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LANDSLIDE-PILE-TUNNEL INTERACTION BY 2D AND 3D FINITE ELEMENT MODELLING

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Abstract. *This paper is focused on the interaction of a railway tunnel with a slow-moving landslide in clay soil. The tunnel, built as a reinforced concrete box structure protected by sheet-piled walls, crosses the accumulation of an earthflow situated at the eastern suburbs of Potenza city, in southern Italy. The landslide develops in the formation of Varicoloured Clays and, due to its very slow but continuous displacements, induces progressive damage to structures and infrastructures built on it. As for the tunnel, there are signs suggesting an evolution of its state of stress and deformation over the last 30 years. The study of the landslide-pile-tunnel interaction required sophisticated FEM analyses to adequately take into account all the involved elements and the real 3D nature of the problem. Analyses were carried out by FEM geotechnical and structural software. Some results selected from a comprehensive numerical study are hereby reported and discussed. A geotechnical software was used in its 2D and 3D versions to obtain the spatial distribution of earth pressure on the tunnel owing to soil movements. The interaction was confirmed to be strongly 3-dimensional, with more evident displacements and bending of the tunnel box concentrated at one end. As a matter of fact, the movements of the landslide seem to make the structure open in horizontal, like a fan. The structural analysis made by applying the above mentioned pressure values confirmed which are the most stressed sections of the tunnel, giving a useful information toward the provision of possible interventions aimed to lengthen the life span of the tunnel.*

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1 INTRODUCTION

Landslides can be responsible for a considerable damage to constructions arising on them such as buildings and infrastructure facilities. The safety of existing tunnels in landslide zones is always a matter of concern, although rarely addressed by a comprehensive understanding of the soil-structure phenomenon taking place. In the case of slow-moving landslides, the time variable plays an important role, and the key question becomes how long a structure can live with the landslide, interacting with it until a level of acceptable damage, and if appropriate building strategies can make this lifespan increase. This is important also in the case of transportation infrastructures crossing the accumulation of a landslide. Some authors (e.g. [1]) have tried to identify some thresholds for displacements by analysing a number of case histories, showing that the vulnerability of linear infrastructures like tunnels is linked to the level of differential displacements that can compromise their performance. The decision of crossing an accumulation area by a tunnel could be justified by the fact that, in some stages of a landslide life, such area can appear as the more stable part, so that the existence of a landslide phenomenon could even not be recognised. On the other hand, acting as a buttress hindering the movements of the upslope material, the accumulation can receive a thrust progressively increasing with time. Current research lacks accurate recommendations on how to study and numerically simulate this interaction, whose effects are frequently predicted by engineering judgement and experience only. Literature is not very rich in examples of slow-moving landslides interacting with tunnels. Unfortunately, in many cases, the collected data are not brought to the attention of the scientific community for several reasons, including the difficulty of interpreting phenomena that sometimes do not seem to have a clear explanation [2].

