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APPLICATION OF NUMERICAL METHODS FOR THE STUDY OF THE 2014 SAN LEO LANDSLIDE (NORTHERN ITALY): CHALLENGES AND LESSONS LEARNED

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EXTENDED ABSTRACT

La frana di San Leo del 2014 è stato un evento franoso molto peculiare, in quanto è stato controllato da una serie di fattori preparatori e predisponenti rilevanti sia individualmente, che nella loro combinazione e interazione. Nei dieci anni successivi all'evento franoso, collegato al fenomeno di espansione laterale del plateau roccioso di San Leo, sono stati condotti numerosi studi che sono risultati nella redazione di report tecnici, nella pubblicazione di articoli scientifici e in presentazioni nell'ambito di convegni di rilievo sia nazionale che internazionale. Diversi di questi lavori hanno incluso modellazioni numeriche, condotte con vari obiettivi e modalità. La modellazione numerica effettuata nel corso delle settimane immediatamente successive all'evento, descritta prevalentemente in report tecnici non pubblicati, è caratterizzata da modalità di "*forward analysis*" e ha avuto come obiettivi la valutazione, gestione e mitigazione della pericolosità residua da frana. Le attività di modellazione in modalità di "*back analysis*", principalmente condotte nell'ambito della ricerca scientifica, si sono invece concentrate sull'analisi dei fattori e processi che hanno controllato la progressiva evoluzione morfologica del versante e della relativa instabilità.

Questo contributo si divide in due parti. Nella prima parte viene presentata una panoramica delle modalità e tecniche di modellazione numerica che possono essere utilizzare nello studio dell'instabilità e della deformazione dei versanti. Queste possono essere caratterizzate da variabili livelli di complessità ed elaborazione, passando da semplici analisi cinematiche e all'equilibrio limite, ad analisi tenso-deformative tramite l'utilizzo di metodi propri della meccanica del continuo e del discontinuo, fino ad arrivare a metodi ibridi e a reticolo, i quali permettono di analizzare sia il comportamento delle discontinuità preesistenti che la rottura fragile della matrice rocciosa. Più il metodo di analisi numerica è sofisticato, maggiore è la complessità dei processi e meccanismi che possono essere simulati e la quantità e qualità dei dati richiesti per la costruzione del modello. Simulazioni attraverso metodi avanzati richiedono anche attente considerazioni relativamente alle incertezze insite nei dati in ingresso, unite a un'adeguata valutazione e validazione dei risultati della modellazione numerica, utilizzando dati di monitoraggio, qualora disponibili, o le caratteristiche morfologiche del versante post-frana e del deposito. La seconda parte del contributo descrive le principali attività di modellazione numerica, sia in *back analysis* che in *forward analysis* che sono state effettuate ai fini dello studio della frana di San Leo, suddivise per metodologia impiegata (analisi cinematiche ed equilibrio limite, metodi nel continuo, metodi nel discontinuo e metodi ibridi o a reticolo). La combinazione tra i risultati delle indagini di campagna e quelli della modellazione numerica ha permesso di identificare i fattori e i processi che hanno controllato l'instabilità della rupe e l'innesco della frana del 2014, tra i quali si evidenziano l'assetto lito-stratigrafico dell'area, le caratteristiche morfologiche del settore nordorientale del plateau roccioso, e lo stato di fratturazione dell'ammasso roccioso. La distribuzione e la magnitudo degli stress interni derivanti dalla combinazione di questi fattori hanno causato un progressivo danneggiamento dell'ammasso roccioso, favorendo la formazione di una superficie di distacco avvenuta per propagazione e connessione di fratture preesistenti e rottura dei ponti di roccia.

Sulla base delle modellazioni condotte nel corso dei dieci anni trascorsi dall'evento, il contributo si conclude esponendo i vantaggi, le limitazioni, e le sfide affrontate nella simulazione della frana di San Leo, e più in generale nelle analisi numeriche di frane in roccia, evidenziando l'importanza del ruolo svolto dalla raccolta di dati e informazioni storiche relative sia al versante di interesse che ad altri siti con simili caratteristiche geologiche e geomorfologiche. Il plateau roccioso di San Leo, alla luce delle indagini ed analisi svolte, può essere considerato come un laboratorio naturale per lo studio, il monitoraggio e la modellazione dei fenomeni di instabilità da espansione laterale tipici della Val Marecchia e in contesti geologici simili.

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ABSTRACT

The 2014 San Leo landslide is a very peculiar landslide, being controlled by a large number of factors that interacted with each other; each one was in turn critical in driving, promoting, or allowing the slope failure. In the ten years after the landslide event, numerous studies were presented in the form of national and international journal articles, conference proceedings, as well as unpublished technical reports. These projects allowed different aspects and mechanisms to be investigated, progressively enhancing our understanding of the landslide. In this paper, we summarize, review, and discuss the various numerical modelling analyses that have been conducted, in order to outline the foundations on which future investigations may be designed. Considering the in depth understanding that has been gained on the geological, lithological, environmental, and engineering aspects of this site, we suggest that the San Leo plateau may be an ideal engineering geological field laboratory useful in investigating the evolution and instability phenomena that affect sites with similar characteristics within the Marecchia Valley region and beyond.

***Keywords**: San Leo landslide, numerical modelling, slope damage, slope kinematics.*

INTRODUCTION

Comprehensive investigation and characterization of landslides is of paramount importance for the effective design of mitigation and monitoring systems.

Traditional field work methods, combined with remote sensing analyses, allow rock mass data, including intact rock and discontinuity characteristics, to be collected and employed to evaluate the mechanical properties, kinematics, and potential failure mechanism of rock slopes (ISRM, 1978; Donati *et alii*, 2022; Lemaire *et alii*, 2024), particularly where stability is controlled by geological structures at various scales.

While the collection and analysis of field data represents a necessary activity to investigate rock slope stability, the application of numerical modelling methods to rock slope and landslide analysis can provide additional insight on the factors and processes that affect, or may affect, their evolution and stability (Stead & Coggan, 2012).

