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ADVANCED NUMERICAL MODELLING OF EARTHFLOW DYNAMICS: APPLICATION OF THE MATERIAL POINT METHOD (MPM) TO THE MONTAGUTO CASE STUDY

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EXTENDED ABSTRACT

Le colate di terra sono ampiamente diffuse in tutta la catena appenninica e generano frequentemente ingenti danni alle infrastrutture di trasporto situate al piede dei versanti. Dal punto di vista cinematico, tali processi franosi sono caratterizzati dall'alt ernanza di stadi con attività a movimento relativamente veloce, che talvolta evolvono in rapide accelerazioni, e stadi con mobilità ridotta o di quiescenza.

Nella letteratura specifica, la cinematica delle colate di terra è stata spesso interpretata attraverso approcci semplificati che simulano il comportamento del terreno come un materiale monofase caratterizzato da un contenuto d'acqua significativamente aumentato. Tuttavia, modellare adeguatamente la complessa cinematica di questi fenomeni rimane una sfida aperta. In particolare, i metodi numerici tradizionali, come il Metodo agli Elementi Finiti (FEM), incontrano spesso forti limitazioni nel tentativo di cogliere le deformazioni eccezionalmente grandi, il complesso comportamento idro-meccanico e la natura impulsiva intrinseca al movimento delle colate di terra, per cui il campo di validità relativo resta confinato alla modellazione della fase di innesco.

Questo studio presenta un'indagine numerica avanzata di una colata di terra a larga scala attraverso l'uso del *Material Point Method* (MPM), una tecnica ibrida Euleriana-Lagrangiana in grado di simulare problemi di grandi deformazioni discretizzando il continuo in un insieme di punti materiali che si muovono attraverso una griglia di calcolo fissa. Tale tecnica è stata applicata alla colata di terra di Montaguto (Appennino Meridionale, Italia), caratterizzata da una fase di riattivazione a movimento rapido tra il 2006 e il 2010, seguita da una lenta e continua decelerazione negli anni successivi. Nel 2014, 2017 e 2020, Lollino e coautori hanno indagato, attraverso tecniche analitiche e numeriche, il ruolo delle sovrappressioni interstiziali generate da processi di carico non drenato potenzialmente attivi nella massa della colata di Montaguto nell'attivazione e nello sviluppo del movimento franoso. Al fine di indagare in modo più appropriato la cinematica della stessa colata tenendo conto del comportamento bifase del terreno, in questo lavoro è stato sviluppato un modello MPM 2D basato sulla caratterizzazione geologica e geotecnica disponibile. In particolare, le analisi numeriche mirano a simulare i meccanismi che hanno dato luogo alla fase di riattivazione e alla successiva evoluzione, sia nelle aree di sorgente che in quelle di canale.

I risultati numerici riproducono con successo le caratteristiche cinematiche chiave della colata in esame. Ciò include la simulazione realistica della distribuzione di velocità e spostamento del flusso incanalato, così come il ruolo delle pressioni interstizi ali, in accordo con i dati di monitoraggio osservati. Sono state condotte analisi di sensibilità per valutare l'influenza di specifici parametri meccanici e idraulici del terreno sulla generazione delle sovrappressioni interstiziali all'interno della massa franosa e sulla mobilità del flusso. I risultati dimostrano l'alto potenziale e la robustezza del MPM come strumento per simulare l'intero ciclo di vita delle colate di terra, dalla rapida accelerazione, alla propagazione, fino alla successiva decelerazione. Tale approccio modellistico può fornire un significativo contributo nell'avanzamento dello studio di questi processi di frana rispetto ai metodi tradizionali, offrendo un potente strumento per una migliore valutazione della pericolosità, per previsioni basate su scenari e per la corretta progettazione di strategie di mitigazione efficaci per la protezione delle infrastrutture critiche interagenti con gli stessi fenomeni franosi.