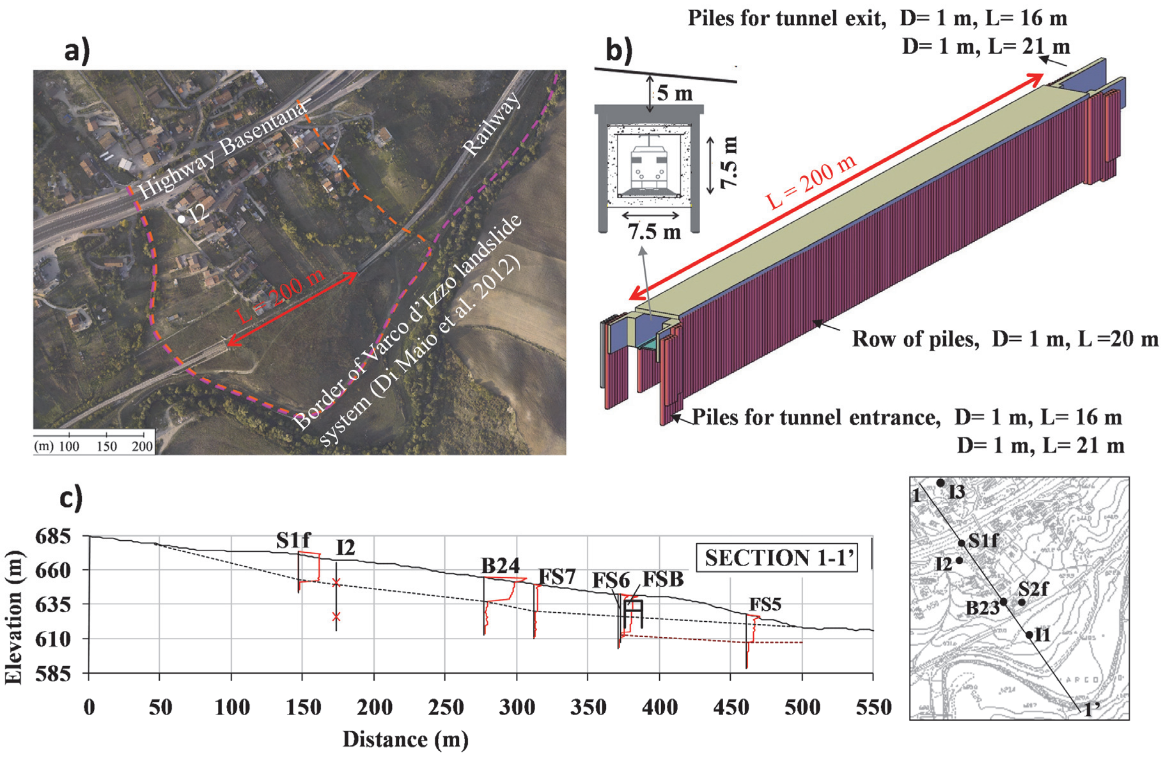

Figure 1: a) Varco d'Izzo landslide view with location of railway tunnel; b) 3D representation of tunnel 'Calabrese' (in grey) with the sheet-pile wall (in purple); c) Vertical section across the landslide with inclinometer profiles (modified from [3]).

The earthflow under study, situated in the eastern suburbs of the city of Potenza in a zone called Varco d'Izzo (Fig. 1a), develops in the Varicoloured Clays formation and is an extremely slow-moving landslide according to the classification by Cruden and Varnes [4]. The tunnel of the National Railway (Fig. 1a-b), which crosses the landslide accumulation, is the focus of this paper. A number of geotechnical investigations, including displacement monitoring, have been carried out in the area in the last 30 years. The geotechnical research group at University of Basilicata has been studying many aspects of several landslide phenomena occurring in the same slope, facing the valley of Basento river [5, 6, 7]. As for the landslide system of Varco d'Izzo [3, 8] all the available monitoring data are relative to the period after the reconstruction of the railway tunnel. Landslide movements were slow but continuous till nowadays, in the order of one to several cm/year. They have caused the unusability of a residential building, the dismantling of a pedestrian bridge overpassing the local highway, and damage to roads and other constructions. In the period 2005-2011, available inclinometer and GPS data have shown no significant changes in displacement rates [3, 9], which have been of about 1 cm/year in the zone of inclinometer I2 (see Fig. 1c). Note that the cross section of the landslide body through I2 will be the control section for displacements in the numerical model. The inclinometer profiles allow reconstructing the geometry of possible slip surfaces or, at least, of parts of them as shown in Fig. 1c. The upper slip surface, which outcrops at the river floodplain, reaches a depth of about 20 m and directly interacts with the sheet-pile wall protecting the tunnel. A second slip surface, or at least a zone with concentrated deformations, seems to be located at about 40 m depth, below the pile-tunnel system.

2 DESCRIPTION OF THE TUNNEL GEOMETRY AND CURRENT CONDITIONS

Tunnel "Calabrese" was re-built in 1992, after the previous one had suffered severe damage due to landslide movements, by the 'cut and cover' method, in which a trench is excavated, the tunnel lining is put in place, and then the whole is covered up to the ground level. The concrete box structure has internal dimensions 7.5 x 7.5 m and an average soil overburden of about 5 m, as shown in Fig. 1b. Along its length of about 200 m, it is made up of eight sectors separated by construction joints at an average length of 25 m. The interaction with the landslide is thus characterised by the fact that the main structural elements (piled walls and box structure) were constructed in sequence and also interact with one another. The piles, in a single row at both sides of the tunnel, are 20 m in length and 1 m in diameter. A double row of piles is present at the tunnel entry and exit (Fig. 1b). The pile-tunnel system, with its low deformability, represents an obstacle to the slow landslide movements, with a possible increase of earth thrust acting from upslope. This justifies the need for accurate soil-structure interaction, along with continuous monitoring of the structure deformation.