Combining field, remote sensing, and numerical modelling investigations, in particular can greatly enhance the understanding of the behavior and stability of rock slopes, particularly when numerical modelling analyses are constrained using monitoring datasets (*e.g.*, Rechberger *et alii*, 2021; Bossi *et alii*, 2016).

In this paper we provide a summary of the various numerical modelling methods that can be used for the investigation of rock slope instabilities. Then, on the occasion of the tenth anniversary of the 2014 San Leo landslide, we review and describe the role, advantages, and challenges of numerical modelling analyses that have been performed to investigate the event over the past decade since its occurrence. We will also present and discuss the lessons that have been learnt and implications for future field and numerical analyses currently being planned.

SUMMARY OF NUMERICAL MODELLING METHODS

Over the past few decades, numerical modelling methods have been developed and greatly improved to assist geoscientists and engineers in outlining the stability conditions of slopes and the controlling factors on instability (Fig. 1).

Different types of numerical modelling approaches are characterized by significantly different capabilities. Stead & Coggan (2012) define three levels (I, II, III) of landslide analysis and failure mechanism that progressively increase in complexity. Level I outlines the simplest landslide failure mechanisms, such as planar and wedge sliding, toppling, and simple rotational sliding. These processes can be investigated through basic stability analysis like kinematic and block theory analyses (*e.g.*, Goodman, 1985), as well as limit equilibrium (LE) methods (Stead *et alii*, 2006). Kinematic and block theory analyses investigate the stability of single blocks and groups of blocks, respectively, through a graphical approach, using datasets that are generally limited to discontinuity orientation and friction angle. LE methods compare the available shear resistance with the stress that exist along the failure surface, deriving a Factor of Safety (FoS) representative of the investigated landslide or block, for the considered mechanism.

Level II analyses allow for the simulation of landslides that displace through complex translation mechanism along stepped or discontinuous failure surfaces (Stead & Coggan, 2012). Complex translation mechanisms entail the formation and accumulation of damage along the sliding surface, in form of asperity shearing (i.e., in case of rough or undulating surfaces) or progressive brittle failure (i.e., in case of rock bridges existing along the incipient rupture surface). Typically, Level II analyses can take advantage of simplified LE methods (*e.g.*, Einstein *et alii*, 1983; Jennings, 1970) as well as more sophisticated stress-deformation, continuum or discontinuous numerical approaches (*e.g.*, Donati *et alii*, 2021). Continuum numerical techniques consider the rock mass forming the slope as a homogeneous, equivalent material, with mechanical properties that are assigned based on averaged characteristics (i.e., strength, deformability) that consider both the intact material and the discontinuity network (Hoek *et alii*, 1991). Typical continuum approaches employed in slope stability analysis include the finite element and the finite difference methods (FEM and FDM, respectively).

Level III modelling allows landslides characterized by complex failure mechanisms, involving a combination of translation, rotation, and internal deformation, to be investigated (Stead & Coggan, 2012). Such analyses are undertaken

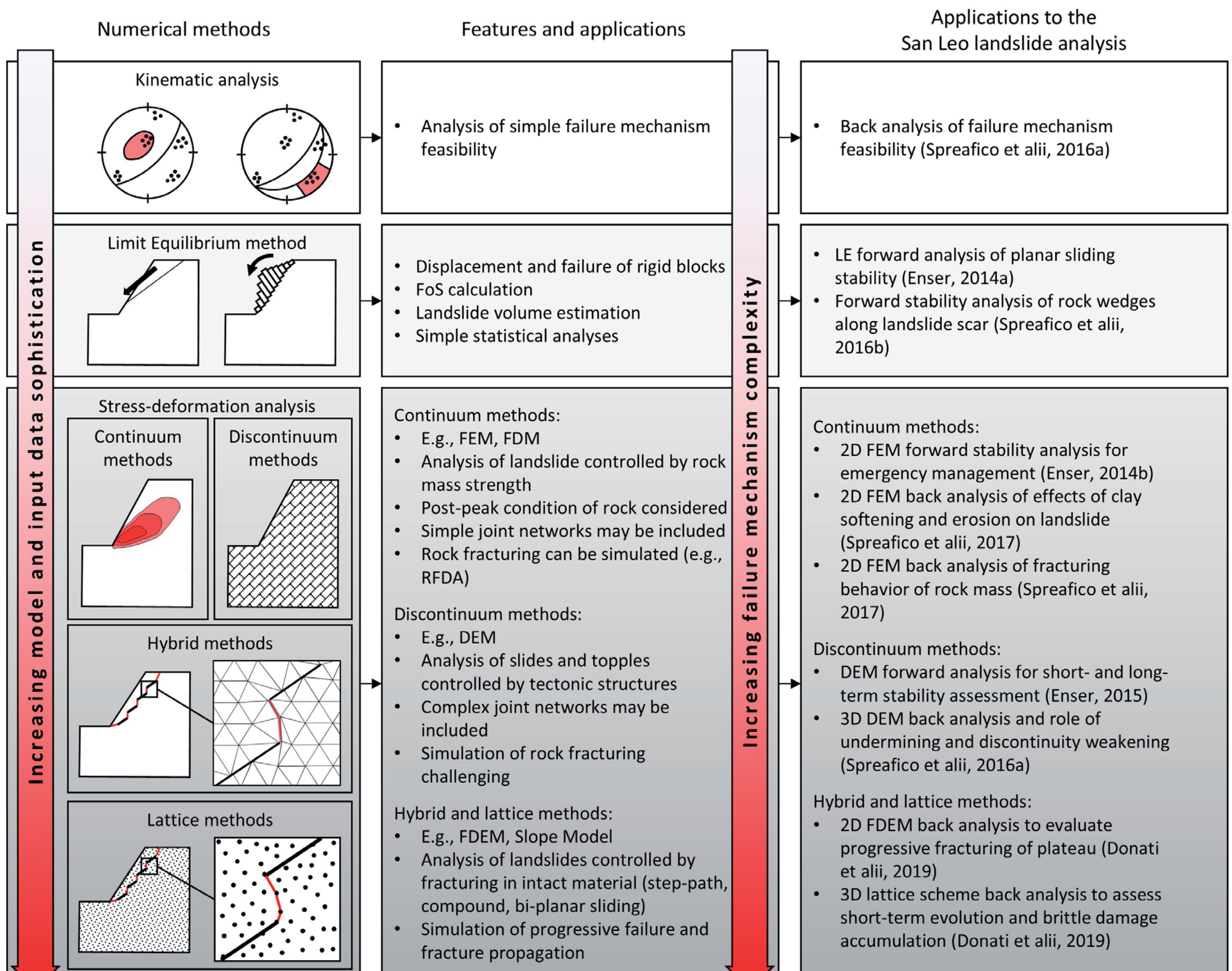

Fig. 1 - Summary and main features of the numerical modelling methods used in rock slope stability analysis, and overview of their application in the analysis of the 2014 San Leo landslide (detailed description in text). The complexity of the simulated failure mechanism progressively increases together with the sophistication of the required input data (Modified from Stead *et alii, 2022)*

