Proceedings of the 21st ICSMGE, Vienna, Austria, 14 – 19 June 2026. Pistrol, Adam & Schweiger (eds.)
Published by: ÖGG, Austrian Society for Geomechanics, Salzburg, Austria, ISBN 978-3-9503898-4-5
https://doi.org/10.53243/ICSMGE2026-2001

Hydro-mechanical numerical modelling of paleo-landslide reactivations due to river erosion

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ABSTRACT: The activity of deep landslides is currently recorded in several stiff clayey slopes along pre-existing shear bands, within chain areas, and in the south-eastern Italian Apennines. In the far past, geological processes caused the first triggering of such shear bands, within which large straining led to soil weakening, whose presence represents nowadays a crucial internal factor, controlling the current slope activity.
When currently active, such landslides can threaten the safety of infrastructures/structures, as for the Chieuti municipality, which is jeopardized by the erosion-induced reactivations of a multiple roto-translational slow-moving paleo-landslide. It was interpreted as the effect of long-lasting river erosion processes controlling slope equilibrium conditions.
The work concerns the modelling of the current activity of the Chieuti clayey paleo-landslide using two-dimensional and three-dimensional hydro-mechanical FE modelling of the soil state evolution due to river erosion. The aim was to prove the capability of the numerical modelling to reproduce the slope stress-strain evolution as a result of the erosion process at the toe.
The erosion-induced straining within the pre-existing shear bands resulting from the modelling successfully matched the vertical displacements recorded at Chieuti by remote sensing technique, and this further corroborated the phenomenological diagnosis of the current landslide activity. Furthermore, the modelling is also suitable to investigate the evolution of the displacement field jeopardizing Chieuti in the future, evaluating either the impact changes in the erosion process intensity maybe affected by the weather-change, or the effects of strategies for risk reduction.

KEYWORDS: Paleo-landslide reactivation; river erosion simulation; pre-existing shear band.

1 INTRODUCTION

Ancient deep landslides are often found to be currently active and, despite being characterized by slow to very slow movements (Cruden & Varnes, 1996), they can jeopardize relevant structures and infrastructures, posing serious threats for their serviceability (Cotecchia et al., 2020) and, with time, for their safety. These ancient landslides are found to recur in slopes formed of marine clays within the Adriatic Foredeep, as is the case of Chieuti (Figure 1; Tagarelli et al., 2025; Santaloia et al., in prep.). In particular, based upon geological, geomorphological and hydrogeological studies, first landslide inceptions can be interpreted as the effect of geological processes, such as marine regression (e.g., Cotecchia et al., 2020), and river erosion (e.g., Levy et al., 2012) among others. These landslide bodies, i.e., paleo-landslides (Clauge, 2022), are under equilibrium conditions controlled by the strength available in the shear bands, which usually include the most weakened soils, and by the current external actions, i.e., changes of the hydro-mechanical state in the soil, either due to soil-vegetation-atmosphere interaction (Tagarelli & Cotecchia, 2025), or caused by processes of the river/sea erosion (Tagarelli et al., 2025; Santaloia et al., in prep.) as it is the case of Chieuti (Figure 1).