In the very last years, an evolution of deformation could be observed and measured [8, 10], thanks to the collaboration with the Italian Rail Infrastructure Manager (RFI). Relative displacements along tunnel joints and a number of vertical fissures have been observed, the more open ones located along the upslope wall facing the landslide, at the western side. Furthermore, Vassallo et al. [8] report, as a result of a 3D laser scan survey carried out in the tunnel in 2015, maximum horizontal displacements of about 5 cm between tunnel roof and base. Deformed shapes at several locations are those expected as the result of unbalanced actions on the upslope and downslope side.

3 NUMERICAL ANALYSES

The earth thrust distribution, the state of stress in the lining and their evolution with landslide displacements have been analysed by a geotechnical FEM software, Plaxis 2D/3D [11], and a structural FEM software, SAP2000 [12]. The former allowed an accurate description of the landslide behaviour and a simplified description of tunnel behaviour, the latter a more detailed description of the tunnel behaviour. To better understand the tunnel behaviour, also a number of structural models with different degrees of interaction between tunnel sectors were implemented.

Mishra [10] considered two mechanisms to numerically activate the landslide displacements in Plaxis: 1) by applying prescribed displacements at a control section chosen far from the tunnel (as in [13]), and 2) by increasing phreatic level (as in [14, 15]). Both of these effects lead to soil movements, hence inducing additional stresses on the tunnel lining. For the scope of this paper, only results of mechanism 1 are illustrated.

In Plaxis 2D/3D, the landslide body was simulated by a linear elastic-perfectly plastic material satisfying Mohr-Coulomb's yield criterion. Although other more advanced constitutive models were available in the software, this simple model was considered adequate to tackle the problem, also given the limited amount of available laboratory results on undisturbed specimens [3]. Peak shear strength and stiffness parameters estimated from such results were used in the analysis. As for slip surface modelling, interface elements with frictional shear strength and zero cohesion were considered. Nil cohesion is consistent with the observation that this active landslide underwent large displacements, so that the residual strength is now available. Stable soil was considered elastic. Being the model described here a total stress model, without explicit consideration of pore water pressures, the equivalent friction angle φ_{eq} assigned to the slip surface is lower than the laboratory determined residual friction angle φ'_r. Such parameter was set so as to obtain a global safety factor of the landslide as close to one as numerically possible before the tunnel construction. Properties of structural materials were inferred from design documents and corroborated by some preliminary in-situ non-destructive tests. Table 1 summarises the used soil and structure parameters.

Plaxis 2D was used to analyse, in plain strain conditions, the median longitudinal section of the landslide. The mesh is made of triangular elements (see Fig. 2) more refined close to the tunnel to carefully evaluate the evolution of stress and strain at critical locations. For the simulation of two concrete members placed next to each other, the software does not allow to use two adjacent plate elements. To overcome this limitation they were placed with a physical gap in between and the nodes in the two concrete members were connected by struts to make the contact transfer only compressive, i.e. without any shear transferred by the piles to the box structure (Fig. 2), accordingly to how the structure was constructed, that is without any specific reinforcement linking the piles to the box.

The model in Plaxis 3D, shown in Fig. 3, was implemented to better analyse the spatial distribution of landslide thrust along the tunnel length. The model geometry was derived from a digital terrain model (DTM) of the landslide area, geomorphological and inclinometer data for the landslide, and from design documents and in-situ survey for the structure. The sheet-piled walls were simulated as two separate equivalent volumes of concrete, crossing the slip surface and embedded for some meters in the stable soil, and were assumed as fully connected to the tunnel box structure.

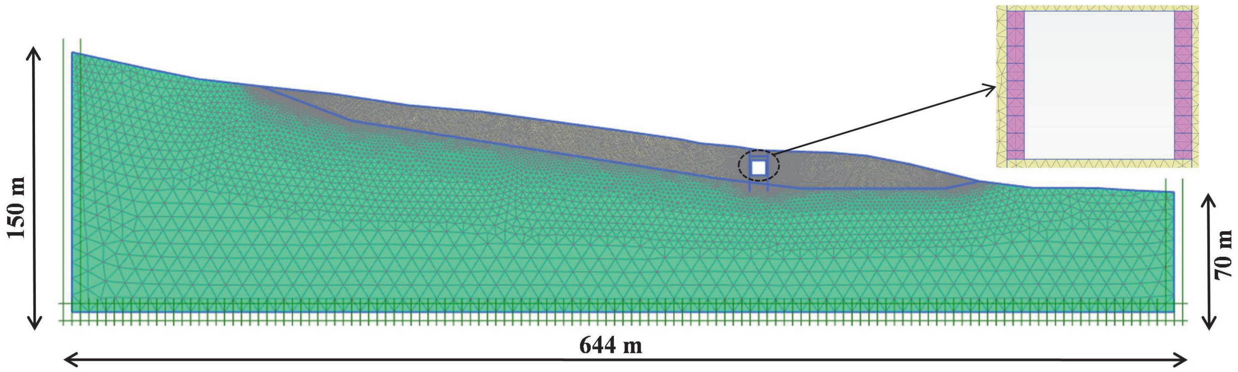

Figure 2: Finite element mesh in Plaxis 2D showing local refinement near tunnel.