using sophisticated numerical modelling approaches capable of simulating plastic deformation and failure of the geological materials constituting the slope, and may range from continuum and discontinuous modelling (*e.g.*, WOLTER *et alii*, 2013; Rechberger & Zangerl, 2022) to lattice-scheme and hybrid continuum-discontinuous analyses (Lisjak & Grasselli, 2014). Discontinuous methods are capable of simulating explicitly the non-linear nature of fractured rock masses. In particular, they allow for modelling the behavior of fractured rock masses using a combination of rigid or deformable blocks, separated by contacts that can also be deformable or rigid (Cundall, 1988). As a result, single blocks can displace and rotate independently from each other, as well as completely detach from the remaining rock mass. Discrete element methods (DEM), such as distinct element methods and discontinuous deformation analysis (DDA), are typical numerical methods employed in rock slope investigation, which differ based on how contacts and blocks are considered (i.e., rigid or deformable). Hybrid models combine multiple methods to exploit their specific features, while overcoming their limitations. A comprehensive description of all possible combinations is beyond the scope of this contribution. Readers are referred to Lisjak & Grasselli, 2014 and Donati *et alii*, 2018 for a more comprehensive comparison and description. For the aim of this paper, we will solely discuss the finite-discrete element method (FDEM).

FDEM exploits the FEM method to simulate the behavior and strength of intact material, and the DEM to model the sliding and opening of discontinuities. The FDEM has the capability of simulating the brittle fracturing of intact material, by including new contacts where the strength of FEM material is exceeded, ultimately allowing the complex mechanical and fracturing behavior of strong rock to be realistically captured and simulated. Lattice-scheme methods are a type of discrete element methods (specifically, particle flow methods), and model the intact material as an assembly of mass-point nodes and mass-less springs. Nodes and springs provide the modelled material with user defined density and mechanical parameters (strength and elastic properties), respectively. During the simulation, as the load applied to a spring exceeds the assigned strength, a brittle fracture is introduced (or extended) by assigning residual mechanical values to the failed spring. Pre-existing discontinuities are simulated by including in the model sets of springs with appropriately low mechanical parameters.

It is important to emphasize the fact that while, on the one hand, progressively more sophisticated numerical modelling methods will allow more complex geological and environmental processes to be realistically simulated (Fig. 1), on the other hand, it will be more difficult to obtain the required level of input data for the simulation to be performed. Kinematic analyses only require slope orientation and discontinuity orientation and friction angle to infer the potential feasibility of simple failure mechanisms. In addition to this, LE block stability analyses will require material density and cohesive strength as additional input information to perform simple dry FoS computations. At the opposite side of the spectrum, sophisticated FDEM stress-strain analyses will require intact material data (both elastic and plastic parameters), discontinuity data (stiffness and shear and tensile strength), as well as fracture propagation parameters (*e.g.*, fracture energy), which can only be derived in a direct manner through advanced geotechnical laboratory tests (*e.g.*, three-point bending tests, Ko & Kemeny, 2013). In all cases, the scale effect should be taken into consideration in transferring lab test results to slope-scale numerical models.

THE 2014 SAN LEO LANDSLIDE

On February 14th, 2014, a 300,000 m^3 landslide detached from the northeastern edge of the San Leo plateau and impacted the clayey deposits below, where an earthflow was initiated due to the undrained conditions that ensued in the material. No fatalities or injuries were recorded, but some residential buildings and a Carabinieri station were evacuated as a precaution (Borgatti *et alii*, 2015), and remain non-operational at the time of writing.

The San Leo plateau is located in the Marecchia River Valley, 9 km West of San Marino (Fig. 2). It is constituted by competent rocky units, namely the Monte Fumaiolo sandstone and the San Marino limestone formations, and lies in unconformity on the Argille Varicolori formation. The origin of the stratigraphical and geomorphic settings observed at this site and elsewhere across the Marecchia Valley (*e.g.*, Sasso Simone and Simoncello, San Marino) has been the subject of considerable debate in the scientific literature. A detailed discussion is available in Landuzzi *et alii* (2024), in the same special issue as this work. The plateau, in the landslide area, has a thickness of roughly 110 m, and prior to the failure significant undermining existed at the contact with the clayey deposits below. Such undermining, together with the identification of rough and fresh surfaces across the landslide scar (Spreafico *et alii*, 2017), allowed the role of progressive brittle fracture propagation in the 2014 landslide to be recognized and highlighted. The most important feature observed in the landslide scar is represented by a pre-existing discontinuity plane, referred to as SL3.1 (Fig. 3). This feature was noted immediately after the failure, due to its significantly weathered and iron-stained surface, which was evidence of air and groundwater circulation, implying a significant aperture of the discontinuity well before the detachment of the landslide. The failure mechanism of the 2014 San Leo landslide is similar to other sites within the Marecchia River Valley, for instance the 2006 San Leo landslide, which detached from the northern edge of the plateau and the 1822 Tausano landslide (see also Discussion) among others (Fig. 2).

MODELLING THE SAN LEO LANDSLIDE: EXPERIENCE GAINED AND METHODS

Over the past decade, progressively more complex and sophisticated numerical analyses were undertaken in order to investigate the role of various geological and geomorphological factors on the stability and evolution of the slope.