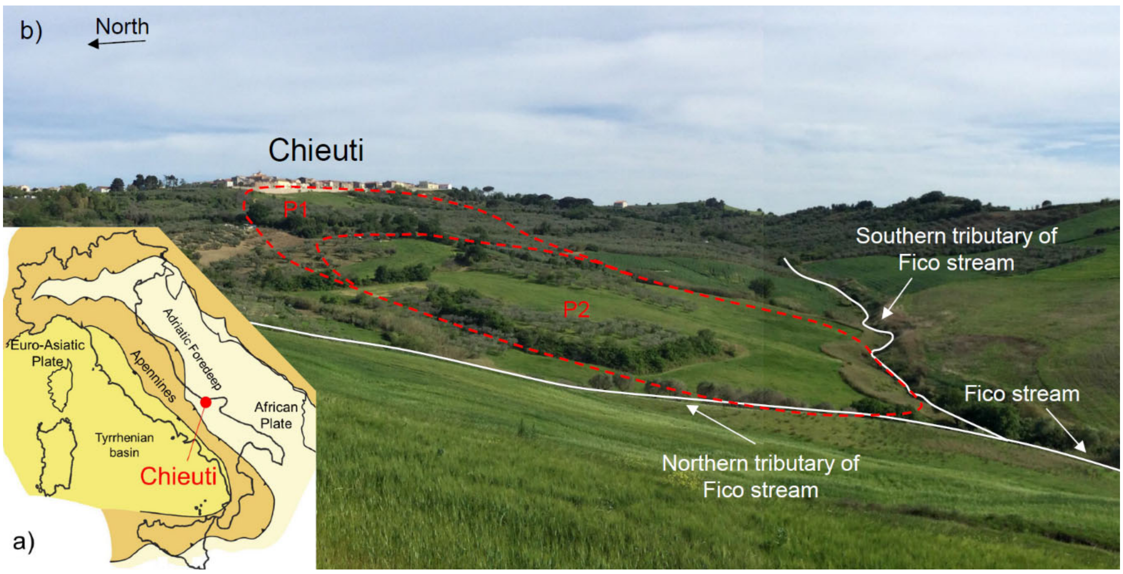

Figure 1. a) Schematic structural map of Italy showing the location of Chieuti town; b) panoramic view of the western slope of Chieuti (picture taken 0.7 km northwest of the town). The landslide borders are shown in red, while the streams are in white. Modified from Tagarelli et al., 2025.

This contribution discusses the numerical modelling of the hydro-mechanical soil state evolution activated within the Chieuti slope, with peculiar reference to the pre-existing shear bands, by the current river erosion process at the toe of the landslide bodies. As such, this work attempts to prove the capability of the numerical modelling to reproduce and simulate the slope stress-strain evolution as result of the erosion process at the toe.

2 THE LANDSLIDE CASE STUDY: THE CHIEUTI SLOPE

Chieuti is a small town founded on the top of a hill at 221 m a.s.l. within the Apulian Foredeep, laying on continental deposits and marine successions (sands, silts and clays) at depth. The western slope of the Chieuti hillslope, crossed by the Fico stream and its tributaries (Figure 1 and 2), is currently the location of several slow-moving landslides, laying within a deep and large paleo-landslide basin, bounded upslope by the town and downhill by the Fico stream (Figure 1 and 2).

Records of recurrent structure damages were monitored with time along the western border of Chieuti (Figure 2; Santaloia et al., in prep.), caused by the landslide reactivations, as shown by satellite monitoring (Figure 3; Sonnessa et al., 2023).

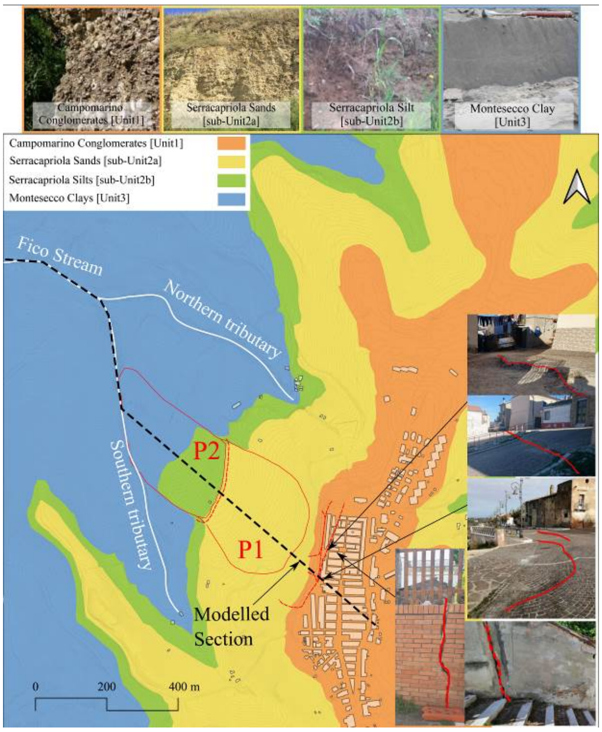

Figure 2. Geomorphological map of the Chieuti hillslope (Santaloia et al., in prep.) and damages locations.