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ABSTRACT

This study addresses the modelling of Apennine earthflows, which threaten infrastructures due to their complex kinematics characterized by alternating rapid and slow phases. Since traditional numerical methods (*e.g.* FEM) are not suitable to simulate the landslide behavior at large strains, this research applies the Material Point Method (MPM) to the Montaguto earthflow in Southern Italy. Focusing on the 2006-2010 reactivation, a 2D MPM model successfully simulated the two-phase soil behavior and the crucial role of excess pore pressures. The numerical results are consistent with the displacement and pore pressure trends recorded by the monitoring system installed in the landslide area. The findings demonstrate that MPM is a robust tool, superior to classical numerical methods for simulating the full life cycle of earthflows, thereby significantly enhancing the assessment of large mobility landslide hazard and the design of mitigation strategies.

Keywords: *earthflows, Montaguto, numerical modelling, Material Point Method*

INTRODUCTION

Earthflows are highly diffuse throughout the Apennines and frequently generate huge damage to the transport infrastructures

located at the foot of the slopes. From the kinematic point of view, such landslide processes are characterized by the altern ation ofstages with relatively fast-moving activity, sometimes evolving into rapid accelerations, and slow-moving or dormient stages. In the available literature, earthflow kinematics has frequently been explained through simplified approaches that simulate the soil behaviour as one-phase soil material, characterized by a significantly increased water content. However, modelling properly the complex kinematics of these phenomena remains a challenge for geoscientists. Traditional numerical methods, as the Finite Element Method (FEM), often encounter severe limitations when attempting to capture the exceptionally large strains, complex hydro -mechanical behaviour and impulsive nature inherent in earthflow movement.

This study presents an advanced numerical investigation of a large earthflow by employing the Material Point Method (MPM), which is a hybrid Eulerian-Lagrangian technique capable of simulating large deformation problems by discretizing the continuum into a set of material points that move through a fixed computational grid (Sulsky *et alii*, 1994). Such a technique has been applied to the Montaguto earthflow (Southern Apennines, Italy), one of the largest and most extensively monitored complex landslides in Europe, which has been characterized by a fast-moving reactivation, between 2006 and 2010, followed by a slow but continuous deceleration in recent years. In 2014, 2016 and 2020, Lollino and co-authors have investigated through analytical and numerical techniques the role of excess pore pressures generated by undrained loading processes in the earthflow mass in the activation of landslide movements.

In order to investigate more properly the examined earthflow kinematics taking into account the two-phase soil behaviour, a 2D MPM model has been developed based on the available geological and geotechnical characterization. In particular, the numerical analyses are aimed to simulate the mechanisms that gave rise to the reactivation phase and its subsequent evolution, both in the source and channel areas. The numerical results successfully reproduce the key kinematic features of the Montaguto earthflow. This includes a realistic simulation of the velocity and displacement distribution of the channelized flow, as well as the role of pore water pressures, in agreement with the observed monitoring data (Lollino *et alii*, 2014, 2020). Sensitivity analyses were carried out to evaluate the influence of specific mechanical and hydraulic soil parameters on the generation of the excess pore pressures within the landslide mass and on the mobility of the flow.

The findings demonstrate the high potential and robustness of MPM as a tool for simulating the full life cycle of complex earthflows, from rapid acceleration, to propagation and subsequent deceleration. Such a modelling approach provides a significant advancement over traditional methods, offering a powerful tool for enhanced hazard assessment, scenario-based forecasting, and the design of effective mitigation strategies to protect critical infrastructure in earthflow-prone areas.

THE CASE STUDY

The Montaguto earthflow, located in the Daunian Apennines of Southern Italy, represents one of the most significant and complex mass movements in the European context, both for the significant size and for the hazard posed to strategic infrastructures located at the toe of the slope, as the National Road SS90 “delle Puglie” and the Rome-Bari railway line. The landslide, which involves a volume of soil estimated between 4 and 6 million cubic meters, with a length of approximately 3 km, has been the subject of extensive multidisciplinary studies aimed at understanding the main geological and geomorphological features, the propagation mechanics, as well as the post-failure behavior (Guerriero *et alii*, 2013a; Guerriero *et alii,* 2013b; Lollino *et alii*, 2014, 2020). The specific scientific works produced on this case study allow for a detailed reconstruction of the phenomenon, which is characterized by cyclic reactivations, with the major events in 1958, 2006, and 2010, and the alternation of stages of relative dormancy or slow residual movement.