Kinematics and limit equilibrium methods

Kinematic analyses likely represent the most widely used method in the preliminary investigation of the stability and failure mechanism of rock slopes. In general, they exploit graphical construction in stereographic diagrams (Wyllie, 2017), however, when coupled with LE analyses, they are capable of providing useful indications in terms of FoS of specific instability mechanisms.

Spreafico *et alii* (2016a) used traditional kinematic analyses to investigate the potential feasibility of planar, toppling, and wedge sliding instability along the pre-failure slope surface. They highlighted that the orientation of the major discontinuity sets potentially allowed planar sliding and toppling failure to affect the slope.

Spreafico *et alii* (2016b) used remotely sensed data (including digital photogrammetry and terrestrial laser scanning, TLS) and geomechanical data (*e.g.*, discontinuity orientation, spacing, persistence) to highlight potentially unstable rock wedges along the 2014 landslide scar (Fig. 3). Multiple wedges were noted, particularly in the central part of the scar, through a visual analysis of high-resolution photographs combined with 3D datasets. All the blocks that may potentially form within the rock mass were investigated. Overall, a low probability of failure was estimated, as only about the 1.6% of all blocks were deemed to be potentially unstable. A comparatively higher likelihood of failure

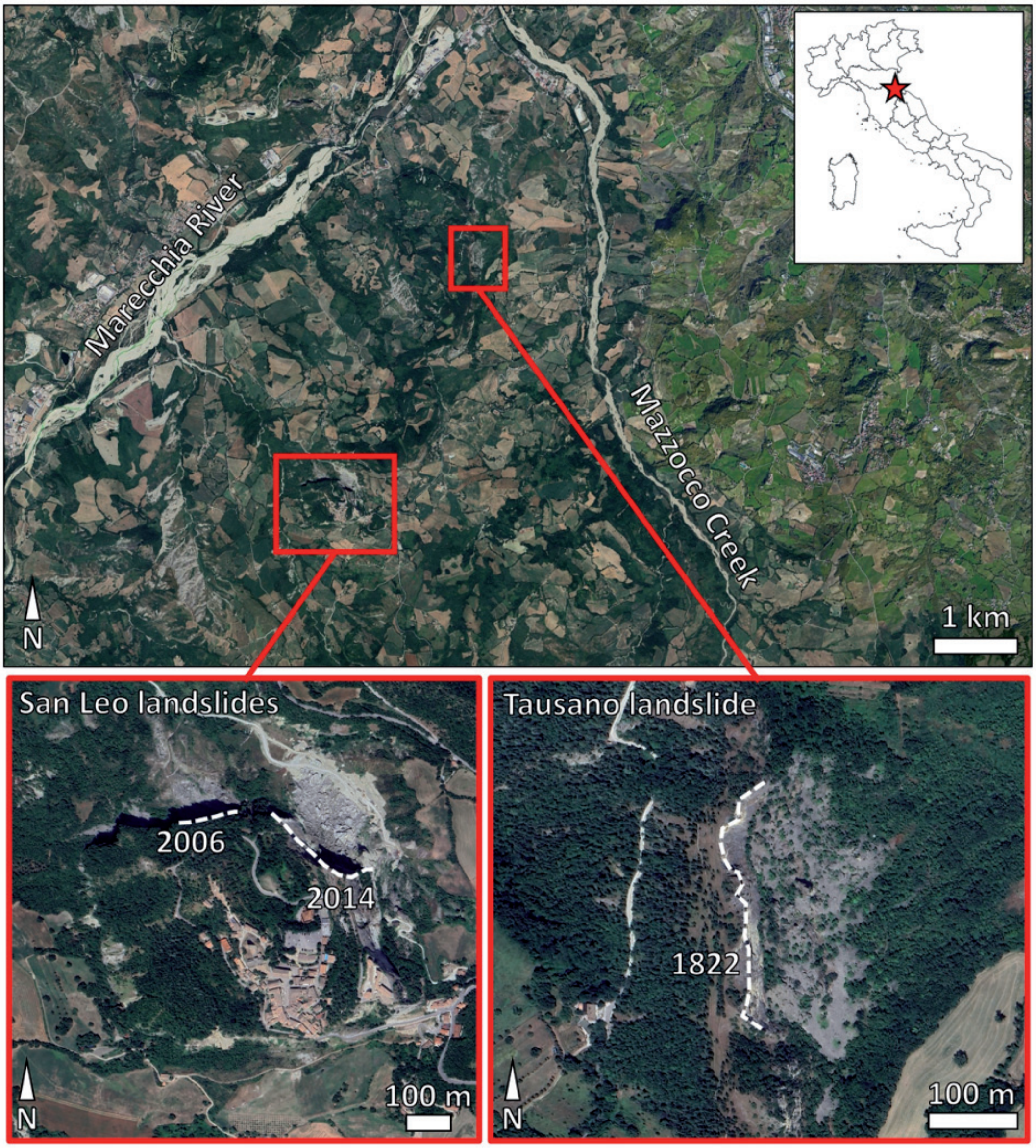

Fig. 2 - Overview of the middle Marecchia River Valley, and detailed view of landslides affecting the San Leo rocky plateau (2006 and 2014) and the Mt. Fotogno-Tausano-Mt. Gregorio cuesta (1822). Dashed, white lines mark the headscarp of the landslides. Satellite imagery Airbus (2024), from Google Earth

was noted for blocks with a basal plane with dip direction similar to the cliff. A statistical block size analysis was also performed using a discrete fracture network (DFN) approach (Mas Ivars *et alii*, 2011), which showed a good correlation between block shape distribution in the DFN model and in the landslide deposit.

The stability of the cliff in the immediate aftermath of the 2014 failure was investigated using a LE approach in the context of the emergency response (Enser, 2014a). The investigation focused on the stability of the slope against a planar sliding mechanism, as preliminary kinematic analyses, based on a structural characterization of the rock mass, showed that a toppling mechanism was not feasible. Except for limited volumes of rock mass at the top of the scar, it was noted that the stability at the global slope scale was ensured by the non-fully persistent nature of the potential sliding surfaces.

