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STRUCTURAL HEALTH OF A ROAD TUNNEL INTERSECTING A LARGE AND ACTIVE ROCK-BLOCK SLIDE

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EXTENDED ABSTRACT

Lo sviluppo di un adeguato apparato infrastrutturale è il principale motore di crescita di un territorio. Tuttavia, spesso la realizzazione delle infrastrutture si scontra con limitazioni naturali, imposte dalla conformazione del territorio stesso. La regione Friuli-Venezia Giulia ne è un esempio emblematico in quanto particolarmente condizionata dalle sue peculiarità morfologiche e climatiche. A Nord vi sono i rilievi montuosi delle Alpi Carniche e delle Alpi Giulie (43% della superficie regionale) e l'intera Regione presenta un sistema idrografico estremamente diversificato, costituito principalmente dai bacini dei fiumi Tagliamento, Isonzo e Livenza, e da un estesa rete di corsi d'acqua a carattere prevalentemente torrentizio. L'elevata piovosità, soprattutto a ridosso dei rilievi montuosi, e l'assetto geologico composto in prevalenza da rocce calcareo-dolomitiche, fanno sì che la regione risulti particolarmente colpita da fenomeni di dissesto idrogeologico. A fronte di ciò, l'importanza strategica del Friuli-Venezia Giulia come collegamento tra l'Italia e paesi quali la Slovenia (a Est) e l'Austria (a Nord), ha portato alla realizzazione di rilevanti infrastrutture, specie quelle viarie, tra cui l'oggetto di interesse del presente lavoro.

All'interno del complesso delle Alpi Carniche meridionali, situate nella parte nord-orientale della regione, si estende in sinistra orografica dell'alta Valle del fiume Tagliamento una porzione della strada statale 52, nota come "Carnica". In particolare, nel tratto tra i centri abitati di Forni di Sotto e Ampezzo, entrambi in Provincia di Udine, la strada si sviluppa per 2212 m all'interno del versante per mezzo di una galleria denominata San Lorenzo, oggetto di studio di questo elaborato. L'area in cui si inserisce il tunnel stradale è chiamata Passo della Morte ed è sfavorevolmente caratterizzata dalla presenza di cinque fenomeni gravitativi, tra movimenti franosi riconosciuti e potenziali instabilità di versante in roccia. L'interazione tra il più rilevante di questi fenomeni franosi e la galleria stradale ha costituito, dall'entrata in servizio di quest'ultima, un fattore di rischio per la sicurezza degli utenti e per l'integrità della galleria stessa. Specialmente in seguito ad eventi meteoclimatici intensi, sono stati registrati distaccamenti della copertura interna della galleria e concomitanti infiltrazioni. Data la rilevanza dell'infrastruttura coinvolta e l'elevato rischio per l'utenza stradale, da più di vent'anni diversi Enti interessati e coinvolti nel monitoraggio delle problematiche legate ai fenomeni franosi della zona hanno condotto studi e progettato misure di sicurezza. In particolare, è attivo da nove anni, un sistema di monitoraggio dello stato di salute della struttura che permette di ottenere un quadro approfondito ed aggiornato, finalizzato alla conservazione strutturale della galleria stessa, alla definizione di interventi di mitigazione e alla prevenzione del rischio.

Questo lavoro ha come scopo quello di utilizzare i dati e le conoscenze raccolte sinora al fine di approfondire le relazioni tra i movimenti del corpo di frana che insiste maggiormente sulla galleria e lo stato di danneggiamento sviluppato nel tunnel stradale. In particolare, tramite un modello ad elementi finiti della porzione di galleria visibilmente più danneggiata, si vuole arrivare a stabilire quale combinazione di forze e sollecitazioni imposte dal fenomeno gravitativo di Passo della Morte ha prodotto lo stato fessurativo e di danneggiamento rilevato. Il modello è stato costruito prendendo in considerazione un singolo concio della struttura, ed è stato testato imponendogli un comportamento globale derivante da semplici ipotesi di movimento e deformazione suggerite dalle fessurazioni stesse. Parallelamente, è stata realizzata tramite fotogrammetria una rappresentazione tridimensionale delle fessurazioni presenti sulla volta della galleria con l'obbiettivo di utilizzare questi dati per la verifica e validazione dei risultati del modello ad elementi finiti.