Damage to these buildings and the streets behind them has been documented since the early decades of the 19th century, as reported in municipal records, which also mention the collapse of some buildings. At present, damage is widespread and continues to evolve across the entire north-western sector of the old town, as shown in Figure 3.

Over time, several retaining structures were installed at the edge of the slope (in 1959, 1986, and 2005) for stabilization purposes, the most recent being a counterfort wall with pile foundations reaching a depth of 12m. However, over time, these retaining structures also became involved in the instability process and suffered damage (Tagarelli et al., 2025; Santaloia et al., in prep.).

While this landslide has caused structural damage at the top of the slope, it has not produced easily detectable geomorphological changes further downslope over the past two centuries.

Synthetic Aperture Radar (SAR) acquisitions for permanent scatterers (PSs) located in the north-western sector of the old town indicate positive displacement rates along the satellite Line-of-Sight (LoS), as shown in Figure 3 for Sentinel-1 (S1) satellites over the period 2015–2021 (9–14 mm/year on the descending track; Sonnessa et al., 2023). As discussed by Sonnessa et al. (2023), the combined analysis of both ascending and descending S1 datasets reveals that the ratio of the vertical to the horizontal east-west component of the displacement rates in this sector is approximately 4. This suggests that the displacements at the top of the slope are predominantly sub-vertical. Further downslope, S1-SAR was not able to detect any displacement rates due to the absence of permanent scatters along the landslide bodies P1 and P2.

On the whole, based upon field monitoring and geotechnical investigations, the Chieuti landslide mechanism was recognized to be composed of a multiple roto-translational process, large part of which overlaps paleo shear bands, also characterized by a retrogressive evolution (Santaloia et al., in prep.). In particular, the shape of the shear bands of bodies P1 and P2 at depth in the slope were reconstructed using inclinometric monitoring data, and through the identification of meso-structure disturbance from several soil cores. Where no information were available, the complete shape of the shear bands have been set as to be geometrically reasonable.

Geological–geomorphological reconstruction combined with numerical modelling (Tagarelli et al., 2025; Santaloia et al., in prep.) indicated that the asymmetrical valley incision by the Bivento River, which affected the Chieuti hillslope during the Middle Pleistocene–Holocene tectonic phase, initiated the first failure within the slope soils (Tagarelli et al., 2025; Santaloia et al., in prep.).

In particular, the asymmetric excavation of the Bivento valley produced relatively steep slopes on the side hosting the Chieuti hillslope; together with further basal undercutting by the hydrological stream network, this process triggered the initial slope failure.

In contrast, the current landslide activity at Chieuti is hypothesized to result solely from toe erosion by the river, representing a long-term evolutionary phase (a reactivation stage) of deep strain localization processes that were initiated in the past by the area's geological history.

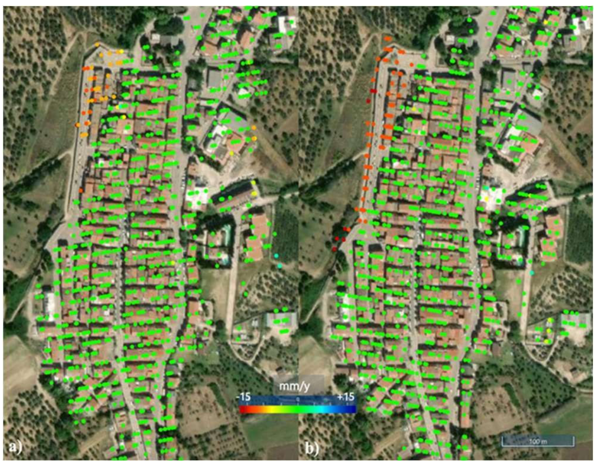

Figure 3. a) Ascending and b) descending mean velocity maps resulting from the processing of the CSK datasets between January 2015 and December 2020 (Sonnessa et al., 2023).

3 THE NUMERICAL MODELLING OF THE CURRENT LANDSLIDE ACTIVITY

To corroborate the diagnosis according to which the river erosion at the toe of the sliding mass is responsible for the current activity of the landslide, fully coupled two-dimensional (2D) hydro-mechanical (HM) numerical analyses have been carried out using the finite element code PLAXIS 2D (Bentley, 2022). This software has been successfully used to simulate the stress-strain behviour of slopes by means of HM numerical modelling in the past (e.g., Tagarelli & Cotecchia, 2022).