Continuum methods

The first stress-deformation numerical modelling analysis that investigated the San Leo landslide exploited a 2D FEM approach and was conducted as part of the emergency response after the 2014 failure. The FEM analysis described in Enser (2014b) was performed by considering the plateau as an assembly of

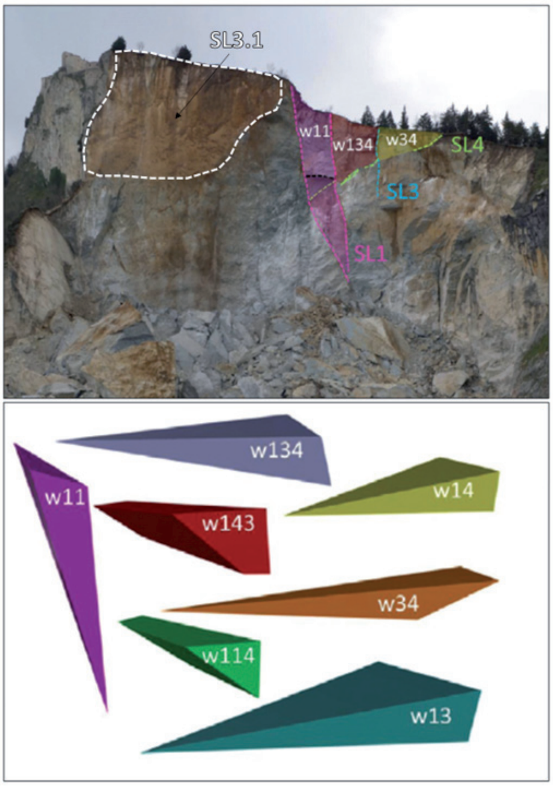

Fig. 3 - Selected wedge-shaped blocks recognized along the San Leo landslide scar (above) and 3D view of individual blocks created considering fully persistent discontinuities (below). Modified from Spreafico *et alii (2016b)*

macroblocks with equivalent mechanical properties of a fractured rock mass, separated by major discontinuities modelled as 0.6 m thick weaker layers. Varied percentages of in-plane rock bridges (Elmo *et alii*, 2018) are considered by intermittently assigning rock mass properties to parts of the discontinuity layers. The stability of the slope (after the 2014 failure) was then quantified by performing a shear strength reduction (SSR) analysis (Matsui & San, 1992), which involves the application of a coefficient, referred to as shear reduction factor (SRF), to the mechanical properties of the material until a condition of limit equilibrium is established. This is a condition in which a further increase or decrease in SRF causes the model to stop converging to a numerical solution, thus indicating unstable conditions of the modelled slope.

Another important numerical modelling analysis exploited the 2D FEM code Phase2, renamed RS2 since version 9 (RocScience, 2022). Spreafico *et alii* (2017) used the FEM code to investigate conceptually different aspects of the failure. First, they investigated the role of the softening behavior and erosion of the clay shale deposit underneath the plateau on the landslide detachment (Fig. 4). To do so, they considered the plateau as formed by a continuous, equivalent material (except for discontinuity SL3.1, which was explicitly included in the model). Then, the depth of undermining below the plateau was progressively increased, until a tensile failure was simulated through the plateau, due to the downward propagation of SL3.1. The results shows that the failure is simulated for a depth of undermining of about 30-40 m, which is in good agreement with field analyses conducted at the site prior to the failure (C.C. Lucente, pers. comm.).

A pseudo-discontinuum analysis was also conducted by implementing in the modelled plateau both a Voronoi tessellation and a simplified discontinuity network, constituted by two sets of intermittent joints (Spreafico *et alii*, 2017), allowing for the initiation of a brittle fracture-controlled failure to be simulated. Also in this case, a good correlation was observed between the simulated rupture surface and the post-failure surface derived from TLS surveys (Fig. 4).

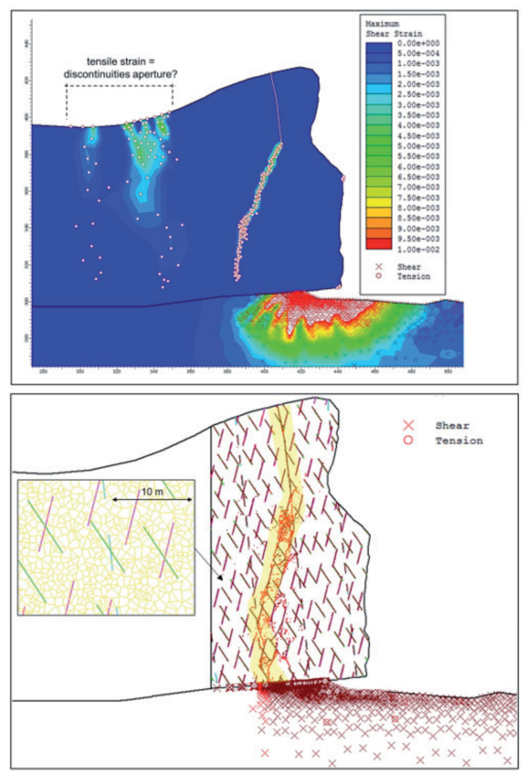

Fig. 4 - Selected results of FEM analyses of the 2014 San Leo landslide. Figure above shows the propagation of the SL3.1 discontinuity following the regressive undermining of the plateau. The lower figure shows the distribution of elements failed in shear and tension in a model where fractured rock mass is simulated using Voronoi tessellation and intermittent discontinuities (modified from Spreafico *et alii, 2017).*

Discontinuum methods

Discontinuum analyses have been performed, at the San Leo landslide site, using distinct element method approaches, both in 2D and in 3D. A preliminary stability analysis using the the 2D discontinuum code UDEC (Itasca, 2018) was conducted, aiming at investigating the residual stability after the detachment of the 2014 San Leo landslide, both in the short and in the long term (Enser, 2015). The analysis evidenced a stability condition close to limit equilibrium, mostly caused by surficial detachment of blocks, the removal of which, in the numerical model, ensured a higher stability (FoS in the order of 1.1 or more) even when considering the softening of the clay for a length of 50 m below the cliff.