In conclusione, questo lavoro presenta la costruzione di un modello integrato, avente l'obbiettivo di mettere in relazione lo stato di danneggiamento rilevato sull'infrastruttura e una riproduzione analitica dei comportamenti dell'infrastruttura stessa, ottenendo così lo schema di sollecitazioni proposto naturalmente dai movimenti franosi. La complessità del caso di studio si è rispecchiata nella costruzione del modello, che è quindi stato progettato seguendo un processo iterativo, caratterizzato dalla gradualità di inserimento delle molteplici variabili connesse alle grandezze in gioco, come mostrato nei risultati conclusivi di questo elaborato

ABSTRACT

This work presents the case study of the San Lorenzo road tunnel, a linear infrastructure located in Friuli Venezia Giulia, northern Italy, affected by the so-called Passo della Morte landslide. This slope instability phenomenon has caused several problems since the beginning of the tunnel construction works, like water seepage and concrete lining detachments, increasing the safety risk for road users. Due to these circumstances, numerous studies have been conducted and a monitoring system has been developed since 2014 to control the ongoing situation of the most damaged portions of the road tunnel. Building on the monitoring data, studies and knowledge accumulated over the years, this paper describes the work done to trace back the sum of landslide-induced stresses directly responsible for the current damages on the tunnel. The first steps taken in this direction have included an adequate representation of the crack pattern on the tunnel vault. This has been used both as an initial goal and as a means of validation in the development of a finite element model. From the latter, it will be possible to infer the landslide-induced stress combination mentioned earlier.

KEYWORDS: San Lorenzo road tunnel, landslide, Passo della Morte, FEM model

INTRODUCTION

The topic of infrastructures impacted by landslides or slope instability phenomena is of great relevance, as it poses a significant danger to human life. Many experts have conducted deep studies on landslides affecting dams, railway and road tunnels both in Italy and around the world (BARLA, 2018; MAJCHERCZYK *et alii*, 2012). FAN *et alii* (2022) thoroughly analyzed the interaction of a landslide and a tunnel from an expressway in northwest Yunnan province, China, as the excavation of the tunnel induced a series of problems both to the slope as a whole and to the tunnel infrastructure. Their research aimed to reveal the relationship between the landslide and the tunnel using field monitoring and numerical simulation. It is precisely within this framework that the case study of interest fits. A comparable approach has been used in this work to achieve a similar goal, as will be presented later.

The San Lorenzo road tunnel connects the municipalities of Forni di Sotto (West) and Ampezzo (East), both in the province of Udine (UD). It is located in correspondence of the segment pk 41 600 - 44 400 m of the SS 52 "Carnica", one of the main transportation lines of the whole region. It was built as a variation of a previous route which was severely affected by intermittent rock falls and snow avalanches (AMPEZZAN, 2017; MARCATO *et alii*, 2021). Indeed, the road runs on the hydrographic left of the upper Tagliamento valley, well-known for its slope instability phenomena (MARCATO, 2007). Nevertheless, its strategic position prompted the design of the double-lane road tunnel, crossing the area and providing a safer path. Shortly after the construction works began in 1994-1996, the 2212-m-long tunnel revealed significant damages, such as detachment of the inner concrete lining or water seepage, which compromised its serviceability and safety. For this reason, the road has been thoughtfully closed from 1997 to 2006. Among the five distinct landslide movements or potential rock slope instabilities mapped in the study area, the damages that emerged were mainly traced to the effect of the "Passo della Morte" landslide (Fig. 1).