Indeed, the modelling was aimed at predicting the evolution of the stress-strain state in the slope (within the shear band), as result of the river erosion. The 2D numerical modelling has been carried out with reference to the section of maximum inclination within the Chieuti hillslope (modelled section in Figure 2); as such, the results hereafter discussed are believed to be meaningful even though this landslide mechanism has strong 3D features, which could be better captured only if 3D numerical modelling is carried out.

3.1 *Slope geotechnical model*

Figure 4 reports the FE model of the slope, whose maximum height is 690m, corresponding to the maximum height of Chieuti (221 m a.s.l.), and total length is 3400m. It includes four soil units which are the Unit 1 (Campomarino Conglomerates), the Unit 2a (sandy portion of the Serracapriola Sands), the Unit 2b (silty portion of the Serracapriola Sands) and the Unit 3 (Montesecco Clays), within which the shear band mainly occur (Tagarelli et al., 2025). The mesh is composed of fifteen-node triangular elements, each containing twelve stress points. Displacements were fixed in the horizontal direction along the left and right vertical boundaries of the mesh, while the bottom boundary was considered impervious, with displacements fixed in both directions.

The inset in Figure 4 depicts the portion of the slope model that includes the pre-imposed shear bands, implemented to simulate the behaviour of weakened soil zones. The geometry and position of these shear bands were derived from geomorphological surveys and inclinometric measurements and subdivided into four segments to allow the assignment of different shear strength properties. This approach reflects the retrogressive behaviour of the Chieuti landslide mechanism, which likely produced heterogeneity in the shear strength parameters along the failure surface (Potts et al., 1997), with lower resistance (about residual value) at the toe, gradually increasing toward the crest of the landslide body.

The inset also marks five control points (A–E), arranged from the upper slope to the toe of the landslide. Point A (highlighted in red in Figure 4) corresponds to the location of the highest landslide-induced displacement at Chieuti (Figure 3) and is therefore used for comparison between the observed displacements and those predicted by the numerical modelling of the erosion process.

3.2 *The HM properties of the slope Units*

The mechanical behaviour of the slope materials was simulated adopting the linear elastic–perfectly plastic Mohr–Coulomb model, whose parameters are reported in Table 1.

These parameters are consistent with the results of undrained triaxial shear tests conducted on material samples (Santaloia et al., in prep.). Soil specimens from both Unit 2a, 2b and Unit 3 exhibited only mild strain softening from peak to critical state during shearing, attributable to their light overconsolidation. For Units 2a and 2b, intermediate parameters between peak and post-peak condition (Table 1) were adopted in the Mohr–Coulomb yield function. For Unit 3, shear strength parameters intermediate between peak and residual values were assigned. The dilation angle ψ was set to zero for all the Units.

Table 1. Hydro-mechanical properties of the soil units.

Soil parameter	**Unit 1**	**Unit 2a**	**Unit 2b**	**Unit 3**
γ_{sat} [kN/m^3]	20	20	20	20
k_{sat} [m/s]	1*10^{-9}	1*10^{-8}	1*10^{-9}	1*10^{-10}
E′ [kPa]	30000	30000	30000	30000
c′ [kPa]	15	5	15	5
ϕ' [°]	20	32	26	20

The soils implemented within the shear bands have a lower shear strength than the intact Montesecco clay (Unit 3), being weakened due to the past shearing. As anticipated, the pre-existing shear band SB_1 (red line in Figure 4) was modelled with shear strength values corresponding to residual stress–strain conditions as measured in the laboratory. In contrast, SB_2 and SB_3 were assigned shear strength parameters consistent with the post-peak behaviour of Unit 3, being then only slightly higher (Table 2).

Table 2. Hydro-mechanical properties of the soil adopted to simulate the shear bands implemented in the slope model.