Spreafico *et alii* (2016a) performed the first 3D analysis using the distinct element code 3DEC (Itasca, 2022) to evaluate the role of the undermining of the plateau. They demonstrated that such a process has been instrumental in causing the detachment of the landslide (Fig. 5), and that a weakening of the shear strength of the discontinuities alone (e.g., due to damage, pore pressure, or other mechanism) could not have alone (*i.e.*, without clay softening or erosion), been the primary trigger of the landslide.

All the discontinuum numerical modelling analyses evidenced the key role played by sub-vertical discontinuities located along the incipient rupture surface, and the stress accumulation along the interface between the clay deposit and the rocky plateau.

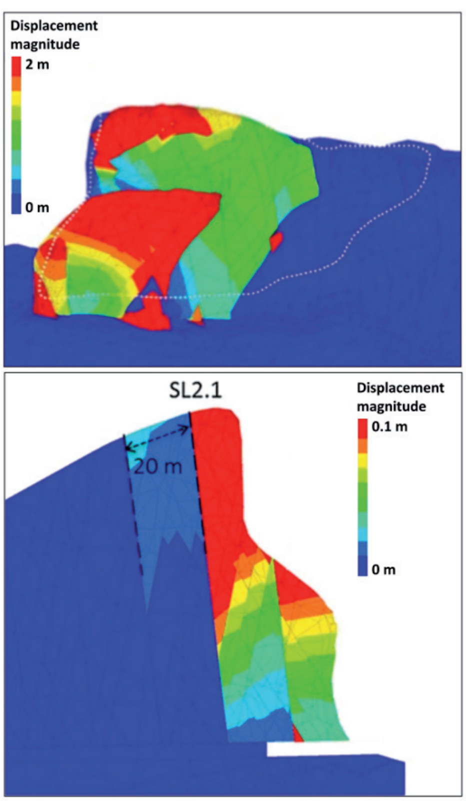

Fig. 5 - Numerical modelling in 3DEC. Above, modelled displacement after simulated undermining. Below, view of the results in a section, showing the role of subvertical discontinuities in the deformation and failure of the plateau (modified from Spreafico et alii (2016a)

Hybrid and lattice scheme methods

Remote sensing analyses conducted at the site after the 2014 event showed the evidence of brittle fractures, in the form of fresh, unweathered, and curved and/or rough surfaces, compared with pre-existing structural discontinuities within the rock mass (Spreafico *et alii*, 2017).

Hybrid FDEM and lattice-spring scheme numerical approaches were therefore employed to evaluate the role of intact rock bridges within the rock mass, particularly along the rear release surface of the landslide.

Both these modelling techniques allow the fracturing of intact rock bridges and the propagation of existing discontinuities to be simulated, exploiting the synthetic rock mass approach (Srm; Mas Ivars *et alii*, 2011). The SRM approach involves the implementation of a DFN within the rock mass volume, and allows the realistic analysis of the non-linear behavior of rock masses, the deformation of which depends on both discontinuity network and intact rock properties. For the analysis of the San Leo landslide, a DFN was created in FracMan (WSP, 2022) using remotely sensed discontinuity data (orientation, persistence, spacing) collected through digital discontinuity mapping on 3D models of the cliff. In the numerical model geometry, the 3D DFN was then implemented only in the plateau.

Donati *et alii* (2019) employed the FDEM code Elfen (Rockfield, 2017) to analyze the accumulation of brittle damage and fracture propagation with the progressive undermining of the plateau (Fig. 6). This 2D analysis was performed along the same section as used in Spreafico *et alii* (2017) for previous FEM modelling and allowed correlation between the undermining of the plateau and the gradual reduction in slope stability, due to the progressive development of a fully persistent rupture surface, to be emphasized. In particular, numerical results show that a fully persistent release surface at the back of the landslide formed through propagation and coalescence of pre-existing fractures, due to stress concentration at their tips.

A 3D analysis was also presented in Donati *et alii* (2019), which used the lattice-spring scheme code Slope Model (Itasca, 2017). The 3D approach, combined with the capability of the code to consider pre-existing geological structures and to simulate the progressive fracturing of the intact rock, allowed an oblique toppling mechanism to be inferred for the 2014 event (Fig. 6).

Documentation of the onset and evolution of landslides at the edges of rocky plateaus

Nowadays, reliable information on landslide evolution and related processes can be provided by videos captured by passersby (He *et alii*, 2022). Further information can also be collected from historical documents such as paintings and writings (Benedetti *et alii*, 2011). This evidence and information can assist in building, calibrating, and validating numerical models.

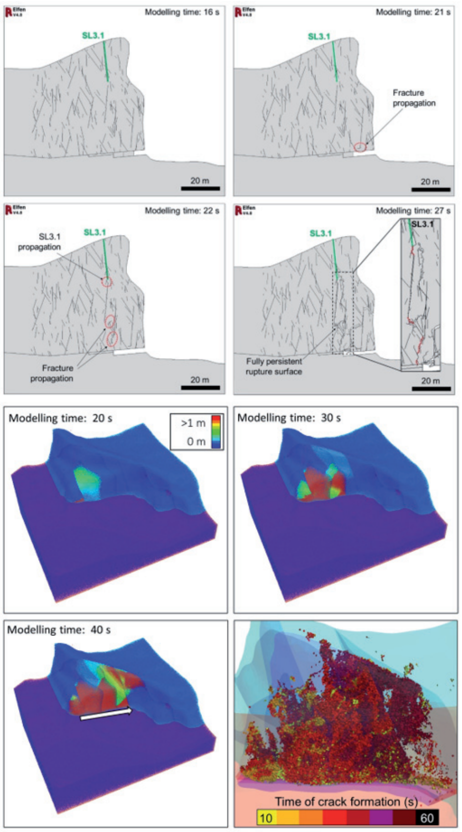

Fig. 6 - Summary of hybrid and lattice scheme modelling at San Leo. Above, 2D numerical model of the progressive damage accumulation using Elfen. Below, 3D numerical analysis in Slope Model showing progressive migration of toppling instability, depicted by the white arrow (lower left image) and the accumulation of brittle damage with time (lower right image) (modified from Donati *et alii, 2019).*

The interpreted failure mechanism that characterized the 2014 San Leo landslide was, in fact, not dissimilar to other sites within the northern Apennines and particularly the Marecchia Valley. Notable examples include the Sasso Simone and Simoncello plateaus, the Maioletto peak (where a landslide destroyed a village in 1700), and the Mt. Fotogno-Tausano-Mt. Gregorio cuesta. The latter site (hereafter referred to as "Tausano cuesta") is of particular interest, because in 1822 it was affected by a slope failure that showed significant analogies with the San Leo landslide (Fig. 2; Guerra & nesci, 2013).

