. The complete dataset is exported as a CSV file, ready for transfer to the 3DEC modeling environment.

The extraction yielded 719360 gridpoints from the refined extraction volume with 0.5 m mesh spacing, providing dense sampling of the velocity field. The complete dataset was exported for subsequent transfer to 3DEC, where application strategies were determined based on import computational requirements.

Stress extraction required additional consideration due to stress storage within FLAC3D computational structure. Unlike velocities, which are computed at gridpoints, stresses are computed and stored within zone centroids, that were thus adopted as representative locations for stress values. The stress extraction process proceeded as follows:

1. The script identified all zones within the extraction volume using the same spatial filtering approach as for velocity extraction (i.e., group reference filtering).
2. For each identified zone, the script extracted all six independent stress tensor components (σ_{xx} , σ_{yy} , σ_{zz} , σ_{xy} , σ_{xz} , σ_{yz}) and zone centroid coordinates to enable spatial mapping during import.
3. Extracted data were organized in file where each row represented a zone and columns contained x-coordinate, y-coordinate, z-coordinate, σ_{xx} , σ_{yy} , σ_{zz} , σ_{xy} , σ_{xz} , σ_{yz} .
4. The complete stress dataset was exported as a CSV file to maintain consistency with velocity data.

Following extraction, some verification procedures were carried out, such as comparing the total number of extracted gridpoints and zones against expected values based on mesh statistics for the extraction volume. Absence of numerical artifacts or extraction

errors, such as number formatting or incorrect use of scientific notation, was also checked by examining velocity and stress magnitudes, and the export file structures were verified to match the documented format specification, ensuring compatibility with subsequent import scripts. These quality assurance steps confirmed data completeness and format consistency, providing a solid dataset for 3DEC import.

4.3.4. Data import strategy for 3DEC

The import strategy for transferring FLAC3D extracted data into the 3DEC tunnel model employed a deliberate redundancy approach to ensure complete coverage of spatial mapping between models. This strategy involved defining an import volume smaller than the extraction volume, creating intentional data overabundance to prevent the assignment of inappropriate parameters in boundary condition specification.

The import volume dimensions were established as 108 m × 20 m × 20 m (Figure 37), maintaining the extraction volume length while reducing height and depth from 30 m to 20 m, creating a geometric buffer for 5 m on the long sides of the model.

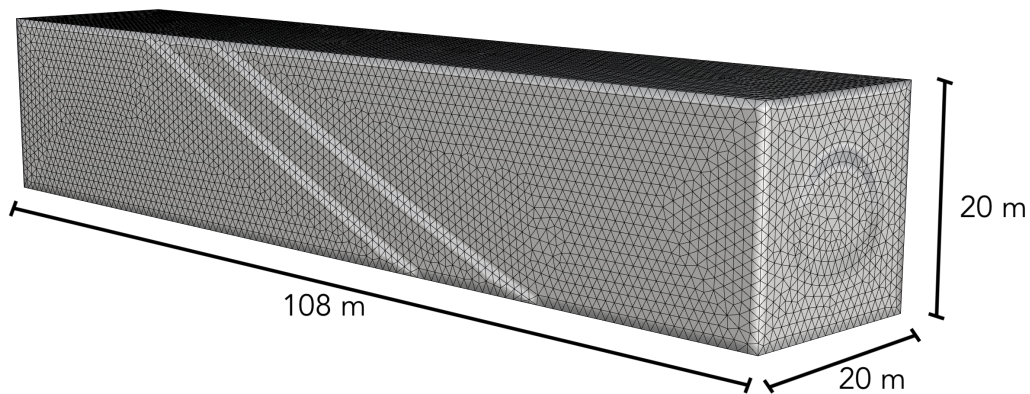


Figure 37 - 3DEC import volume

The rationale for this dimensional reduction reflects a conservative approach to data transfer. Given the discrete nature of data source points, i.e., gridpoints and zone centroids, and the need to map these points to a differently discretized 3DEC mesh, some uncertainty existed regarding coverage completeness near volume boundaries. By defining a smaller import volume, the procedure ensured that the true nearest neighbor source point is available in the input dataset, without being cut off due to an excessively small extraction volume. The dimensional reduction also reflects practical considerations regarding the tunnel model domain. The 20 m height and depth dimensions provide sufficient rock mass around the tunnel (approximate diameter 11 m with lining) to capture stress redistribution while maintaining computational efficiency for the subsequent detailed 3DEC analysis.

The spatial correlation between extraction and import volumes is critical for successful data transfer. Both volumes must share the same coordinate system origin and orientation, resulting in the import volume being positioned centrally within the extraction volume. This concentric arrangement ensures symmetric data availability around the import volume.

4.3.5. *Stress transfer implementation*

Stress transfer from FLAC3D to 3DEC employed a proximity-based mapping algorithm implemented using Itasca's internal Python console. The core challenge in stress transfer lay in identifying which FLAC3D zone stress tensor should be assigned to each 3DEC zone, given the different discretization and volume dimensions between models. The proximity-based approach solved this through nearest-neighbor mapping: for each zone in the 3DEC model, the algorithm identified the closest FLAC3D zone centroid from the extraction dataset and assigned that zone's stress tensor. The stress transfer algorithm implemented through a Python script proceeded as follows:

1. All zones centroid coordinates within the 3DEC import volume were computed and all stress values and zone centroids coordinates were loaded.
2. For each 3DEC zone centroid, Euclidean distances to all FLAC3D zone centroids in the extraction dataset were computed:

$$d = \sqrt{[(x_{3DEC} - x_{FLAC3D})^2 + (y_{3DEC} - y_{FLAC3D})^2 + (z_{3DEC} - z_{FLAC3D})^2]}$$

3. The FLAC3D zone with minimum distance to the current 3DEC zone was identified and its stress tensor was assigned to the 3DEC zone.
4. Steps 2-3 were repeated for all 3DEC zones in the import volume.

A critical decision in both stress and velocity transfer involved whether to apply them as initial conditions or boundary conditions. Initial conditions specify the starting state of the model, which may then evolve during calculation. Boundary conditions, instead, impose constraints that persist throughout analysis.

For stress transfer, initial condition application was selected for several reasons. The stresses extracted from FLAC3D represent a snapshot of the stress state in the landslide at a particular calculation stage. These stresses are not rigidly fixed values that must persist but rather represent the starting state from which the 3DEC model should evolve towards tunnel excavation and other modelling stages. Hence, applying stresses as initial conditions allowed the 3DEC model to undergo an initialization phase where small inconsistencies between the imported stress field and the 3DEC mesh geometry were resolved through stress redistribution, ultimately reaching mechanical equilibrium with

the imported stress field. This avoided potential numerical instabilities that might arise from rigid stress boundary conditions incompatible with the 3DEC discretization.

Following stress import, it was verified that all zones in the import volume received stress assignments and that the assigned values corresponded to those extracted from FLAC3D, in order to ensure that no systematic errors or data corruption had occurred. A visual comparison of stress field contours between FLAC3D (pre-export) and 3DEC (post-import) was eventually carried out to verify that major stress distribution patterns were preserved (Figure 38). These verification steps confirmed that the proximity-based algorithm successfully transferred stress information while maintaining spatial coherence of the stress field.

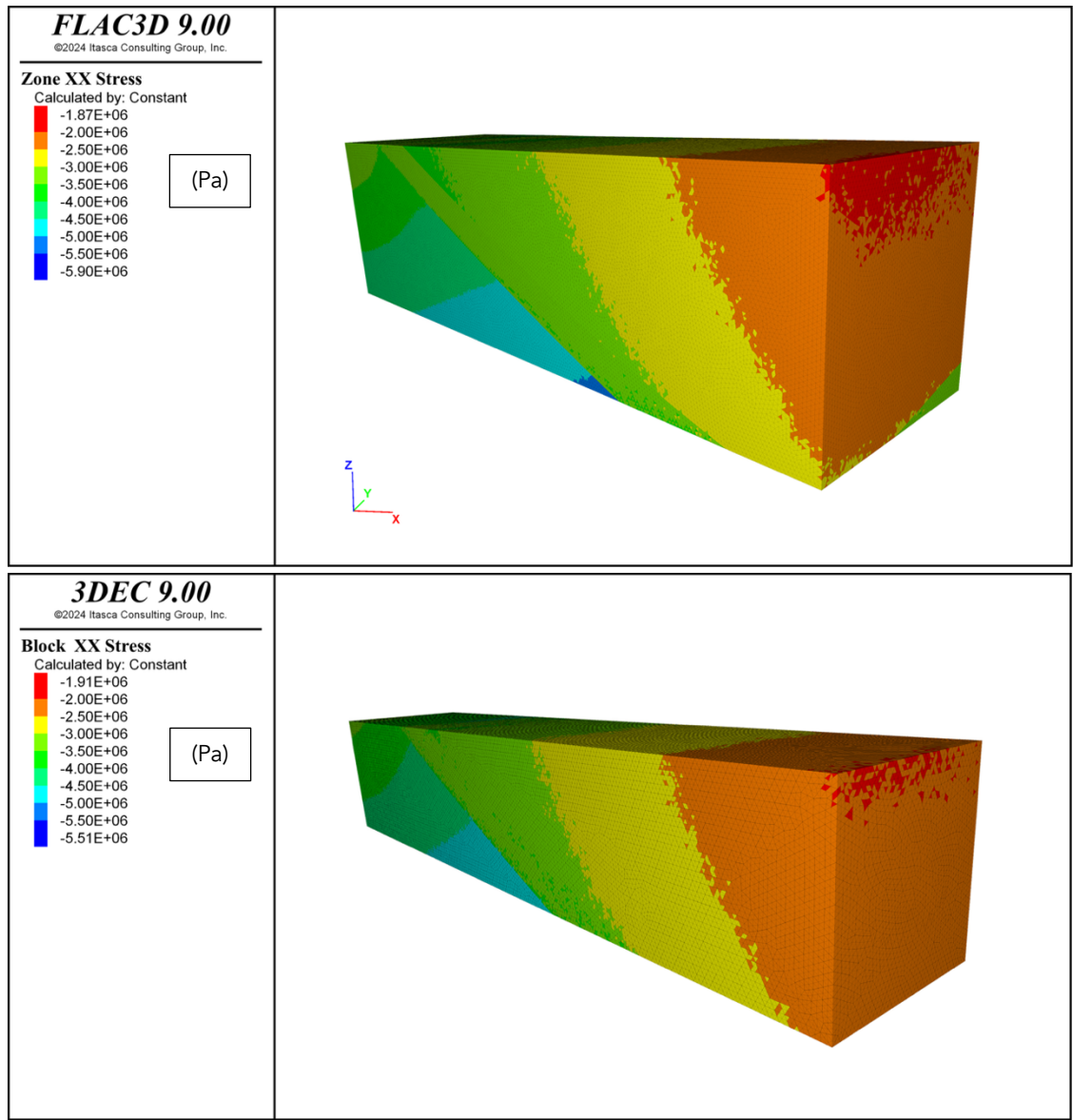


Figure 38 - Comparison between FLAC3D and 3DEC stress distributions; the XX-stress component has been chosen as representative quantity; the discrepancy in values between FLAC3D and 3DEC outcomes is related to the difference in volumes dimensions

4.3.6. *Velocity transfer implementation*

Velocity transfer presented distinct challenges compared to stress transfer due to specific limitations in 3DEC's Python interface regarding velocity boundary conditions. While Python methods exist for querying gridpoint velocities and setting them as initial conditions, no Python commands seemed to be available for prescribing velocities as persistent boundary conditions that maintain their values throughout analysis. This distinction is critical for the multi-scale approach, as velocity boundary conditions continuously impose landslide-induced motion, whereas initial conditions would immediately begin to evolve once calculation commenced, potentially departing from the intended landslide loading pattern. To overcome this limitation, velocity application employed a hybrid approach coupling Python scripting for spatial mapping with FISH scripting for boundary condition application.

A Python script, employing the same nearest-neighbor algorithm used for stress transfer, processed the FLAC3D velocity export data. For each gridpoint in the 3DEC model, the script identified the nearest FLAC3D gridpoint through Euclidean distance computation and generated a new CSV file pairing each 3DEC gridpoint ID with its corresponding nearest FLAC3D gridpoint coordinates and velocity vector. Velocity boundary condition application required a two-stage FISH implementation to properly fix velocities at gridpoints:

1. A FISH function read the mapped velocity data and applied velocities to gridpoints through repeated execution of 3DEC's *'block gridpoint apply velocity'* command; this command assigns velocity values to gridpoints based on their ID from the CSV file.
2. A second FISH function converted the applied velocities into fixed boundary conditions by iterating through all gridpoints, identifying those with applied velocities (magnitude > 0) and propagating these velocity values to linked gridpoints, effectively fixing the velocity field at specified locations to prevent evolution during subsequent calculations.

Referring to this second step, it is worth mentioning that gridpoints of juxtaposed blocks share the exact same location but different IDs. Therefore, a supplementary small script was required to ensure all 'linked gridpoints' were assigned the same velocity and became fixed. This was necessary because direct velocity fixing commands in 3DEC required an additional propagation step to ensure that the velocities persisted as boundary conditions rather than as initial values (Itasca Consulting Group Inc., 2023).

Initial attempts to apply velocity boundary conditions to all 3773067 gridpoints in the import volume revealed prohibitive computational requirements. Each gridpoint required individual processing through the FISH scripts, and runtime for completing

volume application exceeded practical limits. This computational bottleneck necessitated restricting velocity boundary condition application to gridpoints on the exterior surface of the import volume, composed of six distinct surfaces. Surface gridpoint identification was accomplished through geometric filtering within 3DEC, using coordinate-based and plane-based range commands. The six volume faces were identified through z-coordinate ranges for top and bottom surfaces, and plane definitions with specified origin and orientation for lateral boundaries. Filtered block faces satisfying these geometric criteria were assigned to group 'Surface', and gridpoints associated with these faces were assigned to group 'external_gp'.

The Python-FISH velocity application procedure was then executed exclusively for gridpoints belonging to this surface group, reducing the number of processed gridpoints from over 3 million to approximately 133016 surface gridpoints. This simplification was justified by recognizing that surface velocity boundary conditions naturally propagate into the model interior through mechanical equilibration with cycling during a 30000 cycles-long initialization phase, as it will be shown in the following section. This represents an acceptable computational trade-off to ensure a reasonable time for the application of velocity boundary conditions. Such an equilibration process enables interior velocities to develop consistently with surface boundary conditions, adequately establishing the kinematic loading environment for tunnel analysis without requiring explicit velocity specification throughout the entire volume.

Following the application of velocity boundary conditions, it was verified that all gridpoints assigned to the 'external_gp' group received velocity boundary conditions through the two-stage FISH procedure, confirming complete surface coverage without gaps. Velocity magnitudes and directions assigned to surface gridpoints were also compared against the FLAC3D extraction dataset to confirm correct proximity-based mapping (Figure 39).

No systematic errors or data corruption were identified, with assigned values corresponding to their nearest FLAC3D neighbors as intended. These verification steps confirmed that the hybrid Python-FISH approach with surface-only application successfully transferred velocity boundary conditions while maintaining the kinematic loading characteristics required for tunnel-scale analysis. This validation and the results presented in the following section demonstrated that the computational trade-off between complete volume application and surface-only specification did not compromise the model's ability to represent landslide-induced deformation patterns, justifying the methodological simplification for this multi-scale application.

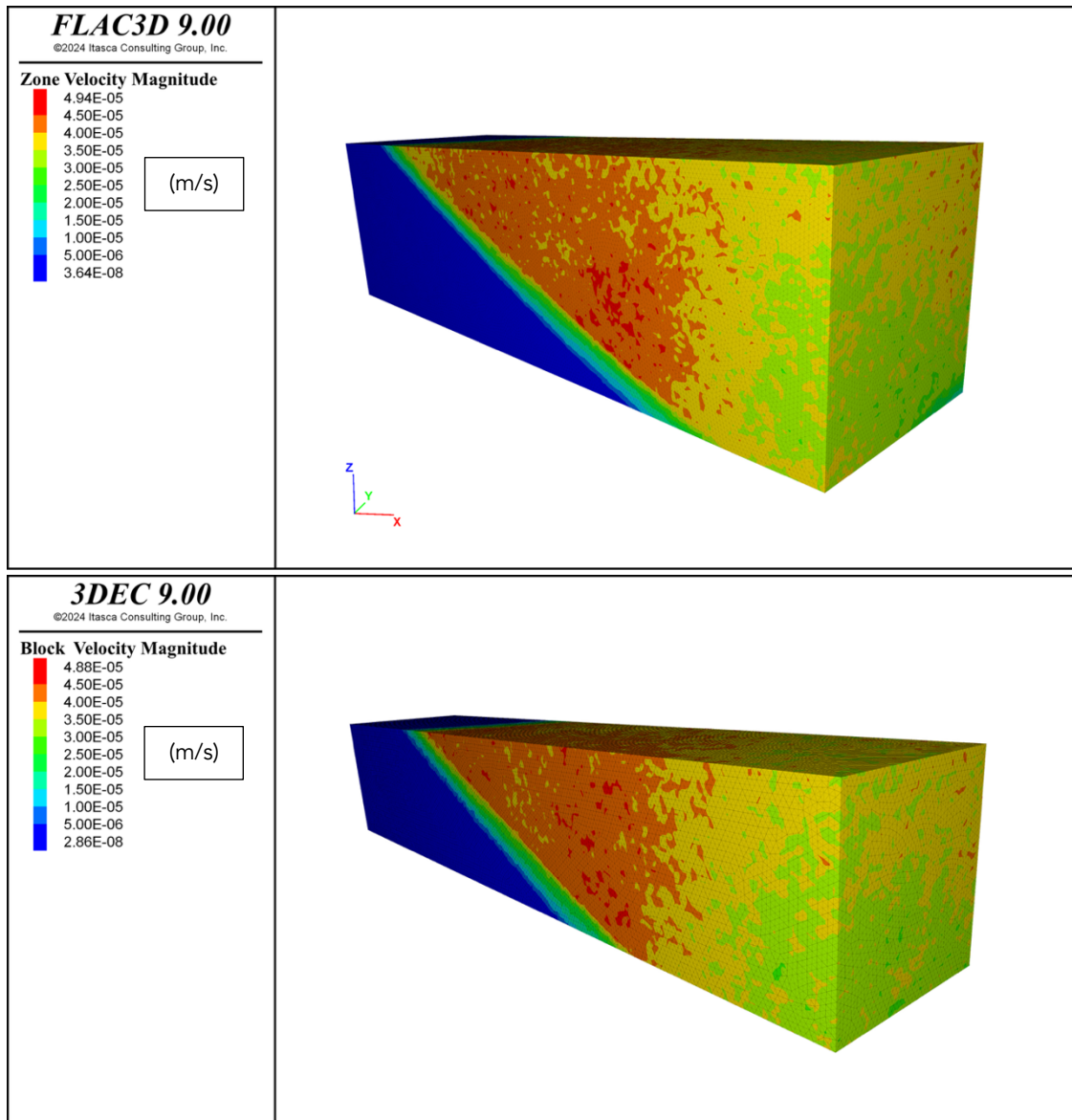


Figure 39 - Comparison between FLAC3D and 3DEC velocity distributions; the discrepancy in values between FLAC3D and 3DEC outcomes is related to the difference in volumes dimensions

4.3.7. Limitations and assumptions

The data transfer procedure successfully conveyed mechanical fields from FLAC3D to 3DEC, as demonstrated by completeness verification, value consistency checks, and qualitative agreement between pre-export FLAC3D and post-import 3DEC field distributions. However, the procedure necessarily involved approximations and methodological choices whose implications must be understood for correctly interpreting subsequent tunnel model results.