Material	Properties
Stable material	Elastic (E = 1000 MPa, ν=0.4)
Slip surface	Rigid perfectly plastic, residual shear strength (φ_{eq}=6.5° for 2D and φ_{eq} = 8.5° for 3D)
Landslide body	Mohr Coulomb (E = 50 MPa, ν=0.4), peak shear strength (c = 50 kPa, φ=14°)
Pile/tunnel lining	Elastic (E = 32,900 MPa, ν=0.2)
Strut	Elastoplastic (compression only, EA=$16.4 \cdot 10^6$ kN/m, spacing = 5 m)
Flexural rigidity (EI)	Per unit width in the out of plane direction EI (kN m^2/m) $1.6 \cdot 10^6$
Axial stiffness (EA)	Per unit width in the out of plane direction EA (kN /m) $25 \cdot 10^6$

Table 1: Material models used in Plaxis.

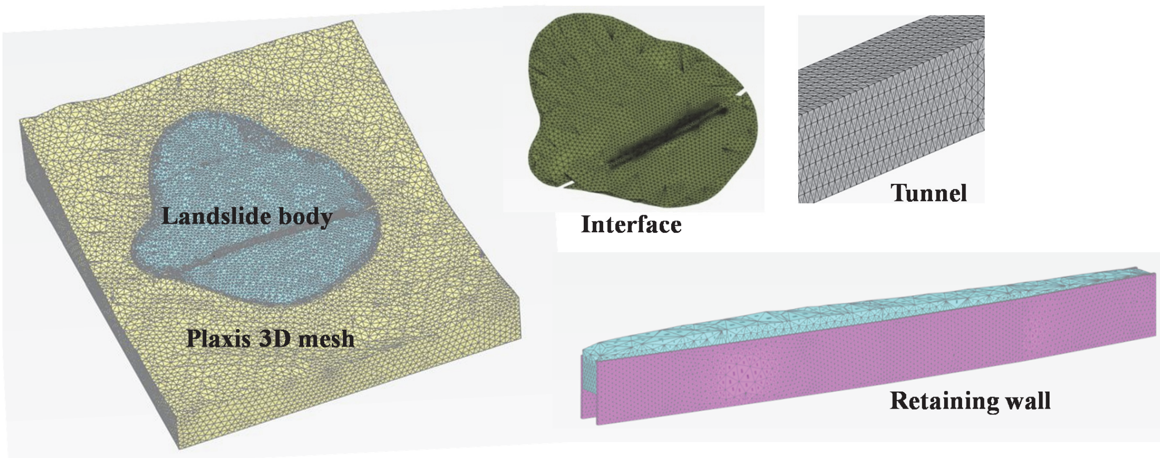

Figure 3: Model in Plaxis 3D: Finite element mesh, the landslide body, view of the slip surface simulated by interface elements, tunnel using plate elements and retaining wall.

This was accepted as a useful compromise to study the effect of the tunnel presence on earth thrust, leaving to the successive structural analysis the detailed study of stress transmission among structural elements. In fact, the geometrical complexity of the 3D geotechnical model did not allow to simulate just a compressive force transfer as in the 2D simulations.

The model is 1200 m x 800 m x 150 m in size, with a total number of 650,000 10 noded tetrahedral elements. The tunnel was modelled as a continuous structure by plate elements.

Structural models in SAP2000 were implemented to deal with the influence of the uneven distribution of earth pressure along tunnel length on the deformation profile of the tunnel. The analyses carried out permitted to evaluate the global response of the tunnel with and without joints. The piles were simulated as single elements, and a number of rigid link elements were used to connect them to the tunnel (Fig. 4a), allowing only compression transfer. The Plaxis 3D output has been used as input data for the SAP2000 model in terms of earth pressures acting from upslope and reactions of the landslide accumulation acting from downslope, simulated by equivalent springs. The model is shown in Fig. 4b, it uses shell elements and has 12,000 nodes and 5473 frame elements.