A cuesta is a gently sloping geomorphic feature, generally cons A cuesta is a gently sloping geomorphic feature, generally constituted by competent rock, bounded by steep cliffs on one side (as opposed to mesas, which are bounded by steep cliffs on all sides, *e.g.*, the San Leo plateau). The Tausano cuesta is located about 5 km north of San Leo. It slopes gently to the west and its sub-vertical cliff defines the western edge of the Mazzocco creek watershed, 5 km south of the confluence with the Marecchia River. From a geological perspective, the cuesta is very similar to the San Leo plateau, as it is constituted by limestone deposits of the San Marino formation unconformably lying on clayey deposits of the Argille Varicolori formation.

The 1822 Tausano landslide event has been described with a surprising level of detail in a missive that was sent to the Delegate of Pesaro by the local gonfalonier (an important communal official in the Italian peninsula during Middle Ages; Fig. 7), stating that:

- the landslide "moved in the evening of Friday 7th" of year 1822 in Tausano;
- the landslide had "shown signs of movements" during the winter "at the roots of Mount de' Scanni";
- during the event, the plateau "opened for a quarter of a mile", "toppled", and caused "a slice" (a block) to displace downslope "for half a mile";
- after the event, "the landslide did not stop, but kept moving", and some blocks "keep falling, every now and then, from the high cliffs".

The historical report indicates important analogies with the 2014 San Leo landslide in terms of failure mechanism and post failure

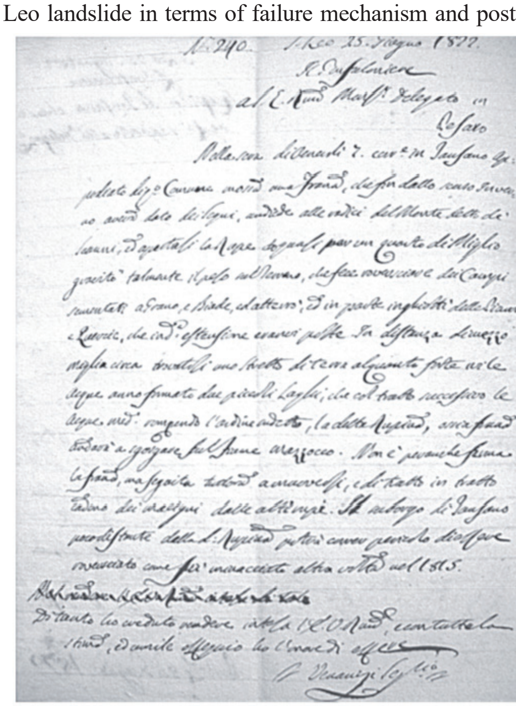

Fig. 7 - Letter, dated June 25th ,1822, from the gonfalonier to the Delegate of Pesaro, describing the Tausano landslide

evolution (Fig. 8). The "opening" of the plateau, the "toppling" and the displacement (most likely after breaking into blocks) of "a slice" clearly describe a toppling failure, likely controlled by pre-existing sub-vertical discontinuities and, possibly, promoted by some degree of undermining of the cliff. The activity of the landslide (which "did not stop") after the detachment suggests that an earthflow might have initiated in the clay, likely due to the undrained loading from the deposit. Additionally, the observed post-failure rockfall activity along the scar in 1822 was also noted in the days following the 2014 San Leo landslide.

In combination with site-specific pre-failure data and information, the analysis of past events can be beneficial in a) defining and/or confirming the interpreted mechanism and evolution of recent landslides, and b) setting up the model and identifying the most suitable numerical technique for simulating the investigated event.

DISCUSSION

Over the past thirty to forty years, the development and use of progressively more sophisticated numerical modelling methods has greatly enhanced the ability of geoscientists and engineers to investigate how different and complex factors interact and contribute to defining and controlling the stability and evolution of incipiently unstable rock slopes.

For the 2014 San Leo landslide, numerical modelling has been undertaken following two separate approaches, namely forward analyses and back analyses. Forward analysis has been largely undertaken in the immediate aftermath of the failure, as a means to evaluate the short-term stability of the slope and assist with the design of emergency mitigation methods. For the most part, forward analyses have been presented in unpublished technical reports, prepared for institutions (*e.g.*, Emilia-Romagna region) tasked with residual risk mitigation and remedial measures planning.

Typically, forward analyses for emergency management face significant challenges due to a) the lack of long-term monitoring data, b) an often incomplete or limited understanding of the processes that controlled the instability, and c) the obvious challenge in forecasting the future behavior of the slope. As a result, emergency forward modelling is necessarily conducted using simplified approaches, in order to limit, as much as possible, the uncertainties related to input data and inferred controlling mechanisms. In contrast, research-oriented back analysis can rely on consistent input databases, including geomechanical, and historical data, that allow more advanced analyses to be undertaken, which can also be constrained using monitoring