Restricting velocity boundary conditions to import volume external surfaces requires interior velocities to develop through mechanical equilibration, introducing deviations

from the exact FLAC3D interior velocity field. Nevertheless, for the relatively compliant rock mass in the tunnel vicinity and the extended equilibration period employed, deviations are expected to be modest. Validation confirmed that these deviations were acceptable for the tunnel analysis objectives.

The transferred data represents a single time instant, meaning this quasi-static transfer cannot capture transient dynamics or time-varying loading patterns. For the slow-moving Passo della Morte landslide, with relatively steady displacement rates, quasi-static conditions are appropriate. Conversely, the application to rapidly moving landslides or those with episodic behavior would require time-series transfer procedures or the application of time-dependent boundary conditions.

4.4. Infrastructure-scale model

A successful small-scale modelling requires several fundamental elements: a geometric representation that captures essential tunnel features while remaining computationally efficient, appropriate constitutive models for both rock mass and concrete lining behavior, and the ability to incorporate boundary conditions from the large-scale model while maintaining sufficient resolution to capture infrastructure-scale deformation mechanisms. This section will follow a logical progression from geometric construction through model validation, structured as follows:

- *Mesh construction and geometric simplification*: development of the tunnel model geometric mesh, including decisions regarding spatial extent, structural representation, and computational optimization.
- *Material characterization and initialization phase*: assignment of rock mass properties, integration of imported stress and velocity fields, and convergence procedure to establish initial conditions.
- *Tunnel excavation and lining implementation*: excavation and lining placement with constitutive model selection and assignment.
- *Deformation analysis and monitoring comparison*: evolution of tunnel structural response and validation against field observations.

4.4.1. Mesh construction and geometric simplification

In the small-scale model development competing demands needed to be balanced: a) a geometric detail sufficient to capture the structural response of the tunnel, b) a sufficient spatial extent of the model domain to minimize boundary effects, and c) computational efficiency to ensure practical model runtimes. For the San Lorenzo tunnel

case, these considerations led to several geometric simplifications implemented during mesh construction in Rhino, reflecting the model's primary objective of capturing segment-scale deformation patterns and inter-segment joint behavior.

The tunnel model domain was defined as a 108 m × 20 m × 20 m volume, meaning exactly the import volume, maintaining the longitudinal extent of the large-scale extraction volume while reducing vertical and lateral dimensions from 30 m to 20 m. Tunnel cross-sectional geometry was simplified (Figure 40) by reducing the horseshoe profile to a configuration with minimized edges and geometrical complexities irregularities (e.g., drainage channels, walkways) that would have increased element count without substantially affecting global structural response. The original tunnel section was therefore streamlined, retaining only the structurally relevant part, resulting in an external diameter of 11.7 m and an internal diameter of 10.1 m for the vault, and an external radius of 9.85 m and an internal radius 8.75 m for the invert. The ultimate thickness was obtained by simplifying lining composition: the two-layer lining system (primary shotcrete lining and final cast-in-place concrete lining) was modelled as a single equivalent thickness. This equivalent single-layer representation maintains total structural thickness while reducing the number of material interfaces requiring explicit modelling. Following this reasoning, it was also decided not to include the reinforcing bars used in the linings within the geometric model.

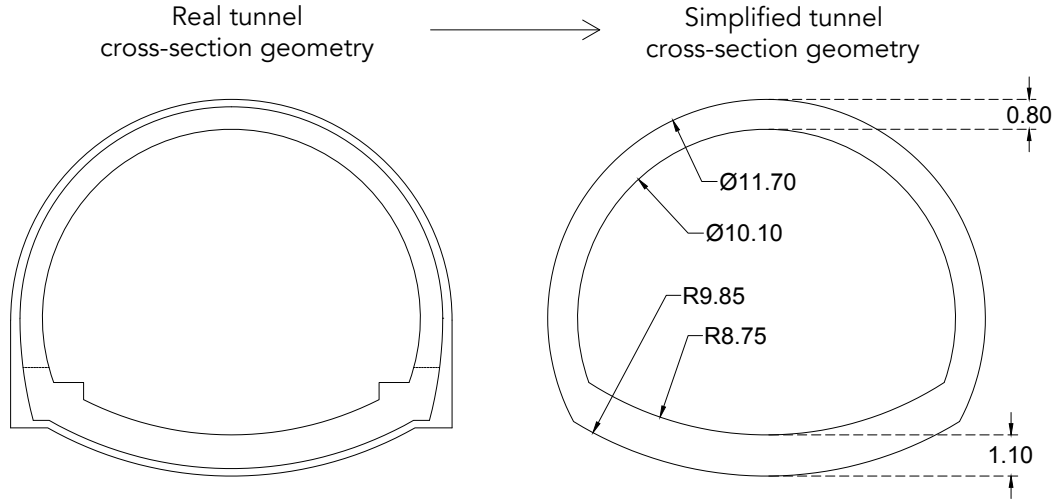


Figure 40 - Tunnel cross-section simplification overview, as routinely used (Zhao et al. 2019; Jiao et al. 2013; Wang et al. 2020; Zhang et al. 2015)

Tunnel alignment was also simplified considering a linear and horizontal development, disregarding the longitudinal slope (humpback profile) and the curvature in plan view. Such a simplification was justified by the limited length of the model domain over which curvature effects in both horizontal and vertical directions remain minimal.

Incorporating nine consecutive 12-m-long segments, centered on segment 28, into the tunnel model allowed damage propagation to be analyzed beyond the shear zone intersection and made it possible to evaluate the influence of the independent segmental construction strategy.

Following the definition of these geometric simplification principles, the tunnel model geometry was constructed in Rhino using the Griddle plugin, following a workflow similar to the large-scale model one. The geometric model incorporated four distinct material units: stable rock material, representing competent rock mass outside the landslide influence zone, landslide material, entirely composed by the clay-rich formations, shear zone, and tunnel lining (Figure 41).

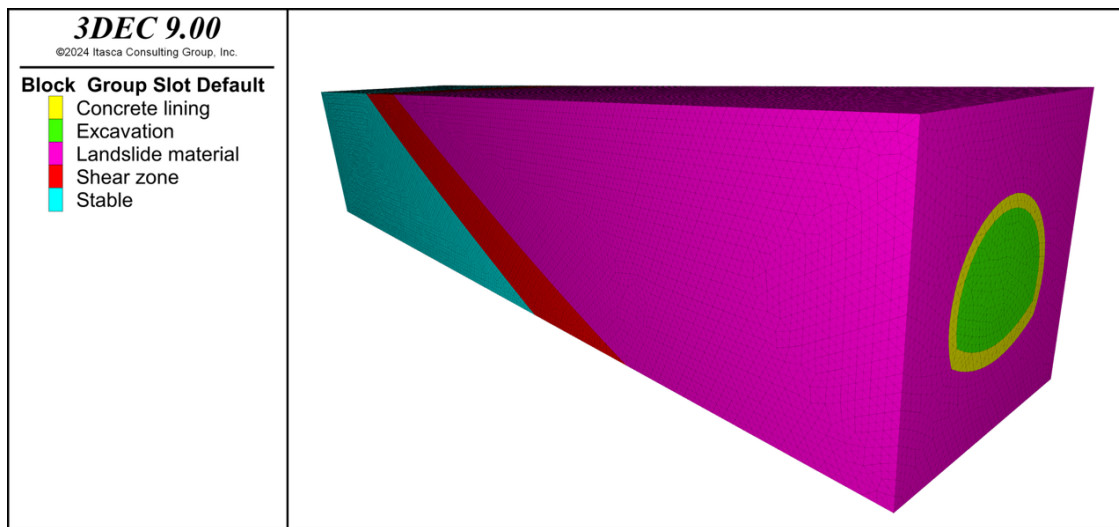


Figure 41 - San Lorenzo tunnel 3DEC model group definition

The element size within the tunnel model was initially set to 1 m to provide adequate resolution for structural response analysis while maintaining consistency with the imported boundary condition data spacing. Although this configuration would have been the ideal solution, it proved computationally prohibitive, resulting in excessive runtimes that jeopardized the feasibility of the research activities within the allocated timeframe.

Consequently, the maximum mesh element size was increased to 3 m. To mitigate the loss of resolution, this coarsening was partially compensated in 3DEC by assigning a zone edge length equal to half that of the corresponding blocks, resulting in zones with an average edge length of approximately 1.5 m. In this way, although the matching with the large-scale model resolution was lost, it was still possible to pursue the validation of the multi-scale approach. This refinement level represents a compromise between detailed structural analysis and computational effort, sufficient for capturing first-order structural response patterns that constitute the primary validation targets (Figure 42).

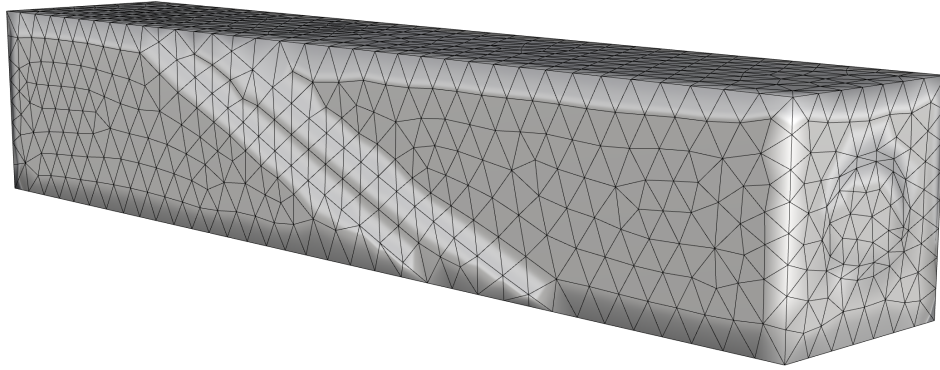


Figure 42 - San Lorenzo tunnel 3DEC final 3-m-mesh output

4.4.2. Model import and material characterization

This geometry was then imported into 3DEC, representing pre-tunnel conditions. This initial state was essential for the staged modelling, that would subsequently incorporate imported boundary conditions, achieve mechanical equilibrium (i.e., propagation of velocities from the boundaries toward the interior), and then simulate tunnel excavation and lining installation. The initial configuration also enabled verification that imported stress and velocity fields, when applied to geometrically identical rock mass representation, would reproduce the mechanical state established in the large-scale model, as discussed in detail in the Data Transfer Procedure section.

Material characterization for rock mass units (i.e., stable rock, landslide clay-rich formations, and shear zone), employed identical constitutive models and parameters as the large-scale FLAC3D model, ensuring consistency in mechanical representation across the scale transition (Table 2).

Stress tensors were imported as initial conditions (i.e., allowing variations during cycling) applied to block centroids throughout the imported volume, while velocity vectors were implemented as boundary conditions (i.e., velocity is fixed throughout cycling) applied to gridpoints on the model surface. Following the import of geometry, material properties, and boundary conditions, the tunnel model required an initialization phase to achieve a mechanical equilibrium consistent with the large-scale model state. Thus, the model was initially run without imposing a cycle limit.

Velocity and stress field distributions were checked throughout cycling to confirm correct propagation of velocity inside the model volume while maintaining the applied stress field spatial distribution. Run to equilibrium was monitored through regular model saves at intervals of 10000 cycles, to enable retrospective identification of the equilibrium state. Progressive examination of saved states revealed that equilibrium was achieved between 20000 and 30000 calculation cycles, when inner velocity field had

stabilized to match the imposed boundary conditions and the stress field had adjusted to reach an equilibrium state. Hence, the model state at 30000 cycles was selected as the initial condition for tunnel excavation. This state represents the mechanical condition of in-situ rock mass subjected to landslide-induced loading, simulating the state that would have existed prior to tunnel construction. This equilibrated state was successfully compared with the FLAC3D source data to ensure efficient transfer to the small-scale model.

4.4.3. Tunnel excavation and lining implementation

Tunnel excavation was simulated as an instantaneous removal of material within the defined excavation void, representing the completed excavation state rather than a progressive advancement. This simplification reflects the model's focus on long-term structural response to landslide loading rather than construction-phase behavior. Within this framework, the tunnel lining was introduced within the same cycle, without allowing a pre-lining stress redistribution, considering the actual installation time of the lining to be sufficiently low and therefore negligible.

The nine-segment configuration was explicitly represented, with discontinuities between adjacent 12-meter segments simulating the actual reconstruction approach that intentionally avoided continuous reinforcement. This representation is critical for simulating observed damage patterns, as structural monitoring data indicates that significant deformation occurs between segments rather than exclusively within individual segments (Figure 43).

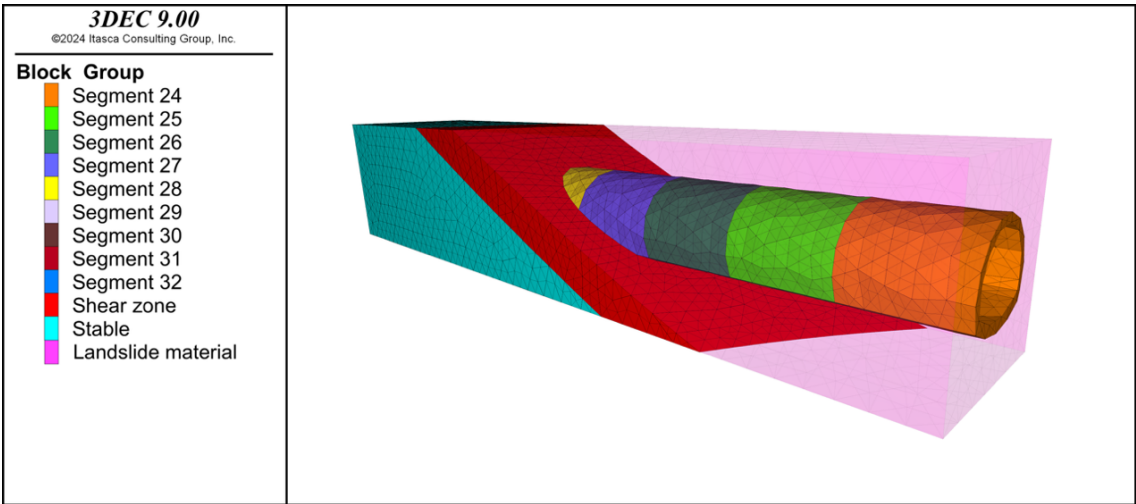


Figure 43 – 3DEC model after tunnel excavation and lining positioning

The selection of an appropriate constitutive model for the concrete lining represented a critical modelling decision that required balancing representational accuracy against practical implementation constraints and research objectives. Although The Mohr-

Coulomb elastic-perfectly plastic model lacks explicit treatment of progressive damage mechanisms specific to concrete behavior, it provides basic representation of material strength limits. Furthermore, the lack of parameters relating to the concrete installed at the site would have required significant uncertainties and assumptions. Therefore, the Mohr–Coulomb constitutive model was ultimately assigned to the concrete lining. The material parameters were derived from construction documentation provided by the stakeholder, ANAS S.p.A., and are reported in Table 3.

Table 3 -San Lorenzo concrete lining material properties

	<i>Density (kg/m³)</i>	<i>Young modulus (GPa)</i>	<i>Poisson coefficient</i>	<i>Internal friction angle (°)</i>	<i>Cohesion (kPa)</i>	<i>Tension limit (kPa)</i>	<i>Dilation angle (°)</i>
Concrete	2500	31	0.2	35	8000	3000	0.0

Following lining installation and property assignment, the model's displacements were reset for the entire domain, while stress fields were reset just within the tunnel lining. This procedure eliminated the equilibration-phase displacements and stresses, ensuring that subsequent deformation represented exclusively the post-equilibrium model response.

4.4.4. Deformation analysis and monitoring data comparison

Following lining installation and stress field reset, the model was executed without imposing a cycle limit to observe the evolution of tunnel deformation under sustained landslide loading. The absence of a predefined stopping criterion reflected the objective of identifying when deformation patterns became sufficiently developed for meaningful analysis and desirable comparison with monitoring data rather than arbitrarily terminating calculation after a fixed duration.

Despite the previously discussed mesh refinement, substantial tunnel deformation required approximately 3400000 model cycles to develop, as a consequence of the low velocity and stress magnitudes extracted from the large-scale model. These low values reflect the slow-moving nature of the Passo della Morte landslide, characterized by documented displacement rates of 2-3 cm/year. The extended cycle requirement also reflects the fundamental scale disparity that motivates the applicability of the proposed multi-scale approach: landslide movement generated infrastructure stresses that accumulated gradually, producing observable damage only after sustained loading. The numerical model similarly requires incremental deformation accumulation over many cycles to reproduce this progressive damage mechanism. The model execution was stopped when the final displacement distribution throughout the model domain reached a maximum magnitude of approximately 3 cm (Figure 44).

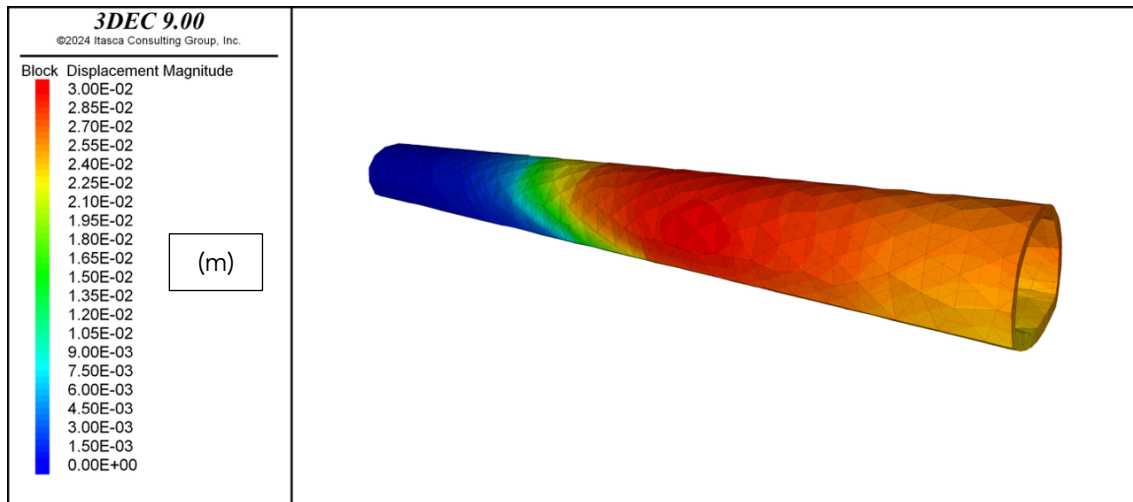


Figure 44 - Displacement magnitude distribution

This displacement magnitude must be evaluated considering the discrepancy between tunnel and landslide deformation rates. Field observations from the San Lorenzo tunnel show that if the tunnel were subjected to deformation consistent with the landslide displacement rate (2-3 cm/year), approximately 10 years of movement would produce cumulative deformation of 20-30 cm. However, tunnel monitoring over the past decade reveals lower maximum crack widths and structural deformations (2-3 cm, visible in Figure 23). Consequently, the modeled tunnel displacement magnitude of approximately 3 cm realistically represents the accumulated deformation over a significantly longer period, potentially a decade or more.