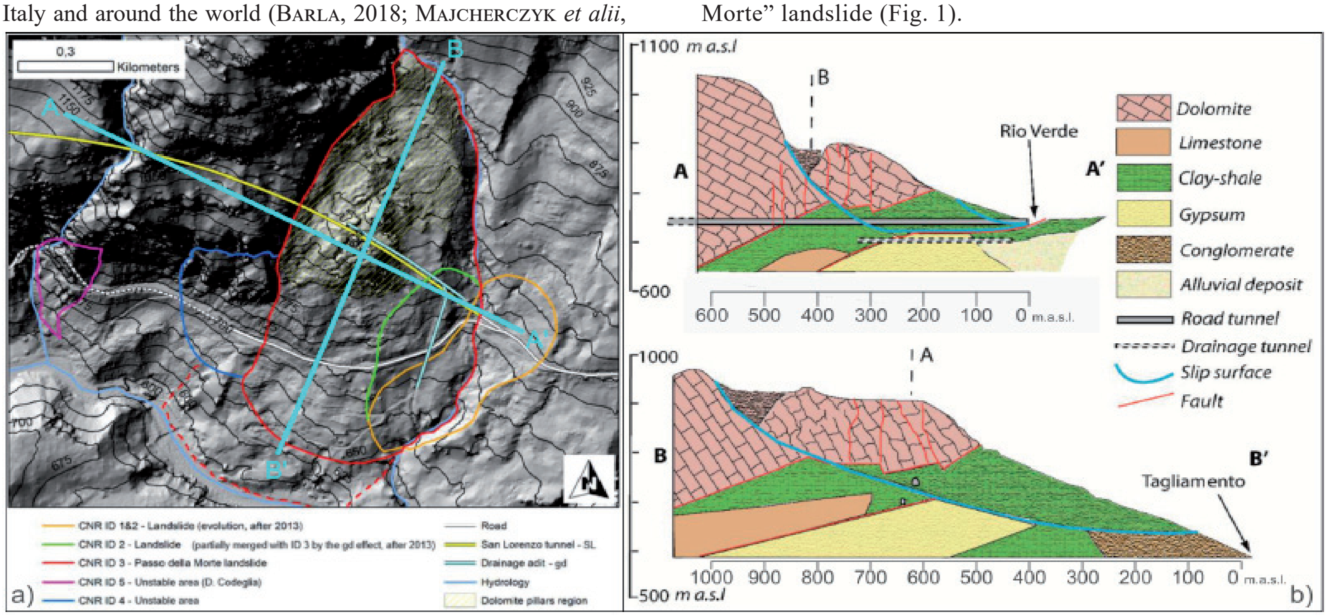

Fig. 1 - a) Planar view of the five distinct landslides mapped in the area of Passo della Morte; b) geological sections A-A' and B-B' of the Passo della Morte landslide intersecting the San Lorenzo tunnel

The latter is the principal active movement of the area and is classified as a rock-block slide (Cruden & Varnes, 1996), with a volume of about 24 million m^3 of material over an extension of approximately 450 thousand m^2 and is characterized by slow movements of 2-3 cm/year. Moreover, it has been estimated that, at 300 m from the eastern entrance, the tunnel crosses the block-slide slip surface (Bossi *et alii*, 2017). Consequently, between 2005 and 2008 the tunnel was rebuilt in the first 370 m from the eastern entry using a succession of 12-m-long independent segments to better allow the dissipation of the landslide-induced deformations. As can be noticed in the general outlook proposed in Fig. 2, a T-shaped drainage tunnel draining in the direction of the Tagliamento River has been also built below the road tunnel to collect the groundwater within the rock mass.

The choice of using the independent segments came from the slow nature of the landslide movements and the need for effective dissipation of the consequent deformations. Similarly, the drainage system has been designed since groundwater is the major threat to the structural health of the tunnel (Sinigardi *et alii*, 2015). In fact, on the geological side, three lithological units mainly constitute the slope: Schlern dolomite characterized by a network of faults, multi-colored silty clay and thin layers of gypsum (Marcato *et alii*, 2005). The network of joints in the dolomite unit allows water coming from meteoric events to flow through, reach the silty clay unit below, and trigger landslide movements by softening it. Partially saturated dolomite rock mass exerts a greater force on the road tunnel structure, further emphasizing the urge of subtracting it from the site.

Despite the effectiveness of the solutions adopted, new damages on the concrete lining in correspondence at segments from the 26th to the 29th reappeared shortly after reopening to traffic. It was estimated that the most damaged portions of the road tunnel, i.e., segments 27th and 28th, are located at the point where the sliding surface of the Passo della Morte landslide intersects the structure (Marcato *et alii*, 2020; Marcato *et alii*, 2022). A specific monitoring system (Fig. 3) has been installed at the four mentioned segments, consisting of 24 crackmeters, 4 bi-axial clinometers and 70 m of optical fiber (Marcato *et alii*, 2020; Marcato *et alii*, 2022). Since 2014, this system collected and stored a continuous streak of data on an online-based platform, enabling quick access to the observations (Bossi *et alii*, 2016). These data, together with the knowledge gained over the years about the many complex variables and aspects of this case of study (Zabuski *et alii*, 2017), are the foundations of the aim of this paper: to put in place a reverse process that starts from the actual state of damages and tries to obtain the stresses combination which generated them.