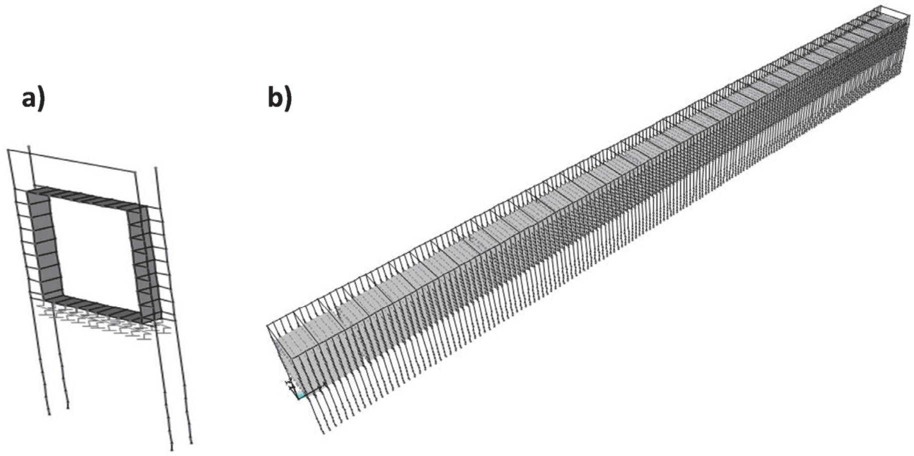

Figure 4: Tunnel model in SAP2000: a) portion of the model with shells and 10 links connection b) 3D view.

4 ANALYSIS OF RESULTS

Distribution of landslide thrust along the length of the tunnel and its comparison with 2D results is one of the main output results of the calculations performed. Fig. 5a shows the evolution of relative shear τ_{rel} (i.e., ratio of acting shear stress to available shear strength) along the slip surface with application of increasing prescribed displacements u*. Based on the landslide activity in the monitoring period, u* = 10 cm can be assumed as approximately representative of a decade of displacements. As written above, shear strength of the landslide slip surface was set so as to obtain a global safety factor approximately equal to one after tunnel construction. Nevertheless, some portions start with local safety factor slightly higher than one, and thus relative shear τ_{rel} lower than 1. As can be seen, as landslide displacements increase such shear strength surplus is utilised first at the entry of the tunnel (west side) and then at the exit (east side). With the increasing value of u*, almost all the force increment acting from upslope becomes an increasing thrust on the tunnel, as more and more portions of the slip surface reach τ_{rel} = 1. Fig. 5b shows contour plots of horizontal earth pressure in the direction orthogonal to the tunnel (i.e., σ_y). A non-uniform distribution of stresses along the tunnel length is observed, with higher values at the western side. Such distribution can be attributed to the local topography and to the assumed geometry of the slip surface, based on the data of a significant number of inclinometers, although not all pertaining to the same monitoring period and prevailingly concentrated on the western half of the earthflow [10]. The scheduled new geological and new geotechnical investigations of the area will hopefully clarify this aspect. A non-uniform earth thrust distribution is the presumable cause of the observed in-situ style of tunnel relative displacements, mainly concentrated at the structural joints and with higher values at the western end of the tunnel, and also of the cracks observed on the tunnel walls.

Fig. 6 shows the increment in earth pressures σ_y acting on the tunnel from upslope as a consequence of prescribed displacements. Results are plotted for three values of prescribed displacements u*. At the mid-height of the tunnel, for u*= 40 cm, $\Delta\sigma_h$ varies from 150 kPa at the entrance to 40 kPa at the exit. The same figure also reports values obtained in 2D conditions. For the sake of completeness, 2D calculations were carried out with two friction angle values available on the slip surface. In fact, we used: a) the friction angle leading, before tunnel construction, to a global safety factor of the landslide SF=1 in 2D; b) the friction angle leading to the same condition in 3D. Irrespective of such differentiation, calculated pressures in 3D have values even half of those estimated in 2D, due to the possibility of sideways movement and the less effective lateral confinement arising in 3D conditions. In the 2D model, in fact, the tunnel acts as a barrier which extends infinitely in the transversal direction providing maximum resistance and hence inducing higher earth pressures.