The deformed configuration after 3400000 cycles revealed a tunnel response consistent with the expected landslide-induced differential displacement. In fact, the tunnel exhibited the effects of a combination of rotation and translation following the landslide movement direction. Specifically, the tunnel segments within the model units belonging to the landslide body simultaneously moved downhill and rotated around the tunnel longitudinal axis towards the downhill side. This roto-translational movement pattern is consistent with the described landslide displacement direction and reflects its imposed differential displacement. Decomposition of the displacement field into X, Y, and Z components confirmed the roto-translational movement pattern:

- X-component: although the values are in the order of millimeters, their distribution suggests a stretching behavior of tunnel portion within the landslide body, moving towards the eastern end; additionally, a concentration of positive and negative values respectively on the uphill side and downhill side, reveals a squeezing effect within the segment 28 (Figure 45).

- Y-component: dominant negative displacements (reaching -2.80 cm) represent the primary translational component, as tunnel segments within the landslide body move downslope following the landslide mass (Figure 46).
- Z-component: negative displacements (up to -1.30 cm), concentrated in the tunnel portion within the landslide body, represent the secondary translational component, as that tunnel portion is carried down by the landslide mass (Figure 47).

The portion of the tunnel within the stable rock mass seems not to be affected by the landslide displacement, showing zero or near zero values for all three components.

The displacement component magnitudes and their spatial distributions suggested that the tunnel experienced true three-dimensional differential displacement. The oblique geometry of the intersection between the landslide shear zone and the tunnel induced pronounced multi-directional loading, resulting in a displacement vector with a magnitude of approximately 3 cm. The tunnel, acting as a relatively stiff linear element embedded in a differentially moving mass, develops internal forces as it resists this imposed three-dimensional deformation pattern.

The successful reproduction of this first-order deformation pattern validates that the imported velocity boundary conditions from the large-scale FLAC3D model effectively drove realistic tunnel response, confirming the mechanical consistency of the multi-scale data transfer procedure.

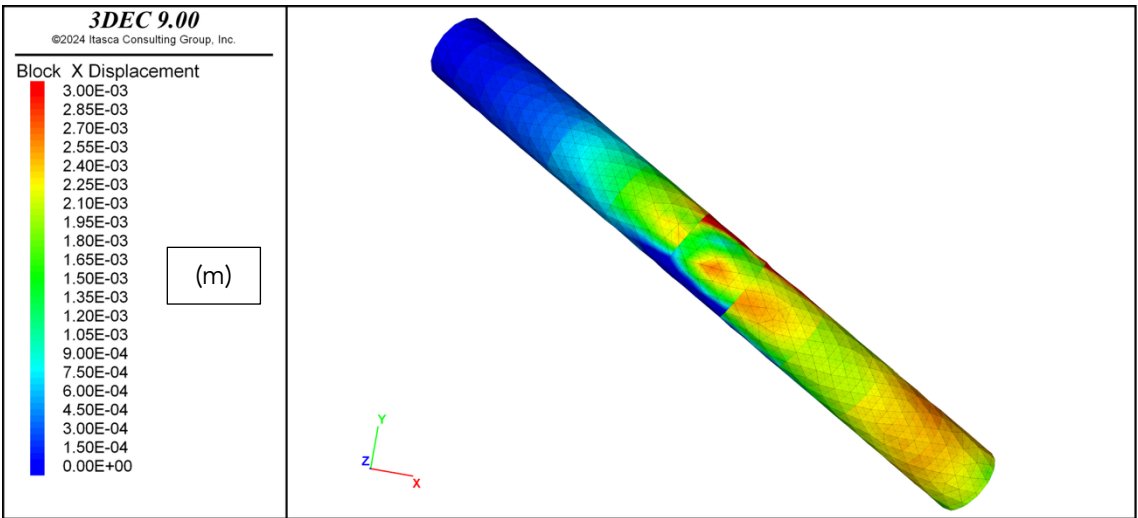
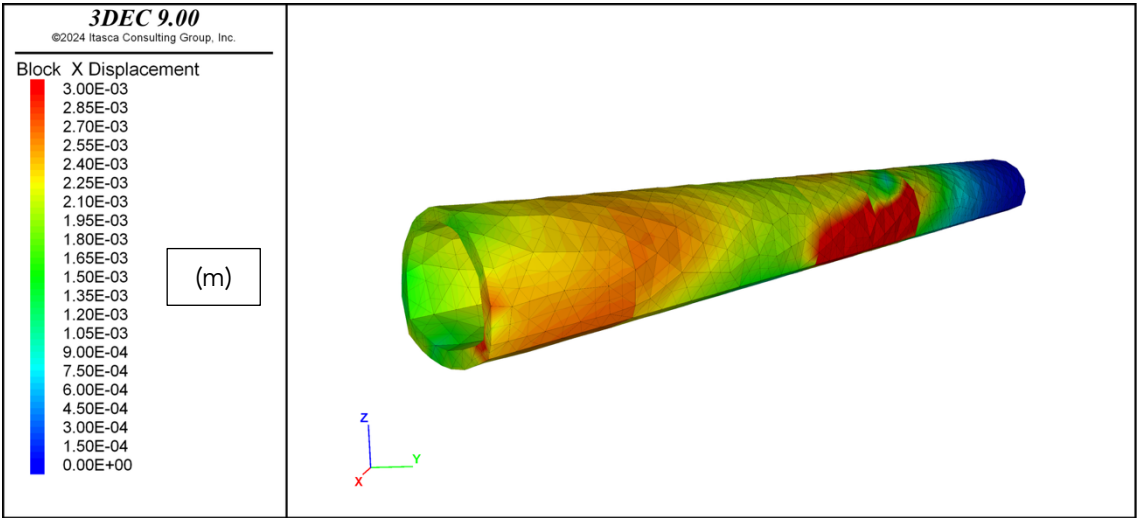
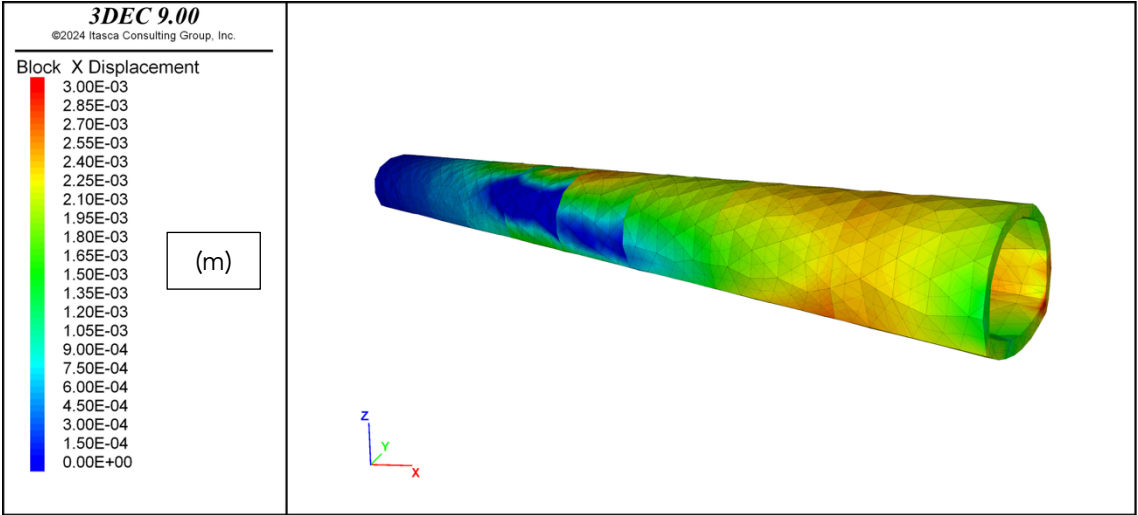


Figure 45 - Displacement distribution in X-direction

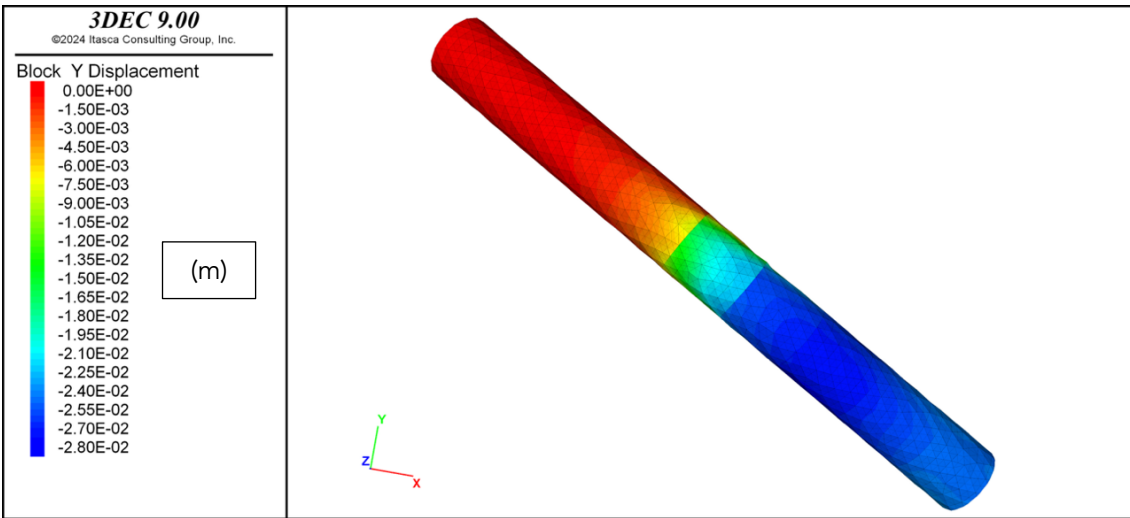
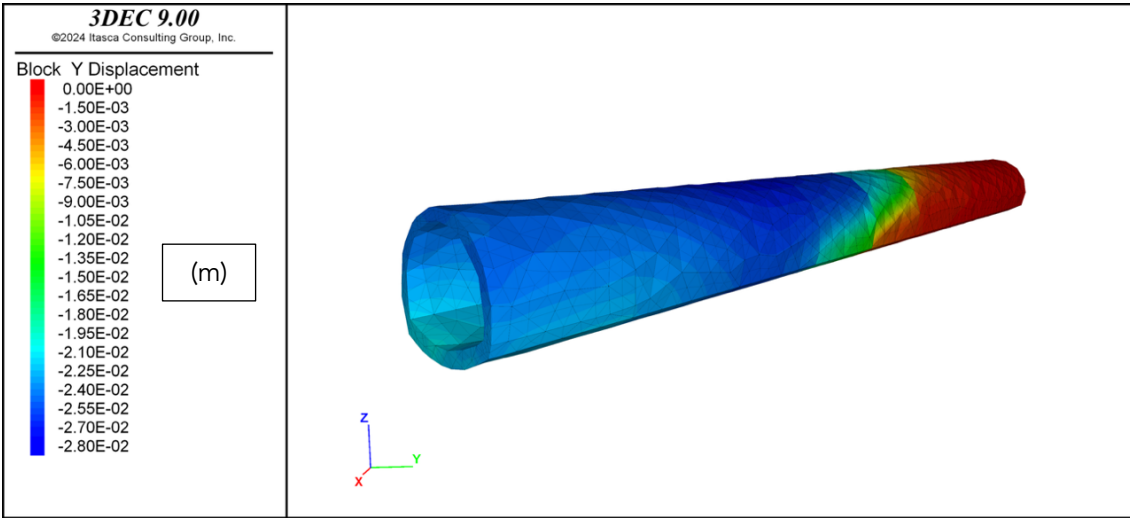
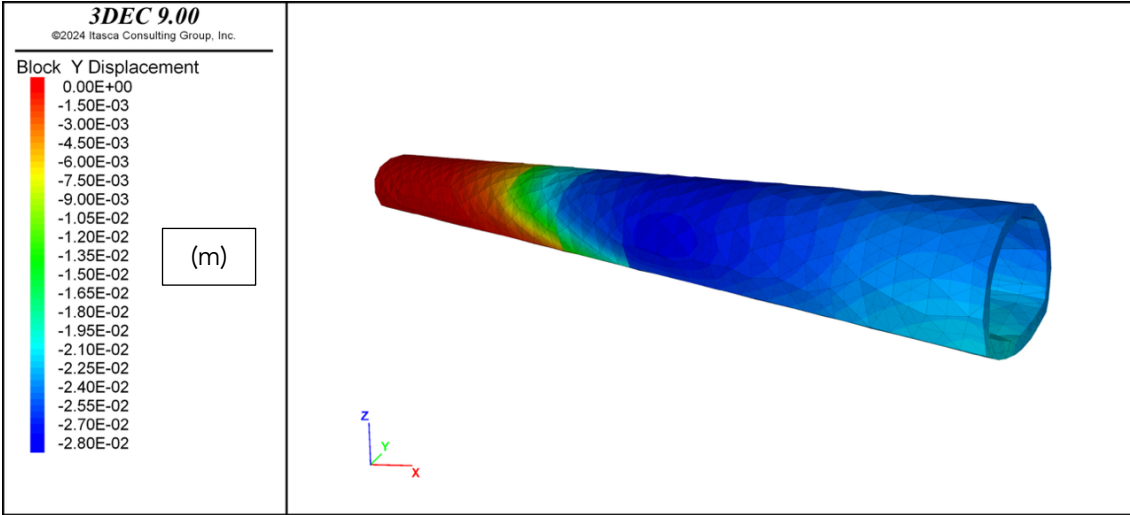


Figure 46 - Displacement distribution in Y-direction

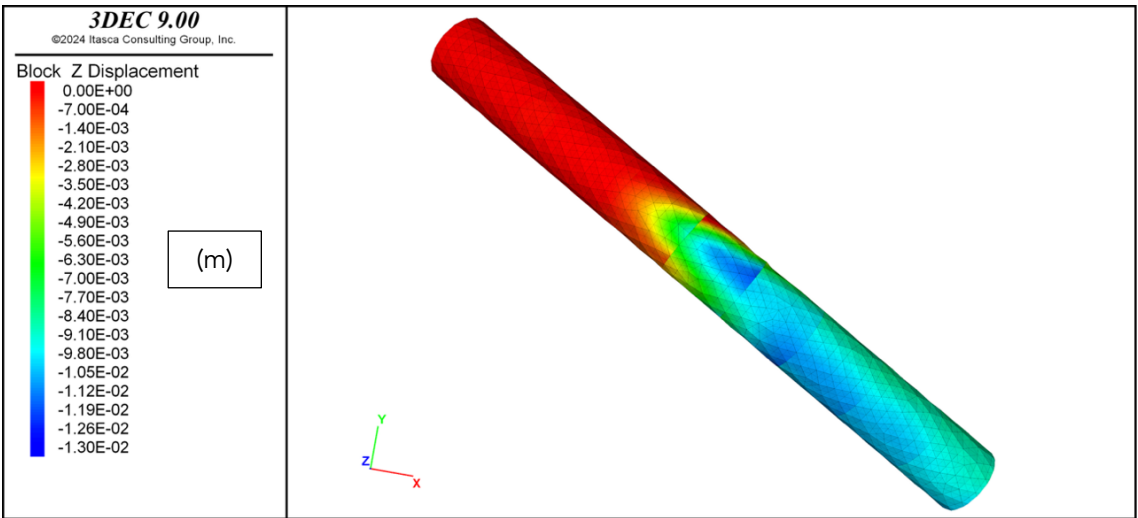
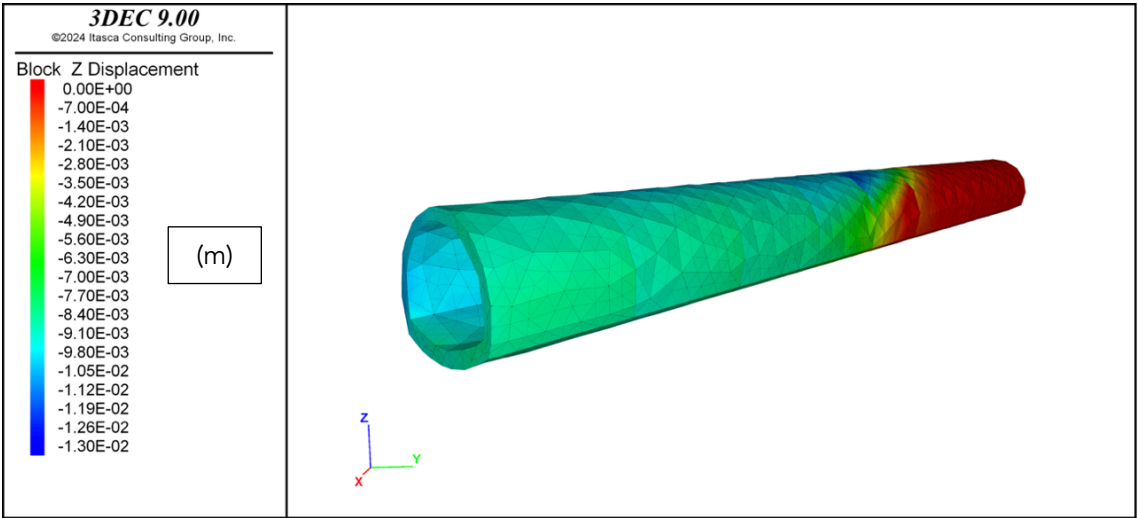
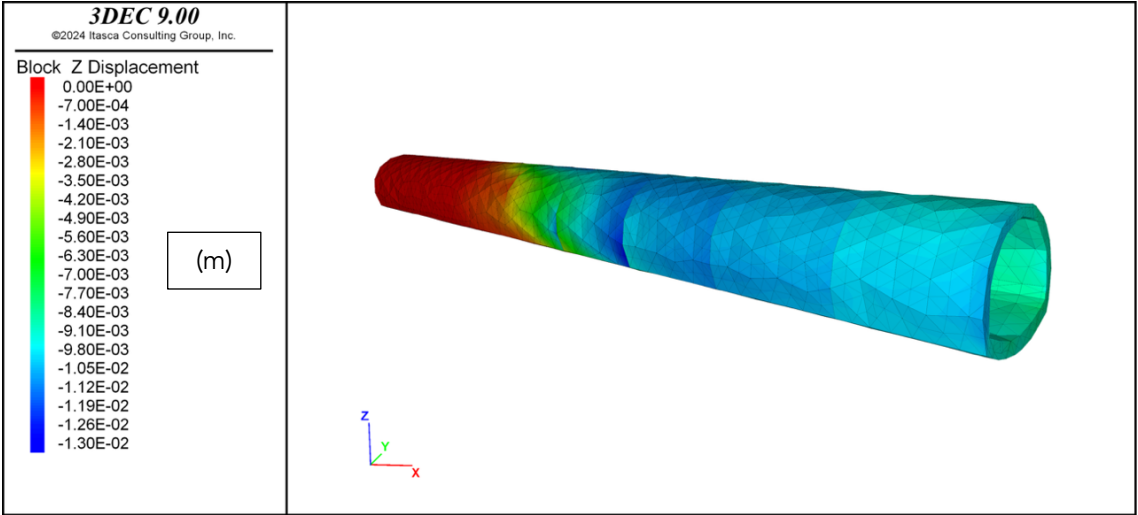


Figure 47 - Displacement distribution in Z-direction

Analysis of principal stresses provided insights into the mechanical state of the tunnel lining. It must be considered that the friction angle, cohesion, and tensile strength of the concrete were moderately higher than typical unreinforced concrete values to partially account for reinforcement effects, not explicitly included in the model.