MATERIALS AND METHODS

A rigorous and reasoned approach has been structured to address the complexity of this case study. To better integrate all

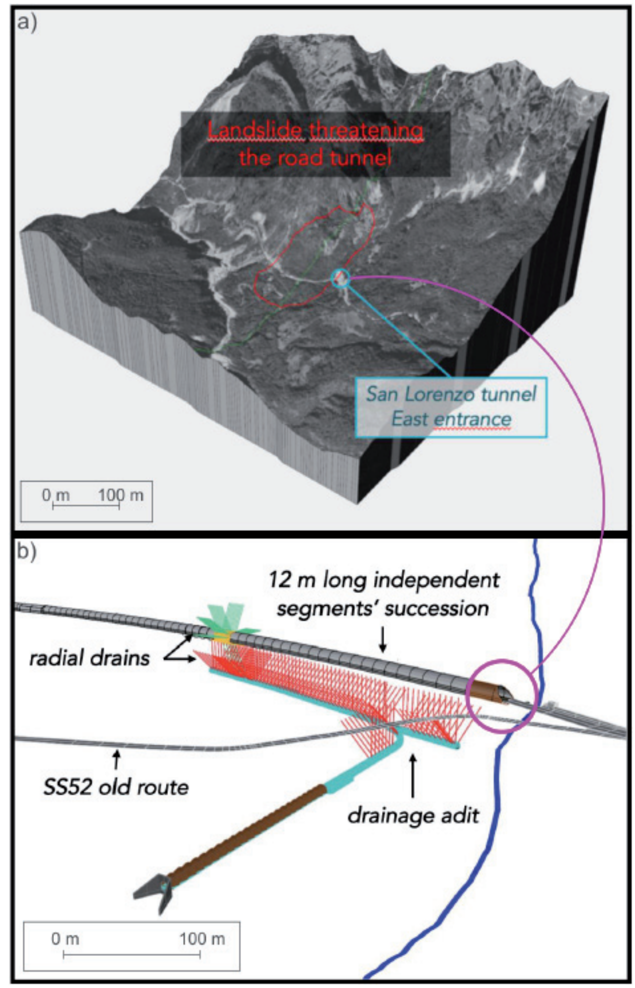

Fig. 2 - a) 3-D visualization of the Passo della Morte landslide (in red); b) overview of the newly built solutions in view of the tunnel eastern entrance (Ampezzo side)

aspects and information, each result was verified and consolidated, adopting well-supported assumptions and simplifications where necessary. Thus, the development of the back analysis has been divided into the following steps:

- Creation of a mesh of the vault of segments from the 27th to the 29th through a photogrammetry process;
- Georeferencing the resulting mesh;
- Clear visualization and highlighting of the most severe cracks of the 28th segment;
- Design and verification of a simplified FEM (Finite Element Method) model of the road tunnel.

Cracks and fractures detection has been a key step both in visualizing the actual level of damage and developing the FEM model. Indeed, the first foreseen outcome of the model was the reproduction of the actual crack pattern. Among the four segments covered by the monitoring system, the vault of the 28th seems