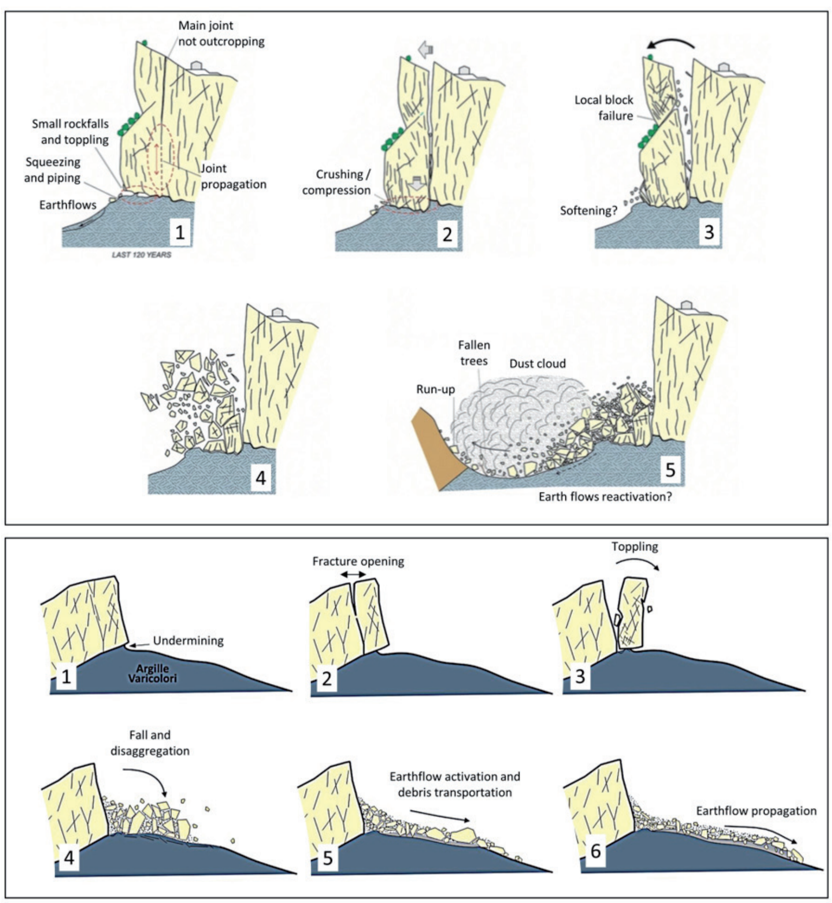

Fig. 8 - Overview of the interpreted evolution of the 2014 San Leo landslide (above, modified from Borgatti et alii, 2015), and the 1822 Tausano landslide (modified from Guerra, 2014). Note the analogies between the two sites, and the role of the undermining of the rocky plateau/cuesta and the pre-existing fracture network

datasets and well-known post-failure conditions. For these reasons, more advanced numerical modelling methods are most commonly applied for back-analysis purposes, and then only when a good understanding of the phenomena has been achieved. Moreover, more advanced numerical methods, while allowing more complex mechanisms to be simulated, also require a set of input data that are generally not readily available for preliminary and forward analyses (*e.g.*, DFN, sophisticated geotechnical laboratory data such as discontinuity stiffness, fracture toughness, and so on). As a general rule, a good understanding of the phenomena is needed to perform solid numerical analyses, particularly when complex processes are investigated.

Numerical modelling of the 2014 San Leo landslide is not an exception to these considerations. The geological investigations conducted at the site show that a complex interaction of factors contributed to the failure. The San Leo plateau is constituted by a competent rock mass. This is evident from the steep edges of the plateau itself, and the type of failure that have been registered even in recent times and in the past, which have been strongly controlled by brittle fracturing processes. Such a combination of geomorphic and lithological factors does not generally occur in weak rock masses (which tend to behave like a continuum material) and, in fact, has been observed at various sites across the Marecchia Valley, *e.g.* the Tausano 1822 landslide, that display similar mechanical characters, stability, and evolution.

OUTLOOK AND FINAL REMARKS

In this paper, we have presented a summary of the most relevant numerical modelling analyses conducted to investigate the short-term instability of the San Leo slope in the immediate aftermath of the failure (*i.e.*, for emergency response management and mitigation measure design) and back-analyses conducted to investigate the factors that controlled the evolution and, ultimately, the failure of the northeastern edge of the San Leo plateau in February 2014. Back analysis has been instrumental in assessing qualitatively and quantitatively the role of lithological and geomorphic factors on the failure.

In particular, it highlighted that the subvertical discontinuity sets, the softening and erosion of the clay, the subsequent undermining of the plateau, and the progressive damage that affected the rock mass, all played a critical role in the detachment of the landslide. For these reasons, the application of continuum numerical methods in the analysis of the San Leo landslide is conceptually challenging. Likewise, the use of traditional discontinuum methods (*e.g.*, DEM) without the implementation of sophisticated approaches such as Voronoi tessellation significantly limits the ability to realistically simulate the progressive evolution of the slope and the controlling instability mechanisms.

Even when a Voronoi tessellation is used, however, major challenges remain, in terms of the definition of Voronoi polygon size, model runtime, and especially the need for an adequate calibration of the microparameters of the contacts. The overview of the numerical modelling analyses presented in this paper clearly shows that, in order to realistically simulate the processes controlling the San Leo landslide and, more in general, the evolution of the San Leo plateau, sophisticated numerical methods are required. These should be capable of modelling both the brittle behavior of the intact material and the post-failure behavior of the slope and the landslide. Importantly, the Slope Model analysis described in Donati *et alii* (2019), highlights the three-dimensional nature of the 2014 San Leo landslide, indicating that fully realistic results can only be provided by 3D analyses.

Although the simulations performed over the past decade, based also on historical documentation of recent and past events, provided a good understanding of the failure process and controlling mechanisms, many research questions remain unexplored. Excess pore water pressure following snowmelt, for instance, has been proposed as a potential contributing factor to the failure, however, limited attention was given in numerical modelling analyses, due to the challenges related to its input in the numerical models. The role of groundwater seasonal variations in the progressive weakening of the rock mass and softening of the clay has not been investigated, as well as the potential influence of seismicity and temperature cycles repeated over tens or hundreds of years. The San Leo plateau also represents an ideal site where damage monitoring using seismic noise and resonance frequency changes (*e.g.*, Grechi *et alii*, 2022) can be preliminarily evaluated using advanced, FDEM numerical modelling before field testing.

In consideration of the knowledge and the extent of the monitoring dataset that has been built over the decade after the event, we suggest that the San Leo plateau should be considered a suitable site for the establishment of a field laboratory (*e.g.*, Fantini *et alii*, 2017) where the geomorphic and stability evolution of rock slopes affected by lateral spreads and processes related to Resistant-over-Recessive (Ror, Jackson, 2002) geological configurations are explored using a combination of techniques, including advanced 3D numerical modelling.

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