Maximum principal stress distribution revealed a critical pattern of tensile stress concentration localized at the shear zone intersection (Figure 48).

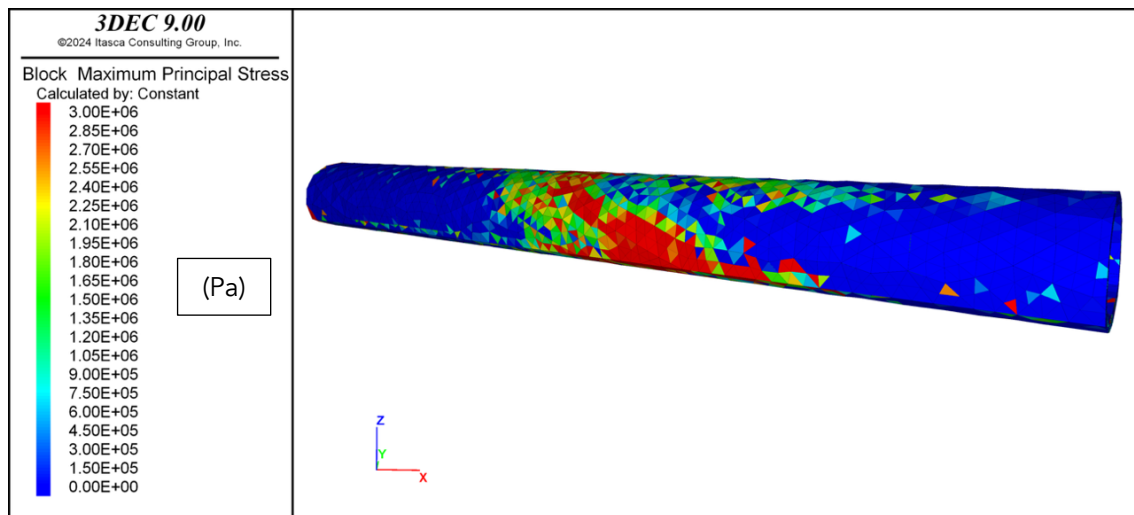


Figure 48 - Maximum principal stress distribution

While the sections of the tunnel domain towards the ends exhibited predominantly low stress values, the shear zone and the adjacent areas showed pronounced tensile stresses. This spatial pattern directly reflects the differential displacement mechanism: as the landslide body imposes a downward displacement and a rotation, the tunnel lining stretches at the intersection with the shear zone. Tunnel segments located in stable ground or entirely within the moving landslide mass exhibit negative maximum principal stresses, indicating that tensile loading develops specifically where differential movement occurs rather than throughout the entire structure.

Minimum principal stress exhibited a distribution similar to that of the maximum principal stress (Figure 49), but with a compressive rather than tensile character. This indicates that, within the shear zone, the tunnel experiences a complex stress state (tension in one principal direction and compression in the perpendicular direction) that results from the differential displacement imposed by the landslide. Beyond the localized stress concentration at the shear zone intersection, the minimum principal stresses gradually decrease toward both tunnel ends, generating stress gradients that spatially mirror the distributions of maximum principal stresses.

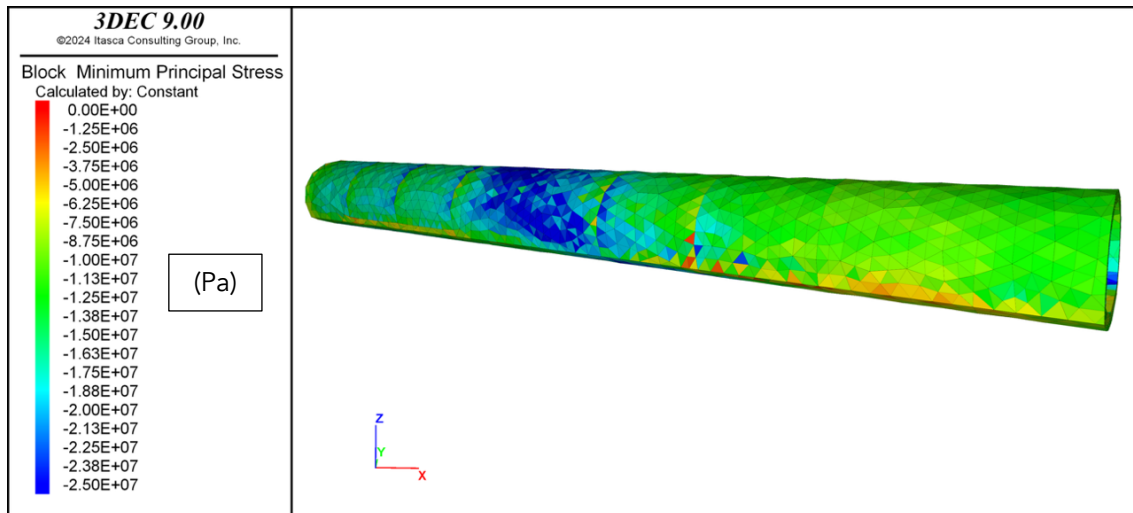


Figure 49 - Minimum principal stress distribution

The tunnel lining, which acts as a relatively stiff structural element bridging stable ground and moving landslide, is simultaneously stretched along the longitudinal axis and compressed along the sides. The stress field analysis confirms that structural distress is highly localized rather than uniformly distributed. Both tensile and elevated compressive stresses concentrate at the transition between stable and unstable portions of the slope, where differential displacement is maximized. The spatial correlation between stress concentration, displacement magnitude, and observed damage demonstrates that failure mechanisms are governed by differential movement rather than uniform external loading (e.g., locally high pore-water pressure).

Analysis of principal strain increments further helped in providing quantification of lining deformation and identification of damage zones. Maximum principal strain increment exhibited predominantly positive values throughout the tunnel domain (Figure 50).

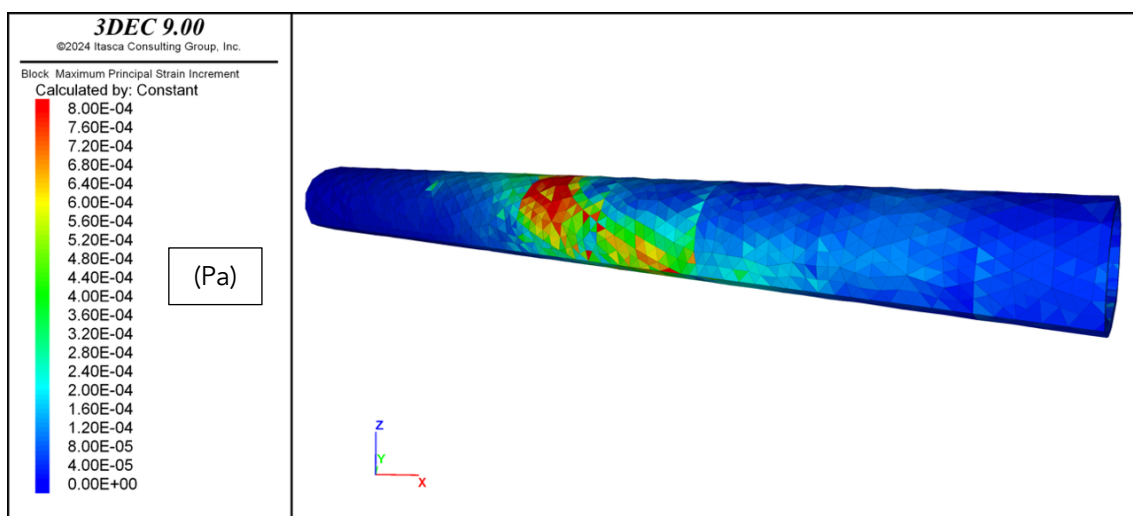


Figure 50 - Maximum principal strain increment distribution

The spatial distribution revealed pronounced concentration of maximum strains where the landslide shear zone intersects with the structure. Similarly, minimum principal strain increment showed a spatial distribution concentrating precisely in the central segments, exhibiting peak values at the shear zone-tunnel intersection (Figure 51).

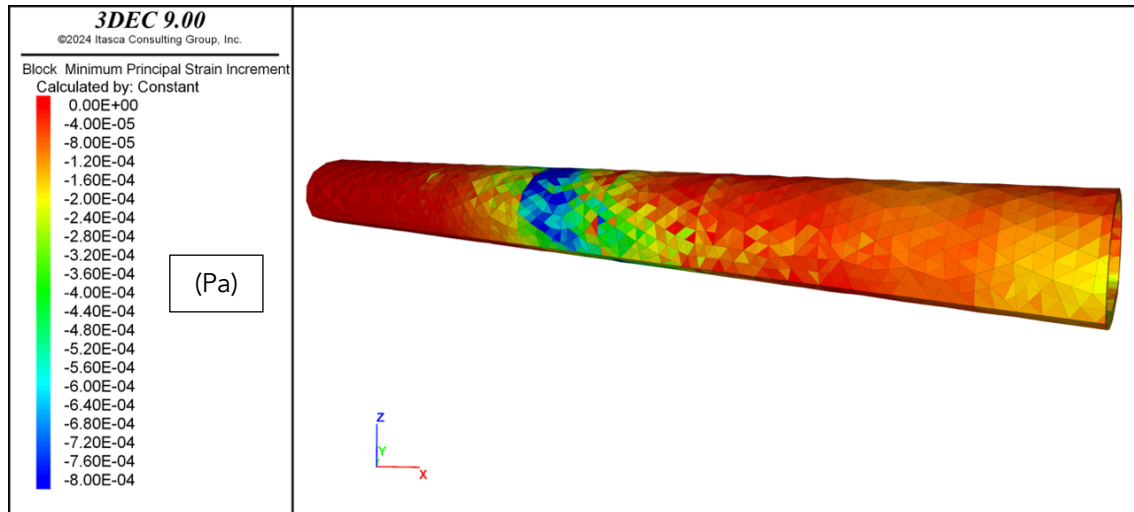


Figure 51 - Minimum principal strain increment distribution

While it seems trivial that this location experiences maximum differential displacement as segments intersect the shear zone, the combination of tensile maximum principal strain and compressive minimum principal strain further indicates that the tunnel lining at the shear zone intersection experiences simultaneous stretching in one direction and compression in the perpendicular direction. Beyond the concentrated peak at the shear zone intersection, strain magnitudes progressively decreased toward both tunnel ends, creating a strain gradient that mirrors the displacement field distribution. Segments anchored in stable ground exhibited minimal strain, while the transition zone approaching the shear zone showed intermediate values, with maximum deformation reached within the shear zone.

This strain distribution analysis is consistent with the roto-translational tunnel behavior and with the crack concentration within the tunnel lining. The oblique tensile stress band observed in the numerical model corresponds closely with to the documented crack locations and distribution in the tunnel, demonstrating good spatial agreement between modeled and real damage (Figure 52).

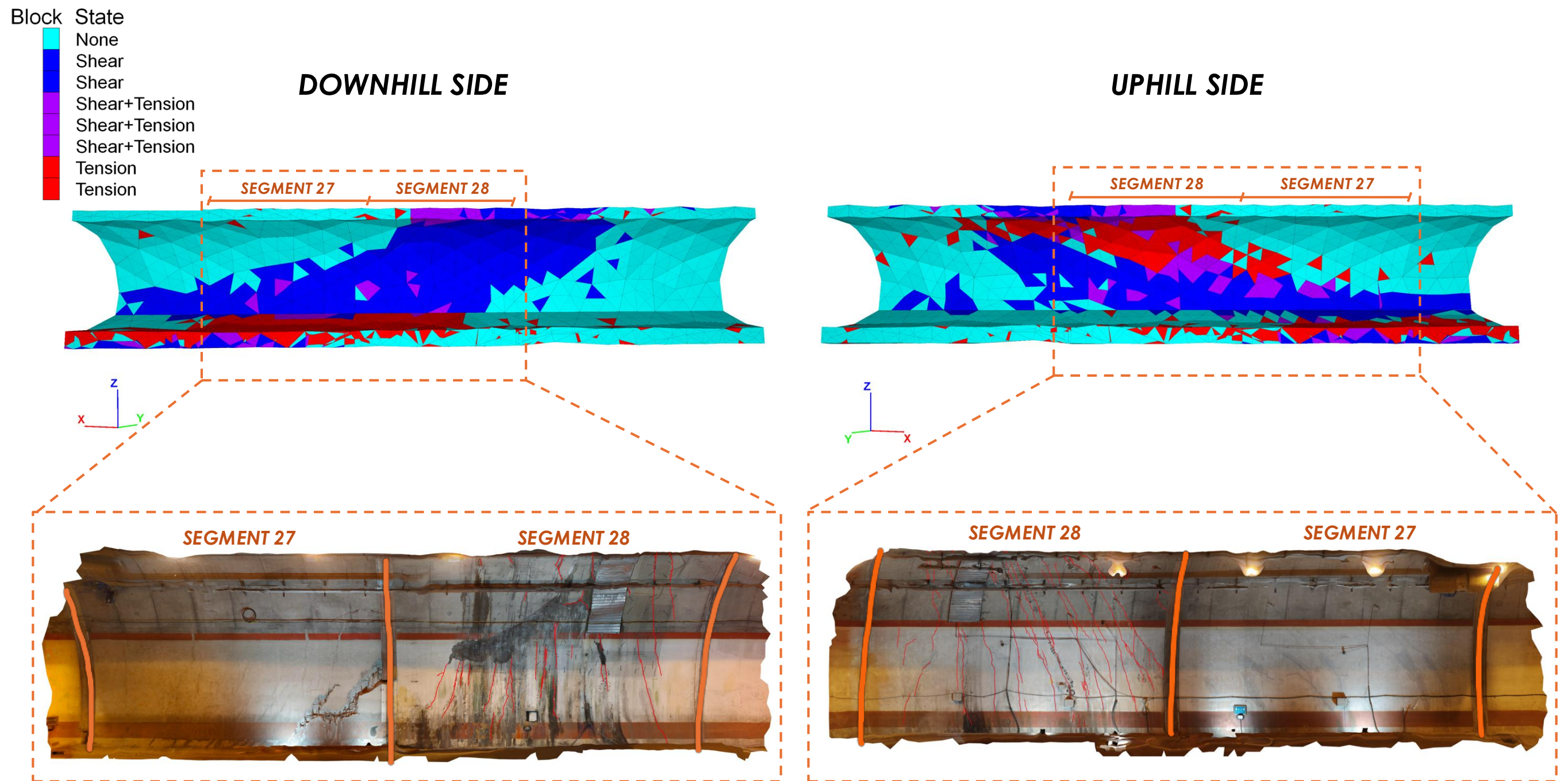


Figure 52 - Comparison between model resulting stress state and actual cracks pattern in the mostly damaged segments (i.e., segments 27 and 28)

The spatial correlation between tensile stress concentrations, elevated principal strain increments, and maximum displacement magnitudes all focusing on the shear zone intersection confirms tunnel response. This consistency corroborates that the multi-scale modelling approach successfully reproduces not only first-order deformation patterns but also the associated stress states that drive crack initiation and propagation observed in field monitoring, thereby confirming the mechanical validity of the transferred landslide loading from the large-scale model.

Results from the numerical analysis were compared with monitoring data from crackmeters located at the interface between segments 29 and 28 (i.e., F17) and segments 28 and 27 (i.e., F18). The numerical model showed on the downhill side a closure pattern, with segments 29 and 28 moving toward each other, and, on the other hand, an opening between segments 28 and 27, both movements consistent with roto-translational conditions. Monitoring data of crackmeter F17 and F18 showed a closing and opening deformation, respectively, in agreement with numerical results (Figure 53).

While absolute magnitudes may differ due to simplified constitutive modelling and incomparability between real and model time, the qualitative comparison presented shows that the employed multi-scale approach could reproduce first-order tunnel response mechanisms, in terms of stress, strain, and deformation patterns and distribution.

The tunnel model successfully achieved its primary objectives within the multi-scale framework:

1. Demonstrating that stress and velocity fields can be transferred from the large-scale FLAC3D model and can provide sufficient mechanical information to drive realistic infrastructure response, validating the data transfer procedure.
2. Capturing the essential deformation mechanisms observed in the field, confirming that the multi-scale approach can reproduce fundamental structural response, and providing quantitative evidence of model validity through direct comparison with monitoring data
3. Reproducing numerically the distribution of stress concentration, displacement field, and damaged zones, allowing comparison with observed crack locations and highlighting the mechanical processes responsible for damage distribution in the tunnel.
4. Demonstrating that the multi-scale approach can effectively address the scale integration challenge.