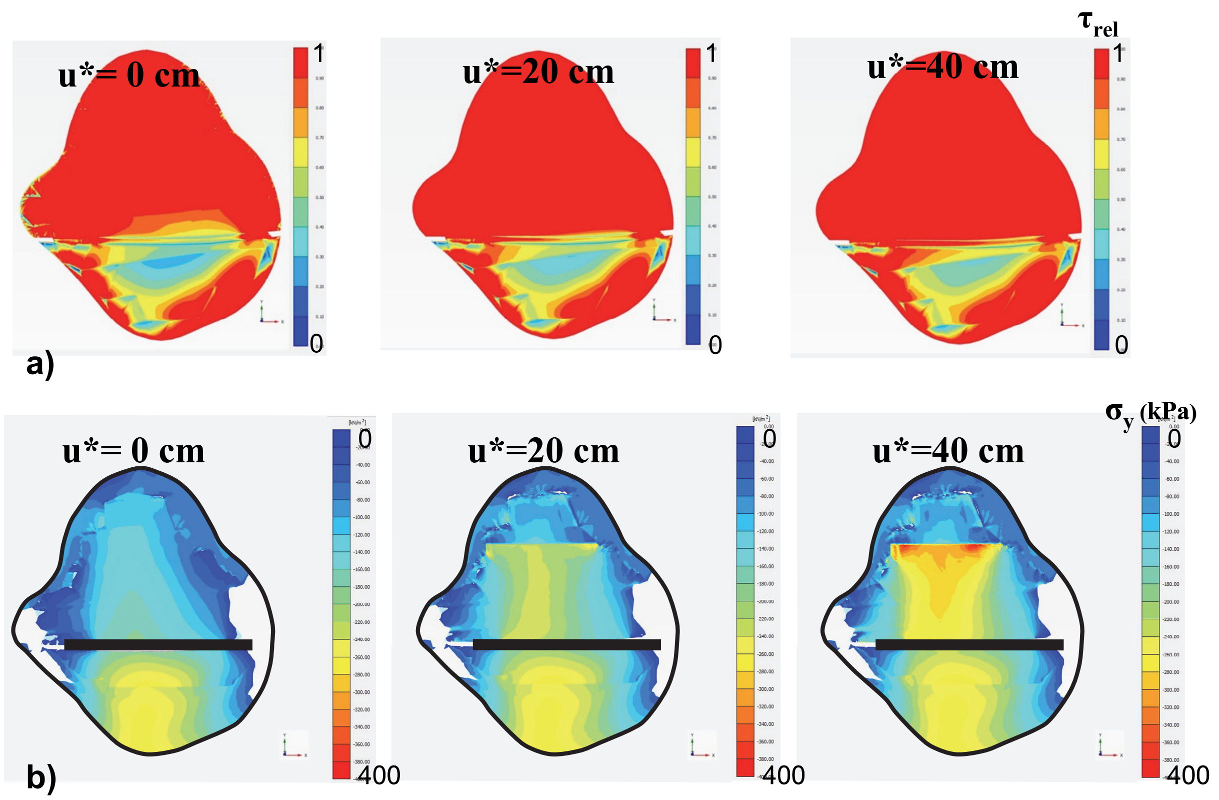

Figure 5: Evolution with prescribed displacement u* applied at the landslide control section of a) relative shear (τ_{rel}) along the slip surface; b) horizontal earth pressure σ_y in a plane at about 10 m depth from the ground surface. Values of u* of 0, 20 cm and 40 cm are considered.