Soil parameter	**SB_1**	**SB_2**	**SB_3**
γ_{sat} [kN/m^3]	20	20	20
k_{sat} [m/s]	-	-	-
E′ [kPa]	12000	18000	24000
c′ [kPa]	0.1	2	3
ϕ' [°]	17	18	19

3.3 *Slope model initialization*

The stress–strain initialization phase adopted here follows the approach of Tagarelli et al. (2025), in which the complete migration history of the Bivento riverbed during the geological evolution of the Chieuti hillslope was modelled. Accordingly, the present modelling inherits all hydro-mechanical boundary conditions and modelling stages from Tagarelli et al. (2025). Specifically, the stress state of the slope was simulated from the end of sediment deposition through to the water table drawdown that occurred following regional uplift, thereby reproducing the consolidation history of the deposit.

In the initial stage, the model comprised a sequence of sub-horizontal strata, and the initial effective stress state was generated using a K_0-procedure with a uniform K_0 value of 0.65 for all soil layers. This value is typical for normally consolidated natural Blue Clays, such as the MC clay, and is also consistent with values reported for sandy soils under low to medium confining stresses. A steady-state seepage analysis was then performed to establish the initial piezometric regime, resulting in a water table located approximately 1 m below ground level, with suction values of around 10 kPa at very shallow depths in the sand layers (Tagarelli et al., 2025).

Following initialization, the pre-defined shear bands in the slope model were activated by assigning soil clusters with reduced shear strength (Table 1), as illustrated in the inset of Figure 4.

3.4 *The numerical modelling of the erosion stage*

After initialising the stress state across the entire slope, river erosion at the toe was simulated by progressively reducing the unit weight of predefined soil clusters located along the Fico stream (indicated by the dashed yellow line in the section shown in Figure 4). Each cluster has a fixed thickness of approximately 1 m. This procedure enabled the simulation of erosion of a specified intensity by decreasing the unit weight of the material within each cluster in proportion to its thickness. This strategy was preferred over the use of very thin, clusters to be deleted, as such this approach would have required an excessively fine but useless mesh in that part of the model, thereby increasing computational complexity and cost.

Five distinct erosion events were simulated using fully coupled hydro-mechanical (HM) transient analyses. The length and timing of these events were selected to match the acceleration phases of the landslide process identified from satellite-based displacement monitoring, which revealed five periods of sharp displacement increase. The timing of the erosion events was therefore defined based on both field observations and remote sensing data, covering the period from April 2015 to May 2022. Each erosion stage typically lasted about one month and was followed by a significantly longer steady stage, lasting less than one year. The exact sequence and duration of erosion and steady stages implemented in the slope model are reported in Table 3.

Table 3. Timing of the erosion and steady stages implemented in the numerical simulation.

Stages modelled	Starting date	Length (days)
Steady	1/5/2015	580
1st Erosion	1/12/2016	45
Steady	15/1/2017	396
2nd Erosion	15/2/2018	44
Steady	31/3/2018	410
3rd Erosion	15/5/2019	17
Steady	1/6/2019	319
4th Erosion	15/4/2020	46
Steady	31/5/2020	415
5th Erosion	20/7/2021	72
Steady	30/9/2021	212

To estimate the intensity of each erosion stage, governing the reduction in unit weight applied to the soil clusters used to model erosion, a simplified approach was adopted to quantify concentrated erosion along the drainage channel of the Chieuti catchment. This channel, the southern tributary of the Fico stream, coincides with the toe of landslide bodies P1 and P2 (Figures 1 and 2).

Specifically, an empirical stream-power-based method was applied, commonly used for small ephemeral gullies and first-order channels (Foster et al., 1981; Nearing et al., 2004). This approach relates the eroded volume (ΔV) to the peak discharge, slope, and length of the incised channel, as follows:

$$\Delta V = k\, Q^m S^n \cdot L \qquad (1)$$

with Q, being the peak discharge (m^3/s), S, the mean slope of the channel, L, the incised length (m), and k,m,n, empirical coefficients accounting for soil erodibility and flow settings.