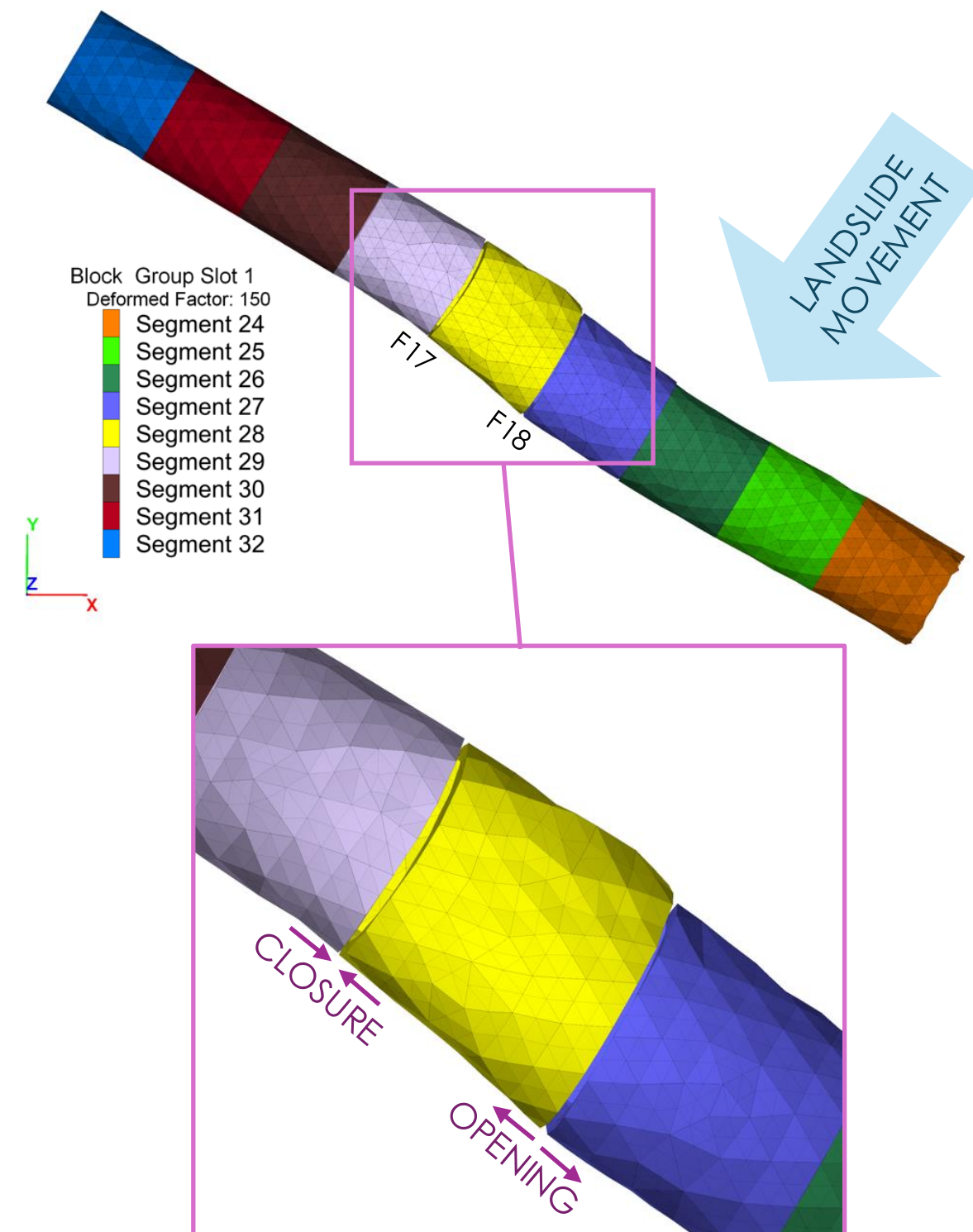
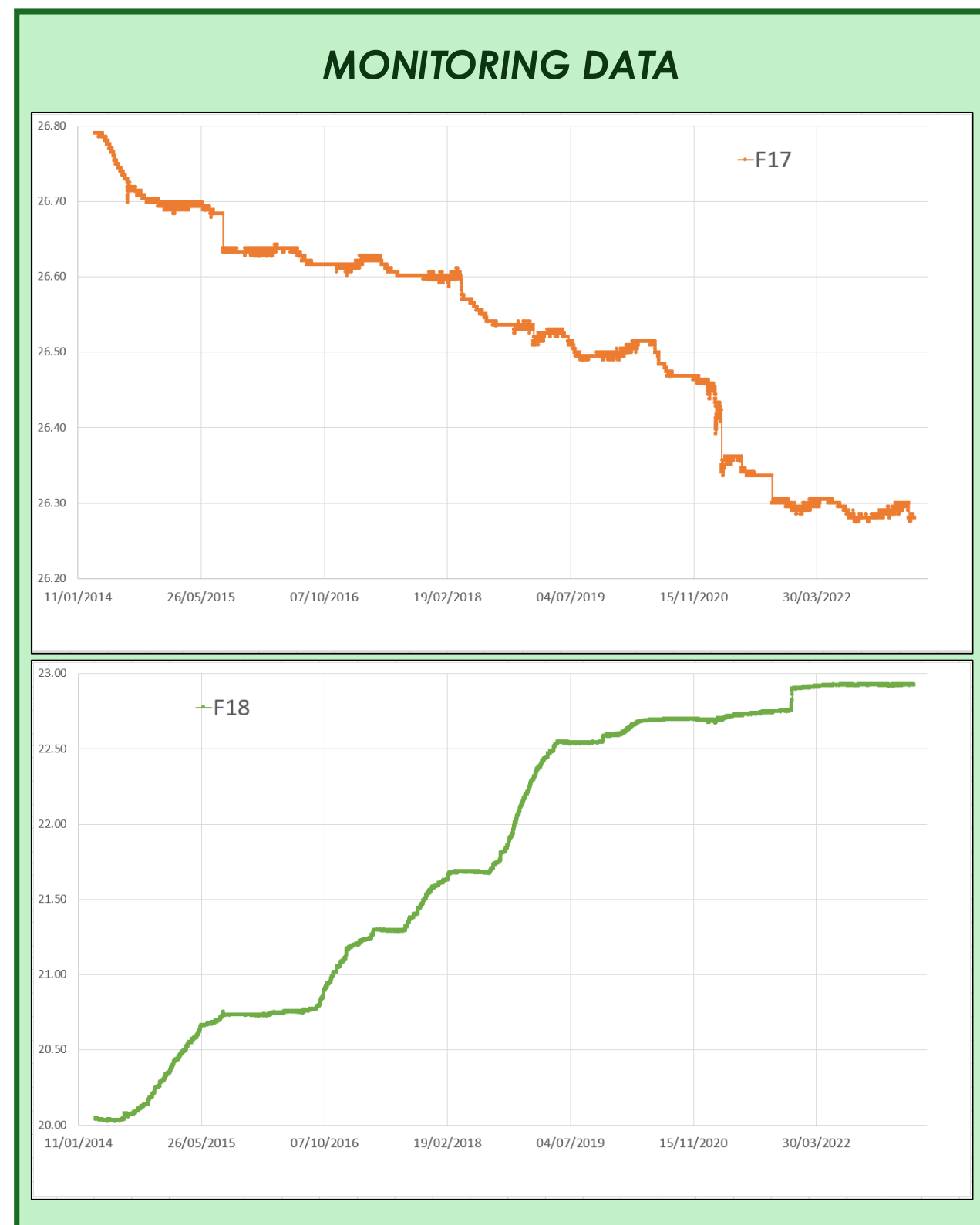


Figure 53 - Comparison of crackmeter measurements with model-predicted crack opening/closing at corresponding locations

4.4.5. Limitations and challenges

The tunnel model necessarily incorporated several simplifications and assumptions, whose implications must be understood for appropriate interpretation of the results.

The simplified tunnel geometry provided computational feasibility to the model. Eliminating non-structural elements from the tunnel section geometry and combining primary and final linings in a single material certainly reduced computational effort, but also prevented the complex behavior of the composite lining to be investigated (e.g., potential delamination, differential deformation). Moreover, tunnel curvature in plan view may induce additional stress redistribution that cannot be captured by the straight-tunnel approximation.

The Mohr-Coulomb model adopted for concrete lining effectively provides basic strength-limit representation but does not explicitly simulate progressive damage evolution or crack propagation paths. The model therefore presently provides qualitative indication of damage zones, rather than precise crack pattern and orientations.

Concrete creep, hydrogeological cycles, seasonal loading variations, and multi-year construction history are not explicitly represented to limit model complexity. This modelling choice is consistent with the primary objective of the thesis, namely, the verification of the proposed methodology, and is further justified by the slow displacement rates and gradual damage accumulation observed both in situ and in the monitoring data. Accordingly, the adopted assumptions were considered appropriate for analyzing the structural response under sustained landslide loading.

As discussed in the data transfer procedure section, velocity boundary conditions were applied only to exterior surfaces of the import volume rather than throughout the interior as a necessary compromise in favor of computational feasibility. While equilibration demonstrated that interior velocities develop consistently with surface conditions, this approach requires an initial run to equilibrium to be performed, resulting in slightly longer runtime during which transient adjustment occurs.

The qualitative agreement with monitoring data confirms that fundamental damage mechanisms are captured, despite the adopted simplifications. Indeed, model validation employed primarily qualitative comparison of deformation patterns rather than quantitative magnitude matching. However, the correspondence in deformation patterns shows that the coupled landslide-tunnel system behavior is realistically captured.

Despite these limitations, the agreement between observed structural damage features and tunnel model results demonstrates that the multi-scale approach can integrate landslide-scale processes with infrastructure-scale response analysis and can provide insights into damage drivers that would be impractical with conventional, single-scale modelling approaches.

4.5. Summary and outlook

This chapter has presented the application of the proposed multi-scale approach to the Passo della Morte LIS. Through the systematic development of a landslide-scale FLAC3D model, a tailored multi-scale data transfer procedure, and an infrastructure-scale 3DEC model, the introduced numerical framework was capable of reproducing key deformation patterns and damage distributions observed in field monitoring data. The landslide model captured displacement gradients consistent with GNSS and inclinometric measurements, the data transfer procedure maintained mechanical consistency across the scale transition, and the tunnel model exhibited stress concentrations and joint behavior qualitatively aligned with documented crack patterns and crackmeter measurements.

However, it is worth outlining some considerations regarding this application, mentioning slight modifications or improvements that might allow model optimization or could be worth exploring further.

4.5.1. *Landslide-scale model potential improvements*

The landslide model successfully reproduced kinematic behavior and provided boundary conditions for tunnel analysis, but several aspects of the implementation represent pragmatic simplifications that could be refined.

Shear zone representation

The uniform 6-meter thickness adopted for the shear zone simplified the spatially variable thickness observed in inclinometric data. Future refinement of the Passo della Morte landslide model should investigate variable shear zone thickness accounting for its documented spatial variability. Sensitivity analysis systematically varying thickness could quantify how this parameter influences both overall landslide kinematics and transferred loading patterns in the tunnel vicinity and thus to the tunnel directly.

Mesh discretization

The variable refinement strategy employed 0.5 m elements in the extraction volume surrounding the tunnel, 3 m elements for the shear zone, 15 m elements in the central landslide domain, and progressively coarser elements toward model boundaries. Further mesh densification of both the extraction volume and the shear zone would certainly enrich the reproduction of landslide dynamics. This would provide higher-resolution reproduction of the landslide movement pattern and consequently of stress and velocity fields, potentially reducing spatial interpolation requirements. The computational cost of such refinement could be offset through domain decomposition strategies that distribute calculations across multiple processors or similar strategies.

Geological simplification

The simplified fracture network implemented in the dolomite unit, but not activated in the present analysis, could represent a significant opportunity for model enhancement. Indeed, activating these discontinuities would allow the dolomite to behave as an assembly of multiple, independent blocks, potentially influencing both the modelled dynamics of the landslide and the response of the tunnel. This modification could substantially alter stress patterns transmission and be exploited for investigating the drainage tunnel's effectiveness, since fracture networks play a primary role in controlling groundwater flow paths. However, such an enhancement may only be possible as and if adequate data, in terms of dolomite deformation and groundwater flow paths, becomes available, to limit uncertainty in the model.

Hydrogeological coupling

With reference to the above, the absence of explicit groundwater modelling represents one of the most significant limitations of the current landslide model. Pore pressures and groundwater flow, seasonal fluctuations, and the influence of the drainage tunnel have not been investigated yet within the landslide model. Incorporating coupled hydro-mechanical analysis would substantially enhance model realism for the Passo della Morte case study. This implementation would certainly require a general strengthening of the geological model. Additionally, it would be required to define permeability distributions for each geological unit based on field testing, specify hydraulic boundary conditions representing the Tagliamento River and the drainage tunnel, and couple pore pressure evolution with mechanical deformation through effective stress calculations. This enhancement would also enable investigation of how precipitation patterns influence landslide displacement and consequently tunnel loading intensity.

Constitutive behavior

The elastic-perfectly plastic Mohr-Coulomb model proved to be computationally efficient but cannot capture time-dependent deformation mechanisms of rock materials. The Passo della Morte landslide exhibits slow, continuous movement, possibly suggesting viscous behavior not represented by rate-independent plasticity. Implementing viscoplastic constitutive would enable simulation of strain-rate-dependent behavior. This refinement would address the current model's limitation to quasi-static snapshots rather than true time-dependent analysis.

4.5.2. Multi-scale data transfer procedure potential improvements

The data transfer procedure successfully conveyed velocity and stress fields from FLAC3D to 3DEC, maintaining spatial coherence as confirmed by field velocity and stress distribution comparisons. However, several aspects could be refined in future applications to the Passo della Morte case study analysis.

Extraction and import volume dimensions

The 108 m × 30 m × 30 m extraction volume and 108 m × 20 m × 20 m import volume provided adequate spatial extent for the nine-segment tunnel section, but these dimensions could be systematically optimized. The 10 m dimensional difference between extraction and import volumes (eventually creating 5 m buffers on four sides) ensured data availability for proximity mapping but may be unnecessarily conservative or insufficient depending on the spatial correlation length of stress and velocity fields. Similarly, the decision to incorporate nine segments could be investigated, looking for differences in adopting a smaller or greater number of segments. Systematic sensitivity analysis varying consistently both extraction and import volumes would establish optimal sizing for the Passo della Morte case.

Spatial discretization mismatch

The resolution difference between the extraction volume in the landslide-scale model and the tunnel-scale model mesh required proximity-based interpolation during data transfer. While this approach proved to be functional, direct element-to-element correspondence would eliminate spatial approximation. For the Passo della Morte application, achieving consistent discretization would require refining the tunnel model to 0.5 m blocks. Further mesh refinement would allow a more detailed reproduction of the spatial distribution of deformation and damage, enhancing comparison with field data (at the price of increasing computational requirements).

Velocity application strategy

To ensure reasonable implementation times within the FISH scripting framework, velocity boundary conditions were applied only to the external surfaces of the import volume, rather than throughout its interior. Nevertheless, the subsequent 30000-cycle equilibration phase required additional runtime to allow interior velocities to develop consistently with the imposed surface conditions and resulted in minor deviations from the original FLAC3D interior velocity field. . The effects of the application of velocities on the entire volume could be explored.

Automation level

The implemented protocol required substantial manual intervention for volume definition, Python script execution, data file management, and FISH script invocation, making this manual workflow time-consuming and potentially susceptible of errors by the user. Developing an integrated procedure that automates the complete sequence, from FLAC3D data extraction, through format conversion, to 3DEC import and application, would enhance reproducibility and efficiency for future analyses.

4.5.3. Infrastructure-scale model potential improvements

The tunnel model successfully demonstrated that transferred landslide loading drives structural response qualitatively consistent with observed damage patterns, but the following aspects may be further explored to evaluate their effect.

Mesh resolution

The change from the intended 1 m to 3 m block size represented a significant compromise driven by computational limitations. Increasing resolution would surely enhance the reproducibility of spatial distribution of damage and, potentially, the ability to reproduce single or clusters of damage features, i.e. detailed crack propagation paths.

Geometric simplification

Several tunnel geometry simplifications prioritized computational efficiency over structural detail. Therefore, restoring complexity would enhance model realism for Passo della Morte.

The current single-layer equivalent lining limited the investigation of interface behavior. Explicit two-layer representation would require defining contact properties between shotcrete and concrete, enabling analysis of potential delamination at their interface.

Material property differentiation reflecting shotcrete's typically lower strength compared to cast concrete would also influence stress distributions and damage locations.

Steel reinforcement bars are implicitly included through adjusted concrete properties rather than explicitly modeled as structural elements. Explicit representation through embedded beam elements or reinforcement layers would capture localized reinforcement effects, assess whether bar spacing influences crack orientations, and enable evaluation of reinforcement adequacy under observed loading.

The straight-tunnel approximation neglects horizontal curvature and the humpback longitudinal profile present in the actual San Lorenzo tunnel. For the 108 m model length, both horizontal curvature and humpback profile introduced modest deviations from the straight geometry, but, if a longer tunnel portion were to be considered, they might potentially affect stress and damage distributions, and interact with landslide-induced loading.

Construction staging

The assumption of instantaneous excavation and lining installation neglects the stress evolution associated with construction sequence. In contrast, construction history of the Passo della Morte tunnel was complex. Initial works were undertaken between 1994 and 1996, interrupted until 2006 due to the landslide-induced damage, and then resumed with the installation of reinforced segmented lining in the first 400 m of the tunnel from the eastern entrance (Ampezzo side).

Tunnel lining constitutive model

The Mohr-Coulomb model captures strength limits but not progressive damage evolution. For Passo della Morte, where crack propagation and opening are primary failure mechanisms, this limitation prevents detailed damage simulation. Implementing 3DEC's Concrete constitutive model or other suitable models (i.e., smeared cracking, plasticity-damage) would enable representation of progressive damage accumulation. Parameterization would require laboratory testing data for the specific concrete mix used in the reconstructed segments but, if such data are unavailable, calibration against the crackmeter measurements could also constrain parameters through inverse modelling. Comparative studies applying different constitutive models to the San Lorenzo geometry would establish which formulation best reproduces observed crack patterns and joint behavior. Further improvements in this direction could involve exploring different possibilities for improving and facilitating the reproduction of the concrete damage mechanism, i.e. the use of Voronoi tessellation to allow brittle fracturing to be simulated.

Hydrogeological representation

Similarly to the landslide model, the tunnel model excludes explicit groundwater representation. This potential enhancement would enable investigation of hydraulic loading contribution to the lining stress, drainage tunnel effectiveness in pressure reduction, and whether observed water seepage patterns correlate with predicted hydraulic gradients. The drainage tunnel could be represented as a prescribed low-pressure boundary or explicitly modelled as a second excavation with appropriate hydraulic boundary conditions. Sensitivity analysis varying pore pressure magnitudes would quantify the relative importance of hydraulic versus mechanical loading for the San Lorenzo damage patterns.

Temporal analysis

The adopted approach accumulates deformation over an unspecified timespan, with cycle count serving as a proxy for time without direct correlation to real time. The 3400000 cycles required to achieve 3 cm displacement cannot be directly converted to years without viscosity parameters. For Passo della Morte case, where monitoring data provides crack opening rates and displacement rates, true time-dependent analysis would enable a more quantitative validation. Implementing time-stepping with viscoplastic concrete models (e.g., Burgers creep model, power-law creep) would transform cycle-based results into calendar-dated predictions, enabling direct comparison with monitoring time series and potentially revealing whether damage accumulation is steady or episodic.

5. Conclusions

This research originated from a fundamental challenge identified through systematic review of landslide-infrastructure interaction literature: the multi-scale challenge. Existing approaches, whether landslide-centric, infrastructure-centric, or systemic, consistently struggle to achieve adequate resolution for both slope processes and structural response simultaneously. Landslide-centric approaches capture regional deformation patterns but treat infrastructure as simplified boundary conditions, precluding detailed structural response analysis. Infrastructure-centric approaches achieve high structural resolution but prescribe landslide-induced actions as simplified loading assumptions, disconnecting tunnel damage and failure from actual slope kinematics. Even systemic approaches, which explicitly incorporate both elements, face computational constraints that require compromises: either landslide representation must be simplified to achieve sufficient tunnel detail, or the mesh of the infrastructure must be significantly coarsened to ensure computational feasibility.

The core difficulty lies in the inherent scale disparity between phenomena. Large landslides extend hundreds of meters and are possibly characterized by complex, heterogeneous material distributions requiring coarse discretization for computational feasibility, while infrastructure damage manifests at centimeter to meter scales, requiring fine resolution to be captured. Modelling both elements within a single numerical domain at meaningful resolutions remains computationally prohibitive for most real-world scenarios. This scale integration problem represents not merely a technical inconvenience, but a fundamental obstacle preventing comprehensive understanding of how slope instabilities translate into localized structural failure.

This thesis proposed a solution for addressing the multi-scale challenge in LIS through a strategy that exploits the nested modelling technique, which has been adopted from successful applications in atmospheric science, hydrology, coastal and mining engineering, and other disciplines facing analogous scale-mismatch problems. The proposed multi-scale approach explicitly separates spatial scales while establishing rigorous procedures for mechanical information transfer between them. A coarser-resolution landslide-scale model captures bulk slope behavior, displacement rates, and stress distribution, while a finer-resolution infrastructure-scale model focuses on structural response, with the two connected through systematic procedures for extraction and transfer of boundary conditions. This hierarchical framework concentrates computational resources strategically: coarse but adequate resolution for slope processes, fine resolution only where required for infrastructure analysis.

The methodological development and validation through application demonstrated that this nested modelling strategy can successfully bridge the scale gap. More

generally, this thesis has demonstrated the validity of an approach based on recognizing the differences, primarily in scale, between phenomena within the same system, giving relevance to each of them and, at the same time, to the system itself, assigning the appropriate degree of detail to each component. Critical variables extracted from slope-scale models effectively drive infrastructure-scale models, while maintaining physical and mechanical consistency across the scale transition. This capability enables the transfer of landslide-induced action and the consequent reproduction of observed deformation patterns and damage distributions. The multi-scale approach therefore provides a robust methodology for scale integration in landslide-infrastructure interaction analysis through a carefully designed coupling procedure.