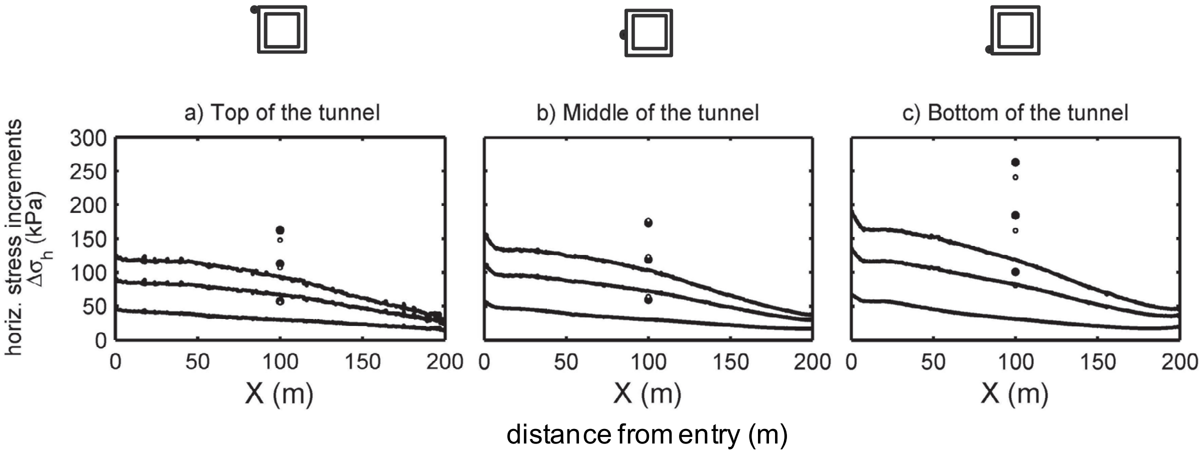

Figure 6: Horizontal earth pressure increment induced by prescribed displacements at the level of a) top; b) middle; c) bottom of tunnel. Plaxis 2D results are also reported for comparison, either as full dots (●) for calculations carried out by assuming the same friction angle along the slip surface as in 3D calculations, or as empty dots (o) for calculations carried out with the friction angle reported for 2D in Table 1.

The effect of the earth thrust on tunnel displacements, also analysed by the structural software SAP2000, is shown in Fig. 7. It is worth noting that the tunnel bears a small percentage of the initial earth thrust due to the presence of the sheet pile walls retaining the excavation, which deform before tunnel construction. To study the effect of collaboration between different sectors, different models were constructed. Case 1 in Fig. 7 is a continuous tunnel having maximum collaboration while case 3 is a tunnel whose joints are considered also extended to the capping beam. Case 2 has just the 7 tunnel joints present in the real situation. The effect of joints in the studied structure does not seem very significant, globally, on displacements. The similar overall trend of displacements in cases 1 and 2 is justified by the fact that the rows of piles well confine all the sectors. Nevertheless, the non-negligible contribution of relative displacements calculated at joint locations in case 2 seems in qualitative agreement with the out of plane separation of tunnel segments observed in-situ. The presence of joints in a tunnel crossing a landslide might be useful even though it can increase displacements because it can help to accommodate the shear deformations throughout the tunnel length. In cases of a local instability of some landslide portion, joints can help to isolate the effects mainly to the affected tunnel segment rather than "dragging" the whole structure with it.

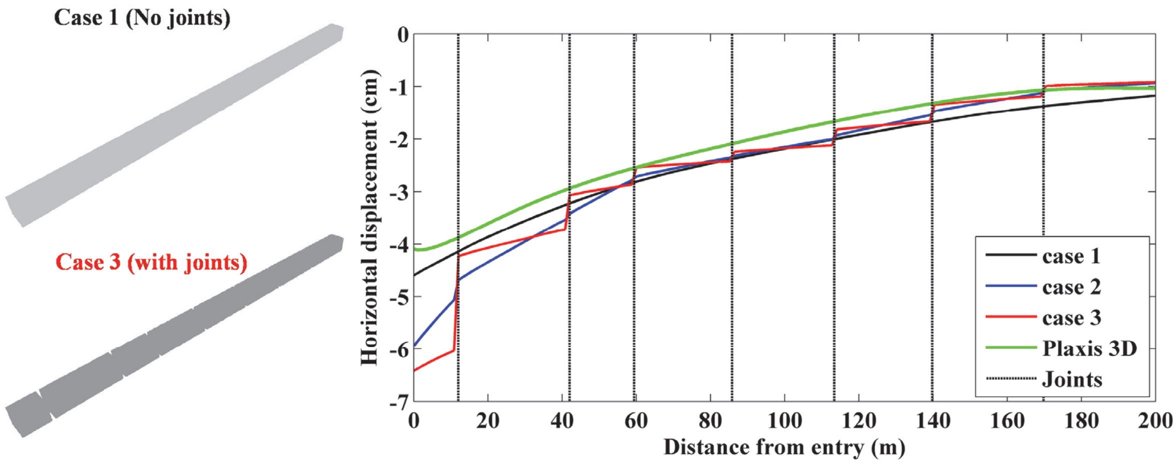

Figure 7: Deformed shape of the tunnel obtained by using different models in Plaxis 3D (Prescribed displacements u*=40 cm) and SAP2000. Displacements are relative to the mid-height of the box structure.