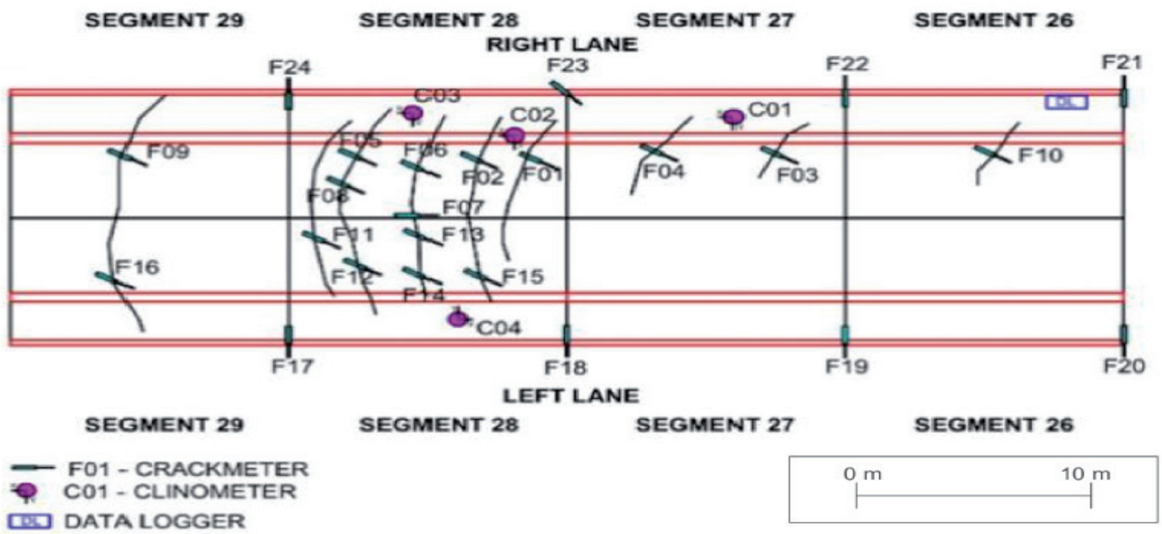

Fig. 3 - – Layout of the monitoring system on the most stressed segments of the San Lorenzo tunnel (Marcato et alii, 2020)

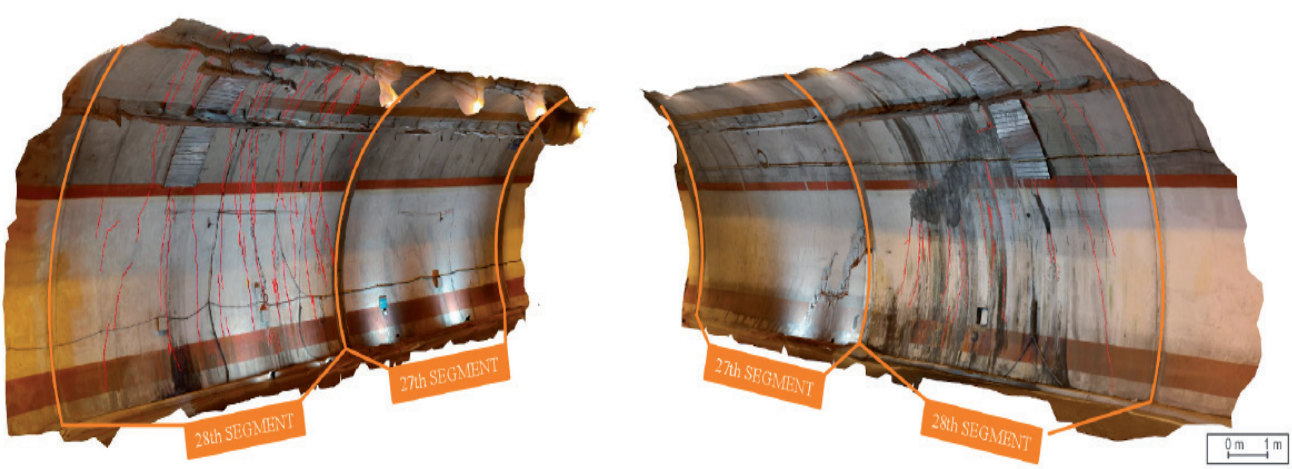

Fig. 4 - Final 3-D textured meshes with the crack pattern highlighted in red in the 28th segment

to be the one containing the most visible fractures. Hence, the following analyses focused mainly on this segment, considering just the neighboring portions of the adjacent ones, i.e., the 27th and the 29th. An appropriate and clear representation of the observable cracks on the 28th segment has been designed as a tool for the immediate understanding of the state of damages and the verification of the FEM model. To do so, a group of 196 photos of a portion comprehending entirely the 28th segment and partially the neighboring segments have been collected. They have been taken with a smartphone camera, as their purpose was not to develop a high-quality result in terms of accuracy and definition but to highlight and map only the most relevant fractures within those of the crack pattern. To facilitate the graphical identification procedure, the photos have been converted into a 3-D mesh through photogrammetric processing. The images have been processed from RGB into spatial information in the form of dense point clouds and textured polygonal models, i.e., the outcoming mesh. To streamline the mesh generation procedure, the portion of the tunnel under consideration has been divided into the sum of two sides, the uphill side and the downhill side, eventually resulting in two distinct meshes.