The Passo della Morte case study has successfully served as a validation testbed for the proposed approach, demonstrating technical feasibility and revealing areas where focused refinement could substantially enhance overall performance. The limitations and improvements identified in the application sections provide a structured pathway for advancing the numerical modelling of this specific LIS, supporting continued research activities and contributing to evidence-based infrastructure management decisions.

This dissertation also revealed that this approach does not represent a ready-to-use solution. Indeed, the multi-scale framework ultimately explores a new perspective for investigating landslide-infrastructure systems, demonstrating that coupled analysis spanning multiple scales is technically feasible and can yield insights unattainable through conventional single-scale approaches. For each case, geological and infrastructure characteristics must be carefully evaluated in order to ensure the method can be successfully applied. Hence, the value of this approach lies not in providing an immediately deployable solution to investigate real-world LISs scenarios, but in establishing a viable pathway to achieve a better and deeper understanding of the landslide-infrastructure interaction and identifying what data, tools and method are required to advance that understanding, and, thus, along that pathway.

5.1. Advantages of the multi-scale approach

The proposed methodology offers several fundamental advantages that distinguish it from commonly used approaches and justify continuing in its development.

Holistic system representation

By explicitly modelling both landslide and infrastructure at appropriate scales, while correlating them through the transfer of relevant data between them, the approach enables investigation of their interaction efficiently and in detail. This holistic

perspective supports analysis of system-level behavior rather than isolated component response, revealing emergent phenomena arising from landslide-infrastructure coupling that would remain hidden in single-scale analyses.

Scale-appropriate resolution

The nested modelling approach allows each subsystem to be represented at a scale that is suitable for investigating the governing mechanisms and processes. Slope-scale deformation, controlled by major scale geological structures and material distributions, can be efficiently modelled with relatively coarse discretization. Infrastructure damage, governed by local stress concentrations and material failure at the scale of single or multiple structural elements requires finer resolutions to be effectively investigated through numerical modelling. This scale decoupling aims at optimizing the computational effort of applying uniform fine discretization throughout large domains while preventing information loss inherent in uniformly coarse models. The strategic allocation of resolution enables analyses that would be computationally unfeasible in single-scale frameworks.

Mechanically realistic boundary conditions

Infrastructure boundary conditions derived from landslide model outputs represent slope-induced stress and deformation fields at the time of the modelled tunnel construction rather than simplified assumptions. Conventional infrastructure analyses typically apply simplified pressure distributions as loading boundary conditions, poorly representing the complex, spatially heterogeneous stress states induced by landslides. The multi-scale approach takes advantage of mechanically derived loading patterns that reflect actual landslide behavior, obviates the need for oversimplified assumptions, and enhances realism of infrastructure response predictions.

Flexibility and extensibility

The nested modelling concept provides a flexible framework that can be adapted to a variety of scenarios. Different numerical methods can be employed at each scale based on problem requirements, as the framework accommodates multi-physics (hydrogeological coupling, thermal effects, seismic loading) at appropriate scales. Multiple infrastructure elements can also be analyzed using boundary conditions from a single landslide model, supporting comparative studies. This architectural flexibility allows the approach to evolve as numerical capabilities advance and case-specific understanding and requirements emerge.

5.2. Challenges and requirements of the multi-scale approach

Despite these advantages, the multi-scale methodology faces significant challenges and limitations, imposing substantial requirements that constrain its practical application.

Data intensity

Successful implementation demands comprehensive characterization and data spanning both spatial scales. For the landslide model, detailed geological mapping, stratigraphic sequences from boreholes, geotechnical property of the different lithologies involved and their spatial distributions, structural feature characterization, and long-term, in-hole and surface monitoring records (e.g., inclinometers, GNSS, piezometers) for calibration and validation are needed. For the infrastructure model, precise geometric documentation, construction method details, material properties, and damage observation and monitoring records are required to build and validate the model. As seen also with the Passo della Morte case, many landslide-infrastructure sites lack this data richness, particularly for older infrastructure where construction documentation may be incomplete, and systematic monitoring was not implemented. Applying the multi-scale approach to data-limited sites would require either variably extensive investigation campaigns or acceptance of greater uncertainty in model performance.

Knowledge requirements for informed simplification

Alongside data quality and quantity, a high level of understanding of the phenomena under investigation is required. The methodology inherently involves simplifications at multiple stages, from the landslide geological and geomechanical aspects to the infrastructure geometry and material modelling. Simplifications and assumptions are not weaknesses per se, but distinguishing essential complexity from negligible detail demands appropriate knowledge of the site. The multi-scale approach demands interdisciplinary expertise, spanning from geotechnical engineering and structural mechanics to numerical methods and site-specific geological knowledge. Inappropriate simplifications motivated by convenience rather than physical understanding can compromise model validity, potentially producing seemingly detailed but inaccurate results.

Computational demands

Even with strategic resolution allocation, the multi-scale approach remains computationally expensive compared to conventional analyses. The landslide model, despite coarse discretization in peripheral regions, must encompass large spatial

domains with sufficient resolution in extraction volumes to support fine-scale infrastructure analysis. On the other hand, the infrastructure model, requiring fine discretization for structural detail, generates large element counts and contact surface areas that demand substantial memory and processing time. Data transfer procedures add overhead through boundary condition application. Furthermore, as trivial as it may seem, it is inherently required to work on two models rather than one. Access to high-performance computing resources substantially mitigates this limitation but introduces additional barriers related to code licensing, job scheduling, and technical expertise in parallel computing. The computational burden therefore limits the applicability of the approach to scenarios where the investment is justified by problem importance and data availability.

Challenges in software-specific implementation

The data transfer procedures are inherently tied to the specific numerical codes employed at each scale. Different software packages employ different models, program structures, coordinate systems, variable conventions, and scripting interfaces. Transferring mechanical fields between codes may require custom protocol development specific to each software pairing. The FLAC3D-to-3DEC transfer demonstrated here benefited from both codes being Itasca products with shared scripting languages (FISH, Python) and similar conceptual frameworks. Coupling codes from different developers (e.g., FLAC3D to ABAQUS, PLAXIS to 3DEC) would face additional compatibility challenges.

5.3. Outlook and future development

These advantages and limitations collectively define the current state of multi-scale landslide-infrastructure interaction analysis and establish a foundation for future development, as the approach is not yet a widely and readily applicable tool for routine engineering deployment.

The primary contribution lies in demonstrating a new perspective for investigating coupled LISs. By adapting nested modelling concepts and developing specific coupling procedures for geomechanical applications, this research establishes that the constraint is technical rather than fundamental. Limitations reside in profound knowledge of the real-world case study under examination, large data availability, numerical method selection, computational power and capabilities, and can be therefore addressed through appropriate methodological frameworks. By identifying these specific requirements for successful multi-scale analysis (i.e., data needed, computational

resources, and expertise), practitioners considering this approach can assess whether their scenarios meet these requirements.

As numerical capabilities continue advancing, computational resources become more accessible, and collaborative communities develop shared tools and procedures, the practical applicability of multi-scale approaches will expand. Sites that currently lack sufficient characterization may receive enhanced monitoring as awareness of risk related to landslide-infrastructure interaction grows. Technical and interdisciplinary teams bridging geological, infrastructural, and computational expertise may become more common as the field recognizes the necessity of integrated analysis.

Eventually, this thesis demonstrates that the *multi-scale challenge* can be successfully tackled. Through careful methodological design informed by data, landslide-infrastructure interaction analysis can achieve the scale integration that is necessary for a comprehensive understanding of the investigated site. The path forward is clear, though demanding: continued refinement of coupling procedure, accumulation of validated case studies, development of community resources, and persistent effort to bridge the gap between methodological demonstration and routine practice. This work establishes methodological general principles of the multi-scale approach and identifies technical requirements that can guide future research toward developing this approach into a mature, widely applicable numerical framework for LIS.

References

- Abbas, Z., Khellaf, M. C., Amarouche, K., & Akpinar, A. (2025). Implementation and calibration of a nested WW3-SWAN model for simulating waves under varying and extreme weather conditions: Case Study of the Algerian Coast. *Ocean Engineering*, 341, 122510. <https://doi.org/10.1016/j.oceaneng.2025.122510>
- Amorim, D. L. N. de F., Proença, S. P. B., & Flórez-López, J. (2014). Simplified modeling of cracking in concrete: Application in tunnel linings. *Engineering Structures*, 70, 23–35. <https://doi.org/10.1016/j.engstruct.2014.03.031>
- ARPA FVG. (2023). Il clima del Friuli Venezia Giulia. <https://www.arpa.fvg.it/temi/temi/meteo-e-clima/pubblicazioni/il-clima-del-friuli-venezia-giulia-2023/> (accessed on 30/10/2025, in Italian)
- Asch, Theodore W.J. van, Jean-Philippe Malet, Ludovicus P.H. van Beek, & David Amitrano (2007). Techniques, issues and advances in numerical modelling of landslide hazard. *Bulletin de la Société Géologique de France* 178 (2): 65–88. <https://doi.org/10.2113/gssgfbull.178.2.65>.
- Ashtiani, M., Palassi, M., & Ahmadi, A. (2010). Effect of excavation of tunnels in the convex slopes using Distinct Element Method. *ISRM International Symposium - EUROCK 2010*.
- Auflīč, M. J., Herrera, G., Mateos, R. M., Poyiadji, E., Quental, L., Severine, B., Peternel, T., Podolszki, L., Calcaterra, S., Kociu, A., Warmuz, B., Jelének, J., Hadjicharalambous, K., Becher, G. P., Dashwood, C., Ondrus, P., Minkevičius, V., Todorović, S., Møller, J. J., & Marturia, J. (2023). Landslide monitoring techniques in the Geological Surveys of Europe. *Landslides*, 20(5), 951–965. <https://doi.org/10.1007/s10346-022-02007-1>
- Augarde, C. E., Lee, S. J., & Loukidis, D. (2021). Numerical modelling of large deformation problems in geotechnical engineering: A state-of-the-art review. *Soils and Foundations*, 61(6), 1718–1735. <https://doi.org/10.1016/j.sandf.2021.08.007>
- Ballaera, A., Festi, P., Borgatti, L., Bossi, G., & Marcato, G. (2024). Investigation and monitoring for ever-updating engineering geological models: the example of the Passo della Morte landslide system. *Geosciences*, 14(4), 94. <https://doi.org/10.3390/geosciences14040094>
- Bao, L., & Wei, F. (2023). Study on the response of tunnel lining under fault dislocation. *sustainability*, 15(6), 5150. <https://doi.org/10.3390/su15065150>

- Barla, G. (2016, August 29). Applications of numerical methods in tunnelling and underground excavations: recent trends. ISRM International Symposium - EUROCK 2016.
- Barla, G. (2018). Numerical modeling of deep-seated landslides interacting with man-made structures. *Journal of Rock Mechanics and Geotechnical Engineering*, 10(6), 1020–1036. <https://doi.org/10.1016/j.jrmge.2018.08.006>
- Berahmand, K., Zhou, X., Li, Y., Gururajan, R., Barua, P. D., Acharya, U. R., & Chennakesavan, S. K. (2025). NEDL-GCP: A nested ensemble deep learning model for Gynecological cancer risk prediction. *Array*, 27, 100468. <https://doi.org/10.1016/j.array.2025.100468>
- Berardino, P., Fornaro, G., Lanari, R., & Sansosti, E. (2002). A new algorithm for surface deformation monitoring based on small baseline differential SAR interferograms. *IEEE Transactions on Geoscience and Remote Sensing*, 40(11), 2375–2383. <https://doi.org/10.1109/TGRS.2002.803792>
- Bossi, G., Schenato, L., & Marcato, G. (2017). Structural health monitoring of a road tunnel intersecting a large and active landslide. *Applied Sciences*, 7(12), 1271. <https://doi.org/10.3390/app7121271>
- Bossi, G., Zabuski, L., Pasuto, A., & Marcato, G. (2016). Capabilities of continuous and discontinuous modelling of a complex, structurally controlled landslide. *Geotechnical and Geological Engineering*, 34(5), 1677–1686. <https://doi.org/10.1007/s10706-016-0057-z>
- Cai, F., & Ugai, K. (2001). Discussion: Slope stability analysis by finite elements. *Géotechnique*, 51(7), 653–654. <https://doi.org/10.1680/geot.2001.51.7.653>
- Carulli, G., & Polonia, A. (1992). Analisi mesostrutturale, macrotettonica e morfogenesi di un settore dell'alta valle del fiume Tagliamento (Carnia Occidentale). *ATTI TICINENSIS DI SCIENZE DELLA TERRA*, 35, 39–45. (in Italian)
- Causse, L., Cojean, R., & Fleurisson, J.-A. (2015). Interaction between tunnel and unstable slope – Influence of time-dependent behavior of a tunnel excavation in a deep-seated gravitational slope deformation. *Tunnelling and Underground Space Technology*, 50, 270–281. <https://doi.org/10.1016/j.tust.2015.07.018>
- Ceccato, F., Yerro, A., & Di Carluccio, G. (2024). Simulating landslides with the material point method: Best practices, potentialities, and challenges. *Engineering Geology*, 338, 107614. <https://doi.org/10.1016/j.enggeo.2024.107614>

- Chen, B., Maurer, J., & Gong, W. (2025). Applications of UAV in landslide research: A review. *Landslides*, 22(9), 3029–3048. <https://doi.org/10.1007/s10346-025-02547-2>
- Chen, Y., Li, P., Lu, S., Sun, Z., & Zhu, S. (2024). Landslide–tunnel interactions and control countermeasures under an orthogonal system. *Applied Sciences*, 14(13), 5479. <https://doi.org/10.3390/app14135479>
- Cheng, Z., Gong, W., Tang, H., Juang, C. H., Deng, Q., Chen, J., & Ye, X. (2021). UAV photogrammetry-based remote sensing and preliminary assessment of the behavior of a landslide in Guizhou, China. *Engineering Geology*, 289, 106172. <https://doi.org/10.1016/j.enggeo.2021.106172>
- Chiu, Y.-C., Lee, C.-H., & Wang, T.-T. (2017). Lining crack evolution of an operational tunnel influenced by slope instability. *Tunnelling and Underground Space Technology*, 65, 167–178. <https://doi.org/10.1016/j.tust.2017.03.004>
- Ciptokusumo, J., Weide-Zaage, K., & Aubel, O. (2009). Investigation of stress distribution in via bottom of Cu-via structures with different via form by means of submodeling. *Microelectronics Reliability*, 49(9), 1090–1095. <https://doi.org/10.1016/j.microrel.2009.07.043>
- CluodCompare. (2021). CloudCompare (Version 2.10.3) [Computer software]. <https://cloudcompare.org/>
- Crosta, G. B., Imposimato, S., & Roddeman, D. G. (2003). Numerical modelling of large landslides stability and runout. *Natural Hazards and Earth System Sciences*, 3(6), 523–538. <https://doi.org/10.5194/nhess-3-523-2003>
- Cruden, D.M., Varnes, D.J., 1996. Landslide types and processes, Transportation Research Board, U.S. National Academy of Sciences, Special Report, 247: 36-75. Special Report - National Research Council, Transportation Research Board, 247, 36–57.
- Damiano, E., Battipaglia, M., de Cristofaro, M., Ferlisi, S., Guida, D., Moliterno, E., Netti, N., Valiante, M., & Olivares, L. (2025). Innovative extenso-inclinometer for slow-moving deep-seated landslide monitoring in an early warning perspective. *Journal of Rock Mechanics and Geotechnical Engineering*, 17(8), 5359–5371. <https://doi.org/10.1016/j.jrmge.2024.10.021>
- Dassault Systemes Simulia Corp (2025). Abaqus. Dassault Systèmes, released. <https://www.3ds.com/products/simulia/abaqus>.

- Del Soldato, M., Solari, L., & Novellino, A. (2024). Landslide monitoring and mapping. *Geosciences*, 14(12), 350. <https://doi.org/10.3390/geosciences14120350>
- Donati, D., Stead, D., Brideau, M.-A., & Ghirotti, M. (2017). A remote sensing approach for the derivation of numerical modelling input data: insights from the Hope Slide, Canada. In: SAIMM (ed.). 'Rock Mechanics for Africa'. Proceedings of the ISRM International Symposium AfriRock Conference. 3-5 October 2017. Paper ISRMAFRIROCK-2017-066. 15 p.
- Duan, X., Hou, T., & Jiang, X. (2021). Study on stability of exit slope of Chenjiapo tunnel under extreme rainstorm conditions. *Natural Hazards*, 107(2), 1387–1411. <https://doi.org/10.1007/s11069-021-04636-6>
- Duan, Xiang, Tian-shun Hou, & Xiao-dong Jiang (2021). Study on stability of exit slope of Chenjiapo tunnel under extreme rainstorm conditions». *Natural Hazards* 107 (2): 1387–411. <https://doi.org/10.1007/s11069-021-04636-6>.
- Eberhardt, E. (2012). Landslide monitoring: The role of investigative monitoring to improve understanding and early warning of failure. In D. Stead & J. J. Clague (Eds.), *Landslides: Types, Mechanisms and Modeling* (pp. 222–234). Cambridge University Press. <https://doi.org/10.1017/CBO9780511740367.020>
- European Environment Agency. (2024). European climate risk assessment. Publications Office of the European Union. <https://data.europa.eu/doi/10.2800/8671471>
- Fan, H., Zhu, Z., Song, Y., Zhang, S., Zhu, Y., Gao, X., Hu, Z., Guo, J., & Han, Z. (2021). Water pressure evolution and structural failure characteristics of tunnel lining under hydrodynamic pressure. *Engineering Failure Analysis*, 130, 105747. <https://doi.org/10.1016/j.engfailanal.2021.105747>
- Fan, J., Zhang, Y., Zhou, W., & Yin, C. (2022). Landslide-tunnel interaction mechanism and numerical simulation during tunnel construction: A case from expressway in Northwest Yunnan Province, China. *Arabian Journal of Geosciences*, 15(16), 1394. <https://doi.org/10.1007/s12517-022-10680-8>
- Feng, J., Zhao, B., & Wang, Z. (2025). Seismic Dynamic Response Analysis Method of Tunnel Considering Coseismic Dislocation. *Rock Mechanics and Rock Engineering*, 58(6), 6557–6573. <https://doi.org/10.1007/s00603-025-04458-z>
- Ferretti, A., Prati, C., & Rocca, F. (2001). Permanent scatterers in SAR interferometry. *IEEE Transactions on Geoscience and Remote Sensing*, 39(1), 8–20. <https://doi.org/10.1109/36.898661>
- Festi, P., Bossi, G., Francioni, M., Marcato, G., Staboli, C., & Borgatti, L. (2023). Structural health of a road tunnel intersecting a large and active rock-block slide. *Italian*

- Flipo, N., Mouhri, A., Labarthe, B., Biancamaria, S., Rivière, A., & Weill, P. (2014). Continental hydrosystem modelling: The concept of nested stream–aquifer interfaces. *Hydrology and Earth System Sciences*, 18(8), 3121–3149. <https://doi.org/10.5194/hess-18-3121-2014>
- Gariano, S. L., & Guzzetti, F. (2016). Landslides in a changing climate. *Earth-Science Reviews*, 162, 227–252. <https://doi.org/10.1016/j.earscirev.2016.08.011>
- Giudici, M., Parravicini, G., Ponzini, G., Romano, E., & Villa, D. (2002). Nested models to simulate groundwater flow at different scales. In *Geophysical Research Abstracts* (Vol. 3).
- Hellsten, A., Ketelsen, K., Sühling, M., Auvinen, M., Maronga, B., Knigge, C., Barmpas, F., Tsegas, G., Moussiopoulos, N., & Raasch, S. (2021). A nested multi-scale system implemented in the large-eddy simulation model PALM model system 6.0. *Geoscientific Model Development*, 14(6), 3185–3214. <https://doi.org/10.5194/gmd-14-3185-2021>
- Hoek, E., & Brown, E. T. (1997). Practical estimates of rock mass strength. *International Journal of Rock Mechanics and Mining Sciences*, 34(8), 1165–1186. [https://doi.org/10.1016/S1365-1609\(97\)80069-X](https://doi.org/10.1016/S1365-1609(97)80069-X)
- Huang, C., Li, X., & Wen, M. (2022). Analysis of crack formation and growth in tunnel linings using Double-K fracture criterion. *Applied Sciences*, 12(3), 1064. <https://doi.org/10.3390/app12031064>
- Huang, K.-P., Wang, T.-T., Huang, T.-H., & Jeng, F.-S. (2010). Profile deformation of a circular tunnel induced by ambient stress changes. *Tunnelling and Underground Space Technology*, 25(3), 266–278. <https://doi.org/10.1016/j.tust.2009.12.006>
- Hungr, O., Leroueil, S., & Picarelli, L. (2014). The Varnes classification of landslide types, an update. *Landslides*, 11(2), 167–194. <https://doi.org/10.1007/s10346-013-0436-y>
- Insana, Alessandra, Marco Barla, & Davide Elmo (2016). Multi scale numerical modelling related to hydrofracking for deep geothermal energy exploitation. *Procedia Engineering*, VI Italian Conference of Researchers in Geotechnical Engineering, CNRIG2016 - Geotechnical Engineering in Multidisciplinary Research: from Microscale to Regional Scale, 22-23 September 2016, Bologna (Italy), vol. 158 (January): 314–19. <https://doi.org/10.1016/j.proeng.2016.08.448>.