For the present case study, the Chieuti catchment is large about 0.8 km². The channelized reach considered, i.e., the Southern tributary is approximately 780 m long, with a mean bed slope of 10 % (≈5.8°). The soil along the tributary mainly consists of soft clay, i.e., the Montesecco Clay, for which literature-based parameters were adopted (k=0.7, m=1, n=0.5). The peak discharge was estimated using the Rational Method (originally proposed by Mulvany, 1851):

$$Q = C_r \cdot i \cdot A \qquad (2)$$

where C_r=0.6 (for clayey soils), A=0.8 km², and i=30 mm/h as a representative rainfall intensity over the critical duration, consistent with local extreme precipitation patterns. This yielded a peak discharge of approximately Q≈14.4 m³. Substituting these values into the stream-power-based equation provides an estimated eroded volume of ΔV≈2470 m³ per year. Assuming a bulk soil density of 1.5 t/m³, this corresponds to approximately 3705 t of material annually removed from the gully channel. To express this in terms of vertical degradation, the eroded volume was normalized by the incised channel length (L=780 m) and its mean width (W≈30 m), resulting in a Δh≈0.105 m/year. Thus, the average annual lowering of the gully bed is approximately 10 cm, which is also consistent with field-based visual estimates.

Accordingly, each erosion step in the modelling was designed to represent the removal of approximately 10 cm of material along the southern tributary section. This corresponds to a reduction of about 2 kN/m³ in the unit weight of the 1 m–thick soil cluster used to simulate erosion.

This configuration was adopted in one of the two analyses presented in this study, referred to as Analysis_A. In contrast, Analysis_B applied a different approach: rather than assigning the same reduction in unit weight (2 kN/m³) for each erosion stage along both the southern tributary and the Fico stream, it implemented variable erosion intensities for each stage. The aim was to more accurately reproduce the field-recorded displacements, particularly at Point A. Analysis_B was conducted subsequently, once it became evident that erosion intensity required refinement beyond the simplified assumption used in Analysis_A, in order to better capture the observed displacement trends over time. This aspect is discussed in more detail in the following section.

4 RESULTS OF THE NUMERICAL MODELLING

The results of the predictions of the erosion-induced reactivation for landslide bodies P1 and P2 at Chieuti were first evaluated by assessing the displacements predicted at control points A to E, whose locations are shown in Figure 4. Figure 5 presents the vertical and horizontal displacement trends for four of these control points, referring exclusively to Analysis_A. Overall, the model successfully predicts displacement increases at Points B, C, D, and E during the erosion stages simulated through the soil cluster lightening.

The displacement patterns appear physically consistent. For the vertical component (Figure 5a), the model predicts settlement at Points B, C, and D, all located at scarps of different landslide bodies, and heave at Point E, located at the toe, where an upward ground movement is expected as part of the landslide kinematics. For the horizontal component (Figure 5b), all control points (B–E) exhibit negative displacements, indicating movement towards downslope, as expected for the landslide bodies.

It is worth noting that the model also predicts small displacements, both vertical and horizontal, during the steady stages between erosion phases, when displacements would not normally be expected. A possible explanation is the use of fully coupled hydro-mechanical modelling, which calculates, at each time step, the dissipation of even small excess pore water pressures maybe generated by the slight unloading associated with erosion simulation. A second possible explanation relates to the implementation and activation of weakened material within the shear bands after the stress state initialization. The perturbation of equilibrium caused by shear band activation may have contributed to these displacements. However, this circumstance requires further investigation, as no definitive explanation has yet been identified.