The geological and structural setting of the slope is one of the main predisposing factors of the Montaguto earthflow (Fig. 1a). The area is located in the external sector of the Southern Apennine chain and is characterized by a complex stratigraphic succession deformed by compressive tectonics. The bedrock consists mainly

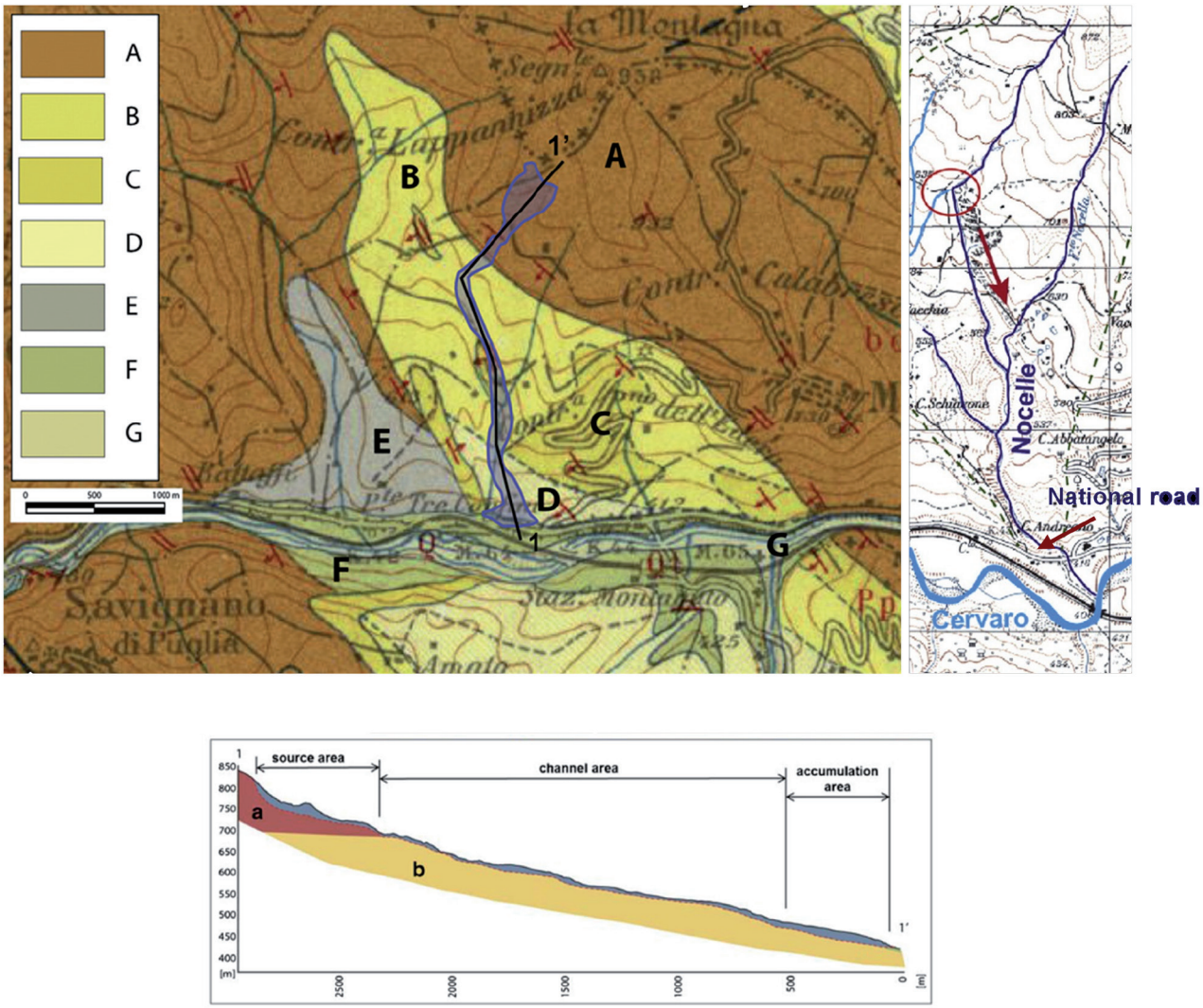


Fig. 1 - (a) Geological map of the study area (1:100,000, Italian Geological Map No. 174—Ariano Irpino) and location of the landslide area (in grey). A): Faeto Flysch formation (Burdig. sup.—Langhiano Inf.); B) clayey marl unit (Messin. Sup.—Plioc. Inf.); C) sandstone unit (Mess. Inf.); D) conglomeratic unit; the B, C, D units have been described as Villamaina Unit; E: Ligurid unit; F: old alluvial deposits G: actual alluvial deposits; 1–1': longitudinal section location (from Lollino *et alii, 2014). (b) Location of the Montaguto landslide area in the topographic IGM map of 1954. The Cervaro River along with the Nocelle streams (modified from* Lollino *et alii, 2014). (c) d Geological longitudinal section of the landslide: in brown Faeto Flysch, in yellow Villamaina Unit, in grey landslide detritum (from* Lollino *et alii, 2014)*

of the Faeto Flysch Formation (Daunia Unit), of Miocene age, and the Villamaina Formation, of Messinian-Pliocene age, which lies unconformably upon it (Pinto *et alii,* 2016). The Faeto Flysch, which outcrops extensively in the landslide source area, is composed of a succession of calcareous, marly, and clayey layers. This lithological heterogeneity is crucial, as the lithofacies characterized by a higher clay content and intense fracturing represent the mech anically weakest portion of the slope and, hence, the primary source for the earthflow. The presence of faults and fractures, particularly those oriented NW-SE and NE-SW, strongly controls the geometry of the source area and the direction of movement, facilitating the detachment of material and the progressive retrogression of the crown (Pinto *et alii*, 2016).

The morphological evolution of the earthflow has been reconstructed through the analysis of multi-temporal maps covering the period from 1954 to 2010, based on aerial photos (stereo pair, scale 1:33.000) and LiDAR data, when available (Guerriero *et alii*, 2013). In 1954, the landslide was relatively contained, with a source area elongated along the drainage line and a limited extension of the toe. A first significant reactivation occurred in 1958, leading to a marked expansion of the source area and the formatio n of a welldefined transport channel (neck) and a