- Itasca Consulting Group, Inc. (2020). Griddle (Version 2.0) [Computer software]. Itasca. <https://itascasoftware.com/it/staging/4017/products/griddle/>
- Itasca Consulting Group, Inc. (2023a). 3DEC 9.0 Software Documentation. <https://www.itascainternational.com/software/3dec>
- Itasca Consulting Group, Inc. (2023b). FLAC (FLAC2D/FLAC3D) 9.0 Software Documentation. <https://www.itascainternational.com/software/FLAC3D>
- Itasca Consulting Group, Inc. (2023c). Scripting Documentation. <https://docs.itascacg.com/itasca900/common/docproject/source/manual/scripting/scripting.html?node7634>
- Iverson, R. M., & George, D. L. (2015). Modelling landslide liquefaction, mobility bifurcation and the dynamics of the 2014 Oso disaster. *Géotechnique*, 66(3), 175–187. <https://doi.org/10.1680/jgeot.15.LM.004>
- Jiao, Y.-Y., Wang, Z.-H., Wang, X.-Z., Adoko, A. C., & Yang, Z.-X. (2013). Stability assessment of an ancient landslide crossed by two coal mine tunnels. *Engineering Geology*, 159, 36–44. <https://doi.org/10.1016/j.enggeo.2013.03.021>
- Kazhdan, M., Bolitho, M., & Hoppe, H. (2006). Poisson surface reconstruction. In *Proceedings of the fourth Eurographics symposium on Geometry processing (SGP '06)*. Eurographics Association, Goslar, DEU, 61–70.
- Koizumi, Y., Lee, J., Date, K., Yokota, Y., Yamamoto, T., & Fujisawa, K. (2010, June 15). Numerical analysis of landslide behavior induced by tunnel excavation. *ISRM International Symposium - EUROCK 2010*.
- Komu, M. P., Guney, U., Kilickaya, T. E., & Gokceoglu, C. (2020). Using 3D Numerical Analysis for the assessment of tunnel–landslide relationship: Bahce–Nurdag Tunnel (South of Turkey). *Geotechnical and Geological Engineering*, 38(2), 1237–1254. <https://doi.org/10.1007/s10706-019-01084-9>
- Konagai, K., Numada, M., Zafeirakos, A., Johansson, J., Sadr, A., & Katagiri, T. (2005). An example of landslide-inflicted damage to tunnel in the 2004 Mid-Niigata Prefecture earthquake. *Landslides*, 2(2), 159–163. <https://doi.org/10.1007/s10346-005-0057-1>
- Lee, C.-H., Chiu, Y.-C., Wang, T.-T., & Huang, T.-H. (2013). Application and validation of simple image-mosaic technology for interpreting cracks on tunnel lining. *Tunnelling and Underground Space Technology*, 34, 61–72. <https://doi.org/10.1016/j.tust.2012.11.002>

- Li, T., Liang, J., & Bo, L. (2025). Dynamic response characteristics of tunnel linings at varied burial depths in landslide systems under seismic loading. *Scientific Reports*, 15(1), 7528. <https://doi.org/10.1038/s41598-025-89774-8>
- Lucieer, A., Jong, S. M. de, & Turner, D. (2014). Mapping landslide displacements using Structure from Motion (SfM) and image correlation of multi-temporal UAV photography. *Progress in Physical Geography: Earth and Environment*, 38(1), 97–116. <https://doi.org/10.1177/0309133313515293>
- Ma, G., Cao, H., Tao, Z., Lu, J., & Zhu, C. (2023). Experimental study on deformation and failure characteristics and monitoring and early warning of surrounding rock of tunnel crossing sliding surface. *Rock Mechanics and Rock Engineering*, 56(12), 9035–9056. <https://doi.org/10.1007/s00603-023-03543-5>
- Marazzi, S. (2005). *Atlante Orografico Delle Alpi*. Soiusa. Suddivisione orografica internazionale unificata del sistema alpino. Priuli & Verlucca. (in Italian)
- Marcato, G. (2007). *Valutazione della pericolosità da frana in località Passo della Morte*, PhD Thesis. University of Modena e Reggio Emilia. (in Italian)
- MIDAS IT Co., Ltd (2024). MIDAS GTS NX. MIDAS IT Co., Ltd, released. <https://www.midasuser.com/en/product/gts-nx>.
- Mikola, R. G. (2022). ORMAS: Online Rock Mass Strength (Version 2.0) [Computer software]. <http://www.roozbehgm.com/codes/ormas/ormas.html>
- Minardo, A., Catalano, E., Coscetta, A., Zeni, G., Zhang, L., Di Maio, C., Vassallo, R., Coviello, R., Macchia, G., Picarelli, L., & Zeni, L. (2018). Distributed fiber optic sensors for the monitoring of a tunnel crossing a landslide. *Remote Sensing*, 10(8), 1291. <https://doi.org/10.3390/rs10081291>
- Minglei, S., Hongwei, L., Yongquan, Z., Xinqiang, G., Huan, L., & Zhengguo, Z. (2022). Deformation and failure mode analysis of the tunnel structure based on the tunnel-related landslides cases. *Frontiers in Earth Science*, 10. <https://doi.org/10.3389/feart.2022.906884>
- Monegato, G., & Stefani, C. (2011). Preservation of a Long-Lived Fluvial System in a Mountain Chain: The Tagliamento Valley (Southeastern Italian Alps). In S. K. Davidson, S. Leleu, & C. P. North (Eds.), *From river to rock record: The preservation of fluvial sediments and their subsequent interpretation* (Vol. 97, p. 0). SEPM Society for Sedimentary Geology. <https://doi.org/10.2110/sepmsp.097.359>

- Nitzsche, K., & Herle, I. (2020). Strain-dependent slope stability. *Acta Geotechnica*, 15(11), 3111–3119. <https://doi.org/10.1007/s11440-020-00971-3>
- Notti, D., Galve, J. P., Mateos, R. M., Monserrat, O., Lamas-Fernández, F., Fernández-Chacón, F., Roldán-García, F. J., Pérez-Peña, J. V., Crosetto, M., & Azañón, J. M. (2015). Human-induced coastal landslide reactivation. Monitoring by PSInSAR techniques and urban damage survey (SE Spain). *Landslides*, 12(5), 1007–1014. <https://doi.org/10.1007/s10346-015-0612-3>
- OECD. (2019). ITF Transport Outlook 2019. OECD. https://www.oecd.org/en/publications/itf-transport-outlook-2019_transp_outlook-en-2019-en.html
- Ota, K., Kuraoka, S., & Takeshi, T. (2013). Numerical analysis to examine the effect of landslides on tunnels. *International Conference on Case Histories in Geotechnical Engineering*. <https://scholarsmine.mst.edu/icchge/7icchge/session05/9>
- Pecoraro, G., Calvello, M., & Piciullo, L. (2019). Monitoring strategies for local landslide early warning systems. *Landslides*, 16(2), 213–231. <https://doi.org/10.1007/s10346-018-1068-z>
- Pisa, G. (1972). Geologia dei Monti a Nord di Forni di Sotto (Carnia Occidentale). *Giornale di Geologia*, 38, 543–688. (in Italian)
- Poisel, R., Mair am Tinkhof, K., & Preh, A. (2016). Landslide caused damages in a gallery. *Rock Mechanics and Rock Engineering*, 49(6), 2301–2315. <https://doi.org/10.1007/s00603-015-0765-3>
- Poisel, R., Zettler, A. H., & Unterberger, W. (1996, September 2). Tunnelling in landslides. *ISRM International Symposium - EUROCK 96*. <https://dx.doi.org/>
- Pu, J., Yu, Q., Zhao, Y., Li, Z., Cao, Y., Le, Z., Yang, Z., & Li, X. (2024). Deformation analysis of a roadway tunnel in soft swelling rock mass based on 3d mobile laser scanning. *Rock Mechanics and Rock Engineering*, 57(7), 5177–5192. <https://doi.org/10.1007/s00603-024-03772-2>
- Robert McNeel & Associates. (2020). Rhinoceros 3D (Version 7.0) [Computer software]. <https://www.rhino3d.com>
- Sestras, P., Badea, G., Badea, A. C., Salagean, T., Oniga, V.-E., Roșca, S., Bilașco, Ștefan, Bruma, S., Spalević, V., Kader, S., Billi, P., & Nedevschi, S. (2025). A novel method for landslide deformation monitoring by fusing UAV photogrammetry and LiDAR data based on each sensor's mapping advantage in regards to terrain feature.

- Shalabi, F. I. (2005). FE analysis of time-dependent behavior of tunneling in squeezing ground using two different creep models. *Tunnelling and Underground Space Technology*, 20(3), 271–279. <https://doi.org/10.1016/j.tust.2004.09.001>
- Shi, Z., Ohtsu, M., Suzuki, M., & Hibino, Y. (2001). Numerical analysis of multiple cracks in concrete using the discrete approach. *Journal of Structural Engineering*, 127(9), 1085–1091. [https://doi.org/10.1061/\(ASCE\)0733-9445\(2001\)127:9\(1085\)](https://doi.org/10.1061/(ASCE)0733-9445(2001)127:9(1085))
- Shreedharan, S., & Kulatilake, P. H. S. W. (2016). Discontinuum–equivalent continuum analysis of the stability of tunnels in a deep coal mine using the Distinct Element Method. *Rock Mechanics and Rock Engineering*, 49(5), 1903–1922. <https://doi.org/10.1007/s00603-015-0885-9>
- Sinha, Sankhaneel, & Gabriel Walton (2021). Integration of three-dimensional continuum model and two-dimensional bonded block model for studying the damage process in a granite pillar at the Creighton Mine, Sudbury, Canada. *Journal of Rock Mechanics and Geotechnical Engineering* 13 (2): 275–88. <https://doi.org/10.1016/j.jrmge.2020.06.011>.
- Stark, T. D., & Choi, H. (2008). Slope inclinometers for landslides. *Landslides*, 5(3), 339–350. <https://doi.org/10.1007/s10346-008-0126-3>
- Stead, D., & Coggan, J. (2012). Numerical modeling of rock-slope instability. In D. Stead & J. J. Clague (Eds.), *Landslides: Types, Mechanisms and Modeling* (pp. 144–158). Cambridge University Press. <https://doi.org/10.1017/CBO9780511740367.014>
- Stead, D., Eberhardt, E., & Coggan, J. S. (2006). Developments in the characterization of complex rock slope deformation and failure using numerical modelling techniques. *Engineering Geology*, 83(1), 217–235. <https://doi.org/10.1016/j.enggeo.2005.06.033>
- Sun, M., Cao, H., & Duan, Y. (2025). A method for landslide deformation detection based on projection surface element matching of 3D models. *Geoscience Data Journal*, 12(2), e290. <https://doi.org/10.1002/gdj3.290>
- Tedesco, G. (2018). Infrastructure maintenance and countermeasures planning in complex geological and geomorphological settings, PhD Thesis. University of Bologna.

- Tedesco, G., Marcato, G., Bossi, G., & Schenato, L. (2020). Monitoraggio della galleria di San Lorenzo in rapporto ai movimenti franosi esterni nel periodo dal 22 novembre 2018 al 21 novembre 2019. (unpublished)
- Tian, X., Song, Z., Cheng, Y., & Wang, J. (2025). Deformation distribution characteristics of a tunnel–slope system and its reinforcement measures. *Bulletin of Engineering Geology and the Environment*, 84(6), 271. <https://doi.org/10.1007/s10064-025-04297-w>
- Tofani, V., Segoni, S., Agostini, A., Catani, F., & Casagli, N. (2013). Technical note: Use of remote sensing for landslide studies in Europe. *Natural Hazards and Earth System Sciences*, 13(2), 299–309. <https://doi.org/10.5194/nhess-13-299-2013>
- Tran, H. T., Wang, Y., Nguyen, G. D., Kodikara, J., Sanchez, M., & Bui, H. H. (2019). Modelling 3D desiccation cracking in clayey soils using a size-dependent SPH computational approach. *Computers and Geotechnics*, 116, 103209. <https://doi.org/10.1016/j.compgeo.2019.103209>
- UN Department of Economic and Social Affairs. (2019). *World Urbanization Prospects: The 2018 Revision*. United Nations. <https://doi.org/10.18356/b9e995fe-en>
- UN DESA/Population Division. (2024). *World Population Prospects 2024: Summary of Results* | DESA Publications. <https://desapublications.un.org/publications/world-population-prospects-2024-summary-results>
- UNDRR. (2025). *Global Assessment Report (GAR)*. <https://www.undrr.org/gar/gar2025>
- Usman, M., & Galler, R. (2013). Long-term deterioration of lining in tunnels. *International Journal of Rock Mechanics and Mining Sciences*, 64, 84–89. <https://doi.org/10.1016/j.ijrmms.2013.08.028>
- van Asch, T. W. J., Malet, J.-P., van Beek, L. P. H., & Amitrano, D. (2007). Techniques, issues and advances in numerical modelling of landslide hazard. *Bulletin de La Société Géologique de France*, 178(2), 65–88. <https://doi.org/10.2113/gssgfbull.178.2.65>
- Vassallo, R., Mishra, M., Santarsiero, G., & Masi, A. (2016). Interaction of a railway tunnel with a deep slow landslide in clay shales. *Procedia Earth and Planetary Science*, 16, 15–24. <https://doi.org/10.1016/j.proeps.2016.10.003>
- Vassallo, R., Mishra, M., Santarsiero, G., & Masi, A. (2019). Modeling of landslide–tunnel interaction: the Varco d'Izzo case study. *Geotechnical and Geological Engineering*, 37(6), 5507–5531. <https://doi.org/10.1007/s10706-019-01020-x>

- Wang, D., Liu, Y., & Kumar, M. (2018). Using nested discretization for a detailed yet computationally efficient simulation of local hydrology in a distributed hydrologic model. *Scientific Reports*, 8(1), 5785. <https://doi.org/10.1038/s41598-018-24122-7>
- Wang, D.-Y., Zhu, H.-H., Wang, J., Sun, Y.-J., Schenato, L., Pasuto, A., & Shi, B. (2023). Characterization of sliding surface deformation and stability evaluation of landslides with fiber-optic strain sensing nerves. *Engineering Geology*, 314, 107011. <https://doi.org/10.1016/j.enggeo.2023.107011>
- Wang, T.-T. (2010). Characterizing crack patterns on tunnel linings associated with shear deformation induced by instability of neighboring slopes. *Engineering Geology*, 115(1), 80–95. <https://doi.org/10.1016/j.enggeo.2010.06.010>
- Wang, T.-T., Jaw, J.-J., Chang, Y.-H., & Jeng, F.-S. (2009). Application and validation of profile-image method for measuring deformation of tunnel wall. *Tunnelling and Underground Space Technology*, 24(2), 136–147. <https://doi.org/10.1016/j.tust.2008.05.008>
- Wang, Z. F., Shi, F. G., Li, D. D., & Li, H. (2020). Tunneling-induced deep-seated landslides: A case study in Gulin County, Sichuan, China. *Arabian Journal of Geosciences*, 13(19), 1039. <https://doi.org/10.1007/s12517-020-06048-5>
- Wei, H., Wu, D., Wu, H., Tang, L., Wang, S., & Sun, H. (2023). Coordinated evolution and mechanism characteristics of the tunnel-landslide system under rainfall conditions. *Engineering Failure Analysis*, 146, 107118. <https://doi.org/10.1016/j.engfailanal.2023.107118>
- World Bank. (2024). *Infrastructure Monitor 2024: Global trends in private investment in infrastructure - Executive Summary*. World Bank. <https://documents.worldbank.org/en/publication/documents-reports/documentdetail/099042225161529126>
- Xu, Q., Zhao, B., Dai, K., Dong, X., Li, W., Zhu, X., Yang, Y., Xiao, X., Wang, X., Huang, J., Lu, H., Deng, B., & Ge, D. (2023). Remote sensing for landslide investigations: A progress report from China. *Engineering Geology*, 321, 107156. <https://doi.org/10.1016/j.enggeo.2023.107156>
- Zhang, J., Wang, F., Guo, Y., Chen, H., & Zhang, Q. (2023). Nested numerical simulation of multi-scale flow characteristics around monopile foundation of offshore wind farm at Weihai coastal water, China. *Ocean Engineering*, 288, 116171. <https://doi.org/10.1016/j.oceaneng.2023.116171>

- Zhang, Y., Li, J., Liu, H., Li, W., Li, J., & Hou, L. (2021). Research on the interaction mechanism between landslide and tunnel engineering. *Advances in Materials Science and Engineering*, 2021(1), 2265459. <https://doi.org/10.1155/2021/2265459>
- Zhang, Y., Yang, J., & Yang, F. (2015). Field investigation and numerical analysis of landslide induced by tunneling. *Engineering Failure Analysis*, 47, 25–33. <https://doi.org/10.1016/j.engfailanal.2014.09.011>
- Zhang, Z., Zhao, Q., Xu, C., & Xu, X. (2017). Interaction analyses between tunnel and landslide in mountain area. *Journal of Mountain Science*, 14(6), 1124–1139. <https://doi.org/10.1007/s11629-016-3999-y>
- Zhao, C., Alimardani Lavasan, A., & Schanz, T. (2019). Application of submodeling technique in numerical modeling of mechanized tunnel excavation. *International Journal of Civil Engineering*, 17(1), 75–89. <https://doi.org/10.1007/s40999-018-0318-8>
- Zhou, L., Zhu, Z., Dong, Y., Fan, Y., Zhou, Q., & Deng, S. (2019). The influence of impacting orientations on the failure modes of cracked tunnel. *International Journal of Impact Engineering*, 125, 134–142. <https://doi.org/10.1016/j.ijimpeng.2018.11.010>
- Zhou, W., Fan, J., Qiu, S., & Zhang, Y. (2025). Failure modes and interaction mechanisms of tunnel under active landslide conditions. *Scientific Reports*, 15(1), 3174. <https://doi.org/10.1038/s41598-025-86584-w>
- Zhou, W., Xu, X., Li, X., & Li, S. (2023). Analysis of the interaction damage mechanism and treatment measures for an underpass landslide tunnel: a case from southwest China. *Sustainability*, 15(14), 11398. <https://doi.org/10.3390/su151411398>
- Zhu, L., Liang, H., He, S., Liu, W., Zhang, Q., & Li, G. (2020). Failure mechanism and dynamic processes of rock avalanche occurrence in Chengkun railway, China, on August 14, 2019. *Landslides*, 17(4), 943–957. <https://doi.org/10.1007/s10346-019-01343-z>

Appendix A: FLAC3D scripts

In the following are reported the scripts used for the modelling activities within the development of the landslide-scale FLAC3D model.