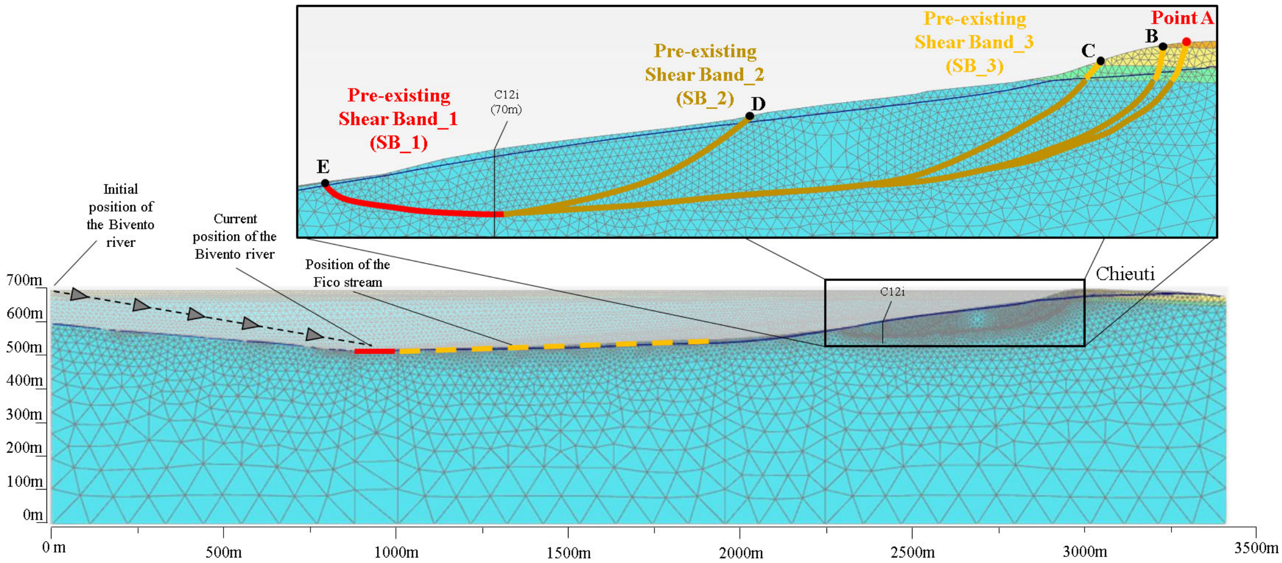

Figure 4. 2D Finite element numerical slope model adopted in the analysis.

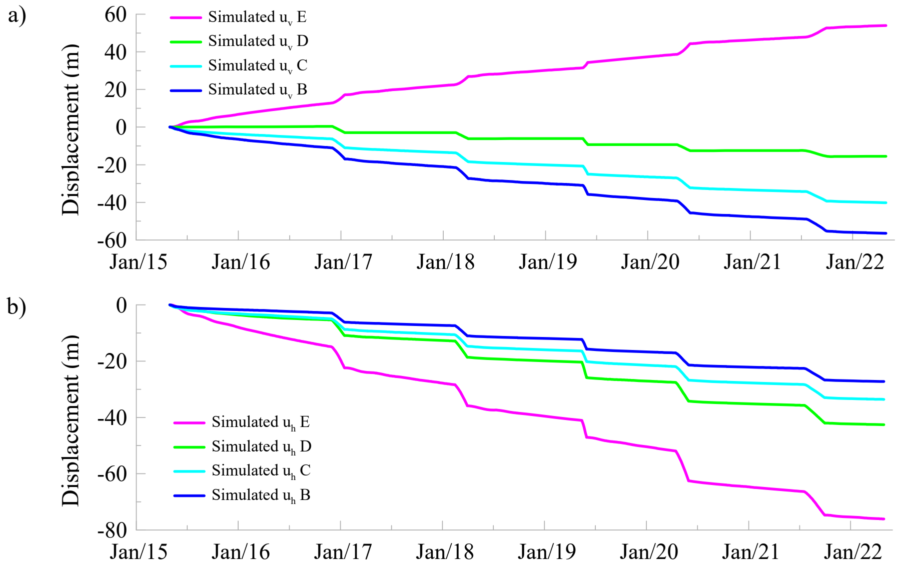

Figure 5. Numerical results in terms of vertical and horizontal displacements at Point B, C, D and E (whose location is in Figure 4).