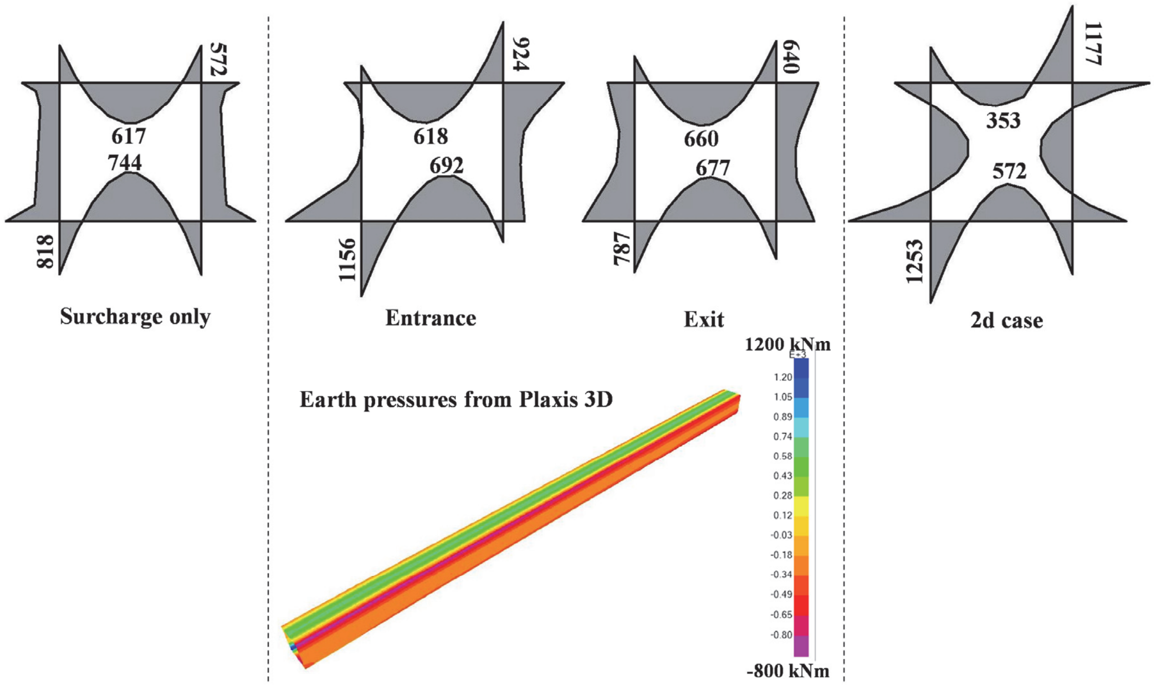

Figure 8: SAP2000 models results: bending moments in tunnel lining in 3D conditions (effect of surcharge only in the middle section, effect of surcharge and landslide thrust at entrance and exit sections) and 2D conditions. Earth pressures due to the landslide were derived from Plaxis models with prescribed displacement u* = 40 cm.

The significant 3D effect in the soil-structure interaction has not negligible consequences also on tunnel's stress state. Fig. 8 reports the comparison of bending moments acting on the tunnel for the cases of a 3D model and a 2D model, both linear. As can be seen, the 2D model shows higher bending moments than the 3D model. Values in the most stressed tunnel section in 3D conditions are 1.3 times lower than those evaluated in 2D conditions. As for the section with the lower bending moment value, the ratio is 1:1.8. Apart from linear analyses, Vassallo et al. [8] performed non-linear 2D analyses to evaluate the stress-strain condition of the structure. The tunnel deformations estimated by such calculations agree satisfactorily with those measured in-situ.

5 CONCLUSIONS

This paper presents a case study of the interaction between a slow-moving landslide with a railway tunnel supplemented by data from in-situ inspections. Earth thrust distribution on the tunnel and its evolution with landslide displacements, and tunnel response, were analyzed by different models, each aimed at studying in detail a certain aspect of soil-structure interaction, but all taking into simultaneous consideration soil and structural behaviour. 2D models gave conservative results on earth pressure values when compared with 3D models. The tunnel behaviour analysed, in this case, is similar to that of a beam which is loaded with a non-uniform pressure distribution and develops vertical cracks due to it.

Less computationally demanding models in SAP2000 allowed to understand the role of joints in the distribution of displacements and stresses in the tunnel lining. The results showed the presence of large differences between stress values at the entrance and at the exit of the tunnel, identifying the most affected areas in terms of possible damage and, thus, to which more attention should be paid in designing retrofit intervention.

Although not generalisable, the discussed results suggest that the realisation of joints, say every 20-30 m, should be considered in the design of tunnels crossing slow landslides to accommodate shear deformations due to landslide thrust. With respect to joint spacing, lower values on the one hand could better accommodate shear deformations but, on the other hand, would have negative consequences regarding the railway maintenance.

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