For the geometry input file, contact the author at pietro.festi@unibo.it

Landslide-scale FLA3D model main script

```
model new
zone import "[insert path to geometry file]\PdM_landslide.f3grid"
model save "1. Geometry call.sav"

;Large strain model approach ON allowing large deformation to be
correctly modelled
model large-strain on

;Zone group definition
zone group 'Stable' range group 'ZG_001' or 'ZG_002' or 'ZG_003' or
'ZG_036'
zone group 'Dolomite' range group 'ZG_004' or 'ZG_006' or 'ZG_007' or
'ZG_008' or 'ZG_009' or 'ZG_010' or 'ZG_011' or 'ZG_012' or 'ZG_013'
or 'ZG_014' or 'ZG_017' or 'ZG_018' or 'ZG_019' or 'ZG_020' or
'ZG_022' or 'ZG_023' or 'ZG_024' or 'ZG_025'
zone group 'Clay' range group 'ZG_005' or 'ZG_035'
zone group 'Shear zone' range group 'ZG_015' or 'ZG_016' or 'ZG_021'
or 'ZG_026' or 'ZG_027' or 'ZG_028' or 'ZG_029' or 'ZG_030' or
'ZG_031' or 'ZG_032' or 'ZG_033' or 'ZG_034' or 'ZG_037' or 'ZG_038'
or 'ZG_039'
zone group 'Box' slot 2 range group 'ZG_035' or 'ZG_036' or 'ZG_038'

;Gravity activation
model gravity 9.81

;Constitutive model assignment
zone cmodel assign elastic range group "Stable"
zone cmodel assign mohr-coulomb range group "Clay"
zone cmodel assign mohr-coulomb range group "Dolomite"
zone cmodel assign mohr-coulomb range group "Shear zone"

;Boundary conditions definition
zone face apply velocity-x 0 range position-z -5 5
zone face apply velocity-y 0 range position-z -5 5
zone face apply velocity-z 0 range position-z -5 5

zone face apply velocity-normal 0 range position-x 3258 3268
```

```

zone face apply velocity-normal 0 range position-x -5 5
zone face apply velocity-normal 0 range position-y 2850 2860
zone face apply velocity-normal 0 range position-y -5 5

zone property density 2600 range group "Stable"
zone property density 2500 range group "Dolomite"
zone property density 2500 range group "Clay"
zone property density 2500 range group "Shear zone"

;History and history points definition
model history mechanical unbalanced-maximum

;Virtual GNSS
;GNSS 2
zone history name 'GNSS2.x' displacement-x position 1939 1308 885
zone history name 'GNSS2.y' displacement-y position 1939 1308 885
zone history name 'GNSS2.z' displacement-z position 1939 1308 885
;GNSS 4
zone history name 'GNSS4.x' displacement-x position 1838 999 702
zone history name 'GNSS4.y' displacement-y position 1838 999 702
zone history name 'GNSS4.z' displacement-z position 1838 999 702
;GNSS 5
zone history name 'GNSS5.x' displacement-x position 1629 1160 716
zone history name 'GNSS5.y' displacement-y position 1629 1160 716
zone history name 'GNSS5.z' displacement-z position 1629 1160 716

;Initial stress state estimation
zone initialize-stresses

model save "2. Boundary conditions.sav"

;Zone property assignment
zone property young 30e9 poisson 0.2 range group "Stable"
zone property young 7.7e9 poisson 0.25 fric 46 cohesion 9.9e5 range
group "Dolomite"
zone property young 3e9 poisson 0.3 fric 39 cohesion 6.6e5 range group
"Clay"
zone property young 7e8 poisson 0.35 fric 29 cohesion 3.3e5 range
group "Shear zone"

model solve elastic only

model save "3. Elastic run.sav"

;Displacement reset
zone gridpoint initialize displacement 0 0 0

```

```

;Zone property modification
zone property fric 14 cohesion 1e5 range group "Shear zone"

;cfr Figure 31
cycle 3000
model save "4. Plastic run1.sav"

;Python scripts for velocity and stress extraction (see below)
program call 'Stress extract.py'
program call 'Velocity extract.py'

cycle 3000
model save "4. Plastic run2.sav"

cycle 4000
model save "4. Plastic run3.sav"

model solve
model save "4. Plastic run.sav"

;FISH function for virtual inclinometer data extraction (see below)
call "VirtualInc_PdM.dat"
[VirtualInc]

```

VirtualInc_PdM.dat

```

def VirtualInc

;I16
x = 1842
y = 1071

sav_Inc = 'Inc_'+string(x)+'_'+string(y)+'.txt'

command
program log on
program log-file @sav_Inc
zone list profile displacement-x begin @x, @y, 735 end @x, @y, 635
segments 100
zone list profile displacement-y begin @x, @y, 735 end @x, @y, 635
segments 100
program log off
endcommand

```

Velocity extract.py

```

import csv
import itasca as it
import sys

```

```

def print_progress(current, total):
    percent = (current / total) * 100
    bar = '#' * int(percent // 2) # every '#' worth 2%
    sys.stdout.write(f"\r[FLAC3D] Progress: [{bar:<50}]
{percent:5.1f}%")
    sys.stdout.flush()

def export_velocity(group_name='Box', group_slot=2,
output_filename='velocity_export_for_3dec.csv'):
    try:
        gridpoints = list(it.gridpoint.list())
        total = len(gridpoints)
        exported = 0

        with open(output_filename, 'w', newline='') as csvfile:
            writer = csv.writer(csvfile)
            writer.writerow(['x', 'y', 'z', 'vx', 'vy', 'vz'])

            for i, gp in enumerate(gridpoints, 1):
                # Verify group
                if gp.group(group_slot) == group_name:
                    pos = gp.pos()
                    vel = gp.vel()
                    writer.writerow([pos[0], pos[1], pos[2], vel[0],
vel[1], vel[2]])
                    exported += 1

                print_progress(i, total)

            print(f"\n\n[FLAC3D] Export complete! {exported} gridpoints
exported of {total}.")
            print(f"[FLAC3D] File saved as '{output_filename}'.")

    except Exception as e:
        print(f"[FLAC3D] Error during the export: {e}")

# --- LAUNCH ---
export_velocity()

```

Stress export.py

```

import itasca as it
import csv

def export_stress(group_name='Box', group_slot='2',
output_filename='stress_export_for_3dec.csv'):
    zone_stress_info = []
    total_zones = it.zone.count()
    print(f"[FLAC3D] Total number of zones: {total_zones}")

    for zone in it.zone.list():
        if zone.group(group_slot) == group_name:

```

```

        loc = zone.pos()
        try:
            stress = zone.stress()
            if stress is None:
                print(f"[FLAC3D] Stress incomplete or absent for
zone {zone.id()}, skip this zone.")
            else:
                sxx, sxy, szx = stress[0]
                syx, syy, syz = stress[1]
                szx, syz, szz = stress[2]

                zone_stress_info.append([
                    loc[0], loc[1], loc[2],
                    sxx, syy, szz, sxy, syz, szx
                ])
        except Exception as e:
            print(f"[FLAC3D] Error in stress of the zone
{zone.id()}: {e}")

    if not zone_stress_info:
        print(f"[FLAC3D] No zone found in group '{group_name}'.")
        return

    with open(output_filename, 'w', newline='') as csvfile:
        writer = csv.writer(csvfile)
        writer.writerow(['x', 'y', 'z', 'sxx', 'syy', 'szz', 'sxy',
'syz', 'szx'])
        writer.writerows(zone_stress_info)

    print(f"[FLAC3D] Export complete! File saved as
'{output_filename}'.")

# --- LAUNCH ---
export_stress()

```

Appendix B: 3DEC scripts

In the following are reported the scripts used for the modelling activities within the development of the tunnel-scale 3DEC model.

For the geometry input file, contact the author at pietro.festi@unibo.it

3DEC Python script to associate velocity vectors from FLAC3D to corresponding external surface gridpoints (to be pasted in dedicated Python dialog window within 3DEC)

```
import csv
import sys
from scipy.spatial import cKDTree
import itasca as it

def print_progress(current, total):
    percent = (current / total) * 100
    bar = '#' * int(percent // 2)
    sys.stdout.write(f"\r[3DEC] Progress: [{bar:<50}]
{percent:5.1f}%")
    sys.stdout.flush()

def
generate_velocity_matching_surf_file(csv_filename='velocity_export_for
_3dec.csv'):
    try:
        positions = []
        velocities = []
        with open(csv_filename, 'r') as csvfile:
            reader = csv.reader(csvfile)
            next(reader)
            for row in reader:
                x, y, z, vx, vy, vz = map(float, row)
                positions.append((x, y, z))
                velocities.append((vx, vy, vz))

        if not positions:
            print("[3DEC] No data found in the CSV.")
            return

        tree = cKDTree(positions)

        # --- 3DEC gridpoints extraction ---
        gridpoints = [gp for gp in it.block.gridpoint.list() if
gp.group("default") == "external_gp"]
        total = len(gridpoints)

        # --- Output file creation ---
        with open('velocity_matching_surf.csv', 'w', newline='') as
outfile:
```

```

        writer = csv.writer(outfile)
        writer.writerow(['gridpoint_id', 'x', 'y', 'z', 'vx',
'vy', 'vz'])

        for i, gp in enumerate(gridpoints, 1):
            pos = gp.pos()
            dist, idx = tree.query(pos)
            vx, vy, vz = velocities[idx]
            gp_id = gp.id()
            writer.writerow([gp_id, pos[0], pos[1], pos[2], vx,
vy, vz])

            print_progress(i, total)

        # --- Final Report ---
        print("\n\n=== REPORT ===")
        print(f"Gridpoints in 3DEC:      {total}")
        print(f"Velocity values in the CSV:    {len(velocities)}")
        print(f"File generated:      velocity_matching_surf.csv")

    except Exception as e:
        print(f"[3DEC] Error during the generation of the file: {e}")

# --- LAUNCH ---
generate_velocity_matching_surf_file('velocity_export_for_3dec.csv')

```

Tunnel-scale 3DEC model main script

```

model new
block import filename "[insert path to geometry file]\tunnel.3dgrid"
model save "1. Geometry call.sav"

;Zonation
block zone generate-new maximum-edge 5

;Definition of surface group
block face group 'Surface' range position-x 1848 1955 position-y 1315
1393 position-z 728.5267 surface
block face group 'Surface' range plane origin
(1953.5146,1335.3297,728.5267) dip 90 dip-direction 30.4 surface
block face group 'Surface' range position-x 1848 1955 position-y 1315
1393 position-z 748.5267 surface
block face group 'Surface' range plane origin
(1943.3827,1318.0860,728.5267) dip 90 dip-direction 210.4 distance 0.1
surface
block face group 'Surface' range plane origin
(1943.3827,1318.0860,728.5267) dip 90 dip-direction 120.4 surface
block face group 'Surface' range plane origin
(1850.2667,1372.7982,728.5267) dip 90 dip-direction 300.4 distance 0.1
surface
block gridpoint group 'external_gp' range group 'Surface'

;Boundary conditions definition (see below)
call 'Velocity application.dat'

```

```

[VelocitiesFromcsv]
program call 'Stress apply.py'
model save "2. Boundary conditions gpapply.sav"

;History and history points definition
history interval 10
block history displacement gridpointid 2437
block history displacement gridpointid 136917
block history displacement gridpointid 133758
model history mechanical unbalanced-maximum

block join
block mechanical damping combined
model large-strain on

;Definition of default contact properties
block contact material-table default property stiffness-normal 1e9
friction 20 stiffness-shear 1e8

;Block groups definition
block group 'STA' range group '001' or '004' or '006' or '008' or
'009' or '010' or '014' or '016' or '021' or '022' or '023' or '027'
block group 'CL' range group '002' or '005' or '007' or '011' or '012'
or '013' or '015' or '024' or '025' or '026' or '029'
block group 'SZ' range group '003' or '017' or '018' or '019' or '020'
or '028' or '030' or '031' or '032'

;FISH function for automatic saving (see below)
call 'Cycle save.dat'
fish callback add [CycleSavFix] interval 1000 1

;Material properties assignment
block zone cmodel assign elastic
block zone property density 2600 young 3e9 poisson 0.3 range group
"STA"
block zone cmodel assign mohr-coulomb range group "CL" or "SZ"
block zone property density 2500 young 3e9 poisson 0.3 friction 39
cohesion 6.6e5 range group "CL"
block zone property density 2500 young 7e8 poisson 0.35 friction 14
cohesion 1e5 range group "SZ"

;Allowing boundary conditions assignment and visualization
model cycle 0

;FISH function for fixing velocities at shared gridpoints
fish def fix
  loop foreach gp block.gp.list
    appvel = block.gp.vel.app(gp)
    if math.mag(appvel) > 0
      loop foreach gplink block.gp.gplinks(gp)
        block.gp.vel.app(gplink) = appvel
      end_loop
    endif
  end_loop
end def fix

```



```

end
[fix]

;Cycling to allow velocities propagation
model cycle 100000

;Tunnel excavation
block excavate range group '006' or '007' or '021' or '022' or '023'
or '024' or '025' or '026' or '027' or '028' or '029' or '030' or
'031' or '032'

;Segments definition
block join off
block join range group '001' or '002' or '003'

block join range group '005'
block group 'Segment 1' slot 1 range group '005'
block join range group '011'
block group 'Segment 2' slot 1 range group '011'
block join range group '013' or '017'
block group 'Segment 3' slot 1 range group '013' or '017'
block join range group '012' or '016' or '019'
block group 'Segment 4' slot 1 range group '012' or '016' or '019'
block join range group '010' or '015' or '020'
block group 'Segment 5' slot 1 range group '010' or '015' or '020'
block join range group '009' or '018'
block group 'Segment 6' slot 1 range group '009' or '018'
block join range group '014'
block group 'Segment 7' slot 1 range group '014'
block join range group '008'
block group 'Segment 8' slot 1 range group '008'
block join range group '004'
block group 'Segment 9' slot 1 range group '004'

;Contact properties assignment
block contact jmodel assign mohr
block contact property friction 20 stiffness-normal 1e10 stiffness-
shear 1e9

block group 'Tunnel' slot 2 range group 'Segment 1' or 'Segment 2' or
'Segment 3' or 'Segment 4' or 'Segment 5' or 'Segment 6' or 'Segment
7' or 'Segment 8' or 'Segment 9'

;Tunnel lining elastic properties assignment and stress initialization
block zone cmodel assign elastic range group 'Tunnel'
block zone property density 2500 young 31e9 poisson 0.2 range group
'Tunnel'

block zone initialize stress range group 'Tunnel'
model gravity 9.81
block insitu topography overburden -3.75e6 ratio-x 0.4 ratio-y 0.4
ratio-z 0.4 range group 'Tunnel'

;Gravity implicitly accounted for in stress import/export

```

```

model gravity 0

;Short cycling for stress redistribution
model cycle 1000

model save "3. Tunnel excavated.sav"

;Tunnel lining plastic properties assignment
block zone cmodel assign mohr-coulomb range group 'Tunnel'
block zone property density 2500 young 31e9 poisson 0.2 friction 35
cohesion 8e6 tension 3e6 range group 'Tunnel'

;Reset cycle count for saving
fish define num
n = 0
end
[num]

;FISH function call to visualize tunnel only deformation
call 'Initialize displacement.dat'
fish callback add [InitializeDispl] interval 1000 1

model cycle

```

Velocity application.dat

```

fish define VelocitiesFromcsv
f = file.open("velocity_matching_surf.csv", "read", "text")
n = 0
  l = file.read(f)
  loop foreach line l
    if n > 0
      tokens = string.split(line, ",")
      id = int(tokens(1))
      pnt = block.gp.find(id)
      vx = float(tokens(5))
      vy = float(tokens(6))
      vz = float(tokens(7))

      command
        block gridpoint apply velocity-x [vx] velocity-y [vy] velocity-z
[vz] range id [id]
      endcommand

      io.out(n)
    endif
    n = n+1
  endloop

file.close(f)

```

end

Stress apply.py

```
import csv
import math
import itasca as it
import sys
from scipy.spatial import KDTree

def print_progress(current, total):
    percent = (current / total) * 100
    bar = '#' * int(percent // 2)
    sys.stdout.write(f"\r[3DEC] Progress: [{bar:<50}]
{percent:5.1f}%")
    sys.stdout.flush()

def apply_stress_from_csv(csv_filename='stress_export_for_3dec.csv'):
    try:
        # --- Load data into a CSV ---
        stress_data = []
        positions = []
        with open(csv_filename, 'r') as csvfile:
            reader = csv.reader(csvfile)
            next(reader)
            for row in reader:
                x, y, z, sxx, syy, szz, sxy, syz, szx = map(float,
row)

                stress_data.append([sxx, syy, szz, sxy, syz, szx])
                positions.append((x, y, z))

        if not stress_data:
            print("[3DEC] No stress data found in CSV.")
            return

        tree = KDTree(positions)

        # --- Apply stress to zones ---
        zones = list(it.block.zone.list())
        num_zones = len(zones)
        num_applied = 0

        for i, zone in enumerate(zones, 1):
            zp = zone.pos()
            dist, idx = tree.query(zp)
            stress = stress_data[idx]
            zone.set_stress(stress)
```

```

        num_applied += 1
        print_progress(i, num_zones)

# --- Final Report ---
print("\n\n=== STRESS APPLICATION REPORT ===")
print(f"Zones in 3DEC:      {num_zones}")
print(f"Stress assigned:      {num_applied}")
print(f"Zones with no stress:   {num_zones - num_applied}")
print(f"Stress values in the CSV: {len(stress_data)}")

except Exception as e:
    print(f"[3DEC] Error during stress application: {e}")

# --- LAUNCH ---
apply_stress_from_csv('stress_export_for_3dec.csv')

```

Cycle save.dat

```

fish define CycleSavFix

    n = n + 1
    if n == 10000
        l = global.cycle
        name = '3. Cycle_Fix_'+string(l)+'.sav'
        command
        model save @name
        endcommand
        n = 0
    endif

end

```

Initialize displacement.dat

```

fish define InitializeDispl
    if global.cycle = 40000
        command
        block gridpoint initialize displacement 0 0 0
        endcommand
    endif
end

```