The photos taken by the smartphone did not contain enough inner information to enable the adopted photogrammetric software (Agisoft Metashape Pro) to consistently self-adjust orientation in space and dimensions of the represented object. The obtained meshes have been accordingly georeferenced using a sufficient number of measurements related to the geometry of the road tunnel. Some simplifications have been made where deemed necessary. The variability of the dimensions of the section of the tunnel throughout its entire length and the degree of usability required for the final representation have been considered. For

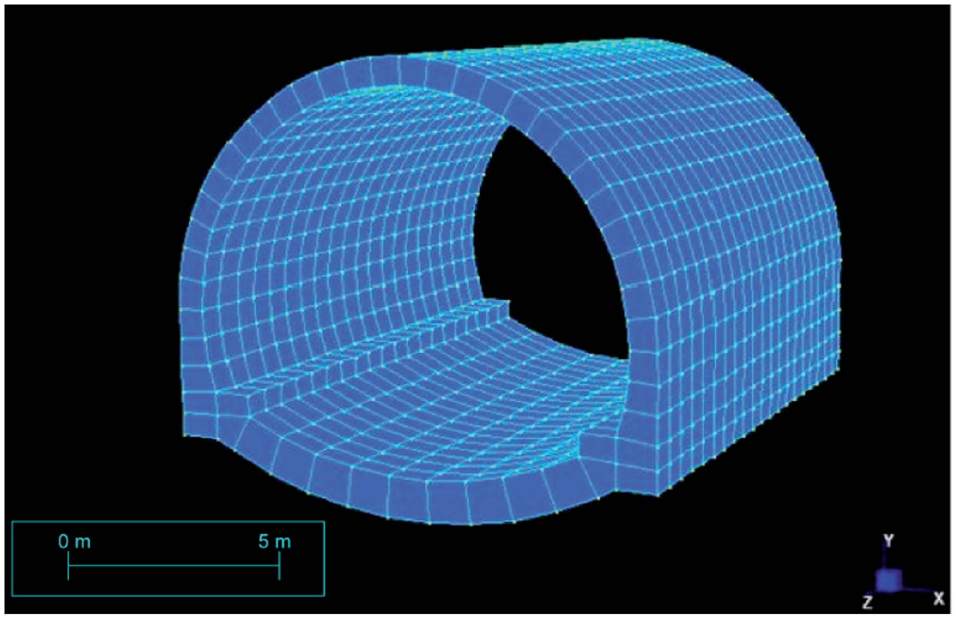

Fig. 5 - Single-segment geometry built in the early stages of the FEM model development

instance, the measurement of the width of the roadway has been kept constant between the different segments, i.e., 10 m, and the height of the sidewalk was not considered. Ultimately, the meshes have been oriented and dimensioned considering: a 10 m width and a 12 m length of the road, a 4.15 m distance between the junction of adjacent segments and the lowest part of a painted red stripe on the vault, and a global orientation of 10° with respect to the north.

The crack pattern has been identified for both sides of the 28th segment and highlighted. The most relevant fractures were traced by creating a specific overlapping red layer. In this way, the sought-after 3-D visualization of the overall damage condition has been obtained (Fig. 4).

The construction of an adequate finite element model began with the decision to continue to focus consistently on the 28th segment while neglecting the adjacent segments. In this way, the desired comparison between the obtained representation of the crack pattern and the hoped-for results of the FEM model tests would be easier. A simplified geometry of a single 12-m-long segment (Fig. 5) has been designed with the selected software (Straus7), considering only the structurally relevant parts of the road tunnel.

Due to the lack of data on the actual concrete used, the general properties of the material to be applied in the model were derived from the tests conducted by Aiello (2021). Several trials have been performed around this simple geometry through the application of appropriate virtual constraints, properties and loading schemes. The initial driving hypothesis for these trials was proposed by Bossi *et alii* (2017) and is schematized in Fig. 6.