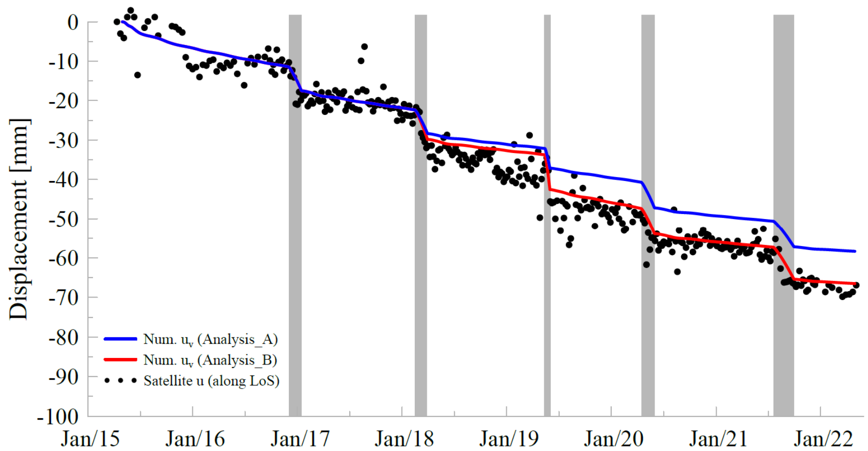

Figure 6. Numerical modelling results in terms of vertical displacements at Point A (whose location is in Figure 4), compared to the satellite monitoring data with reference to the same location reported by Sonnessa et al., (2023). Shaded in grey the periods during which the erosion has been activated.

Figure 6 shows the vertical displacement results at Point A, located in the western part of the Chieuti municipality, which is the area most affected by landslide-induced damage (location also shown in Figure 4 inset). Results are reported for both

Analysis_A (blue line) and Analysis_B (red line) and are compared with the satellite monitoring data from Sonnessa et al. (2023). Although the satellite data represent displacement along the Line of Sight (LoS), the comparison remains meaningful, also quantitatively, since, as discussed by Sonnessa et al. (2023) and Santaloia et al. (in prep.), displacements in the western sector of Chieuti (Figure 3) are nearly vertical.

As described earlier, Analysis_A considered five identical erosive stages: in each stage, a 10 cm-thick material layer was removed along the Fico stream, corresponding to a 2 kN/m³ unloading for the relevant soil clusters. In contrast, Analysis_B assigned variable erosion intensities to each stage, proportional to the accumulated vertical displacement at the end of each phase, in order to better match the field-measured displacement at Point A.

In both analyses, the numerical model reproduced the displacement evolution upslope at Point A, in the scarp area of Body P1, showing good agreement, both qualitatively and quantitatively, with satellite-monitored displacement trends during the active phase of the Chieuti landslide. Analysis_B, with erosion magnitudes calibrated to the monitored displacement data, achieved a closer match to the observations, while the results from Analysis_A remain fully satisfactory.

On the whole, these findings demonstrate the capability of the proposed numerical modelling approach to reproduce the slope's stress–strain evolution in response to toe erosion along the southern tributary and Fico stream, and to generate displacement patterns consistent with those observed in the field.

CONCLUSIONS

The erosion-induced displacements along pre-existing, weakened shear bands were investigated through finite element modelling, applied to the case of the Chieuti landslide mechanism (Santaloia et al., in prep.). The simulation results provide strong numerical evidence supporting the phenomenological interpretation of the current landslide activity, which attributes its reactivation to progressive riverbank erosion at the slope toe.

The close agreement between the predicted displacement patterns and the observed field data not only validates the modelling approach but also strengthens confidence in its use as a predictive tool. This enables a more detailed exploration of potential future scenarios for the Chieuti hillslope, including the assessment of how variations in erosion intensity—possibly amplified by climate change—may influence the landslide kinematics and hazard levels over time.

Moreover, the validated model offers a valuable means to test and compare alternative mitigation strategies aimed at reducing landslide risk. By simulating the mechanical response of the slope under different erosion-control or toe-protection measures, the model can guide decision-making towards interventions that are both effective and sustainable in the long term.

Overall, this work demonstrates that coupling field-based observations with advanced numerical modelling provides not only an explanation for the current instability mechanisms but also a robust framework for anticipating and managing future slope behaviour under evolving environmental conditions.

5 ACKNOWLEDGEMENTS

The authors are grateful for the financial support provided by the project PNRR, MISURA M4_C2_1.4, National Centre for HPC, Big Data and Quantum Computing (CN_00000013) - Spoke 5 "Environment and Natural Disasters". The Regional Commissioner for Landslide Risk Management of the Apulia Region is also acknowledged for the funding provided through the research agreement "Diagnosi della frana di Chieuti e lo studio dell'instabilità del centro urbano".

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