Analyzing and interpreting the data and observations, the global behavior of this portion of the tunnel has been assumed. The 28th segment appears to behave as constrained to the stable slope on the left, while being stressed by the landslide-induced movements on the right, consequently working as a loaded cantilever. Furthermore, cracks orientation and widening suggest that the 27th segment has taken advantage of the independent segments design solution and has undergone roto-translation. On the other hand, the 29th segment seems to be mostly located in the stable region, with the crackmeters showing negligible displacements. Additionally, the landslide-induced load is hypothesized and reported as a pressure with an increasing triangular trend, applied on both the longitudinal and lateral half of the 28th segment. Virtual constraints, imposed movements and loading schemes have been coherently designed and applied under static conditions, seeking to properly recreate the described configuration and reproduce the damage state visualization.

RESULTS AND DISCUSSION

Addressing a complex case study requires a deep understanding of the whole variables and phenomena involved. A careful decision-making process should be put in place to implement in the most appropriate stage of the work all the information gathered. For instance, when elaborating a FEM model, it must be kept in mind that its development will need a slow and thoughtful progression, in which every assumption or decision must be well supported. There is no need to rush since there will always be room for improvement during the construction and exploitation phases. This kind of approach is further justified by the significant number of physical entities involved, as it has been extensively explained earlier in this

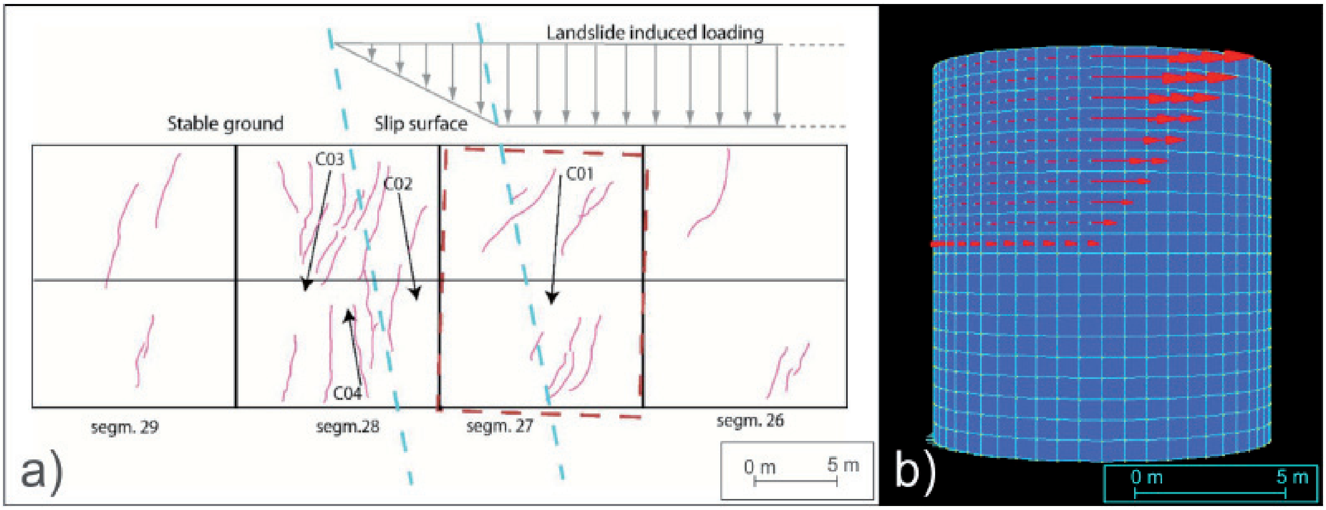

Fig. 6 - a) Suggested loading scheme and road tunnel response; b) above view of San Lorenzo tunnel mesh with triangular trend face pressure loading

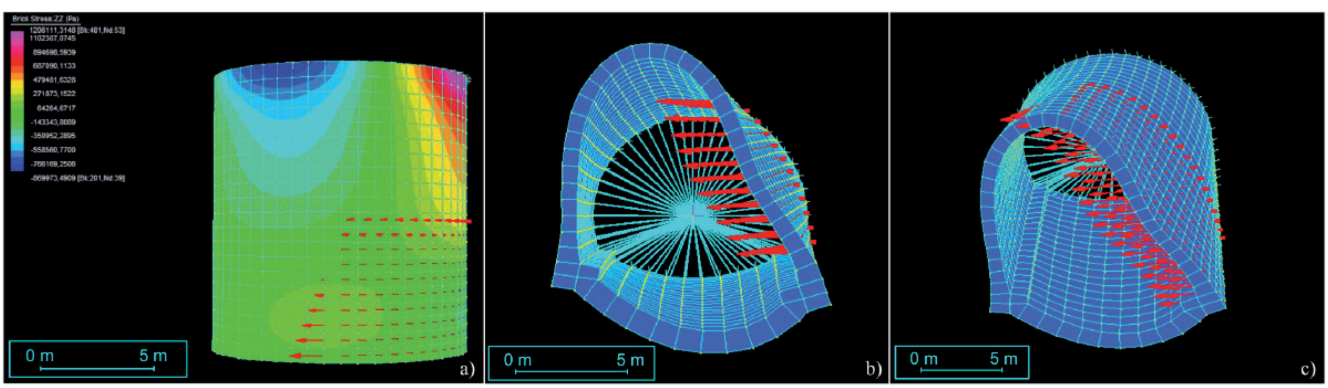

Fig. 7 - Above view of San Lorenzo tunnel mesh with triangular trend face pressure loading; b) first view of the deformed San Lorenzo tunnel mesh with triangular trend face pressure loading; c) second view of the deformed San Lorenzo tunnel mesh with triangular trend face pressure loading

disquisition. Following these considerations, the development of the 12-m-long segment FEM model was characterized by an iterative process in which each construction and testing outcome provided a piece of information to proceed further. To begin with, a configuration of the model element that best reconstructs the proposed loaded cantilever mechanism has been set up. The entire elaboration process was designed to obtain a stress distribution that could justify the occurrence of the fractures highlighted in red in the final damage visualization on the 28th segment. The tests performed so far have shown a peculiar step-wise nature that emphasizes the previously mentioned trial-and-error feature inherent in iterative model construction. The last trial showed some confirmations of the expected loaded cantilever behavior in terms of deformations and stress distribution (Fig. 7), representing a relevant validation of the goodness of both the loaded cantilever hypothesis and the applied iterative procedure. However, further verification should be sought after, as the evidence for the correspondence between stress spread and fracture location is weak and inconspicuous.

As it was said at the beginning of this dissertation, other researchers dealing with the same topic developed approaches other than the one presented in this paper. In the previously mentioned case pursued by Fan *et alii* (2022), the work has been focused on slope stability and failure mechanisms. Also using numerical modeling to further the analysis, hypotheses of slope failure modes have been designed and studied, and then a connection with the damages on the tunnel has been consistently drawn. In the approach proposed in this paper, instead, a back-analysis has been carried out, focusing on the cracks' pattern observable on the concrete lining of the tunnel. This was dictated by the need to provide an analysis of the ongoing situation from the perspective of the road infrastructure.

Despite the differences between the two approaches, some hints can be drawn for the foreseeable future developments of this work. An adequate geological model of the Passo della Morte landslide and the possibility of taking advantage of the expanded knowledge of the study area to observe the situation from a slope perspective can be considered reasonable insights for this case study.

CONCLUSIONS

The main considerations arisen from this study can be summarized as follows:

1. the case study of interest is meaningful both in terms of depth of knowledge and data availability, and in terms of relevance of case history to which it relates;
2. the topic of nature-generated hazard for human infrastructure is of central importance in the present time, so the future of this work can be useful for many other researchers in the same field;
3. the presented work has been able to produce a clear picture of the fractures caused by movements and forces induced by the Passo della Morte landslide on the most damaged portion of the road tunnel;
4. The obtained visualization also proved to be a useful tool for the development of a FEM model, both for reasoning behind the initial assumption of the cantilever behavior and for verifying the latest results of the model;
5. the first steps in building the FEM model and the accompanying trail-and-error process were shown and should be considered as the path to follow, progressively adding much more information;
6. one of the next means of verification and source of relevant information to be implemented should be the continuous data streak of the monitoring system;
7. a geological model could be developed and integrated with the FEM to enlarge the potential of this work by including geological information.

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