fan-shaped accumulation area. Following this event, the landslide experienced a long period of apparent dormancy, although internal deformations continued to modify the slope morphology. Between 2003 and 2005, precursors to a new major phase of activity were observed, with the formation of new ponds and the enlargement of the source area, culminating in the paroxysmal event of April 2006 (Guerriero *et alii*, 2013; Lollino *et alii*, 2014). This event resulted in the massive mobilization of material that moved along the entire slope, filling the V-shaped valley of the Rio Nocelle and invading the national road at the toe (Fig. 1b). The morphological analysis allowed for the recognition of distinct kinematic zones: the head, characterized by retrogressive rotational slides; the hopper, where debris material converges towards the channel; the neck, the narrowest point of the flow controlled by geological structures; the body, where the flow moves translationally; the toe, characterized by accumulation and spreading phenomena.

The mechanics of the 2006 propagation were analysed through mathematical models to investigate the high mobility exhibited by the earthflow, which reached velocities in the order of several meters per day. In particular, the 2006 event can be interpreted as the result of two distinct debris surges (Lollino *et alii*, 2014). A first surge (Surge A), originating from the remobilization of the 1958 deposits, is supposed to have been triggered by a smaller flow coming from the upper part in the winter of 2004-2005. Subsequently, a second and larger surge (Surge B), fed by the main source area, has travelled down the channel, reaching the toe and overlapping the previous deposits. As such, Lollino *et alii* (2014) demonstrated, through a back-analysis performed using a 1D sliding-consolidation model, that the large earthflow mobility was sustained by the generation of excess pore water pressures resulting from undrained loading processes. These pressures, generated by the rapid accumulation of material or by the thrust

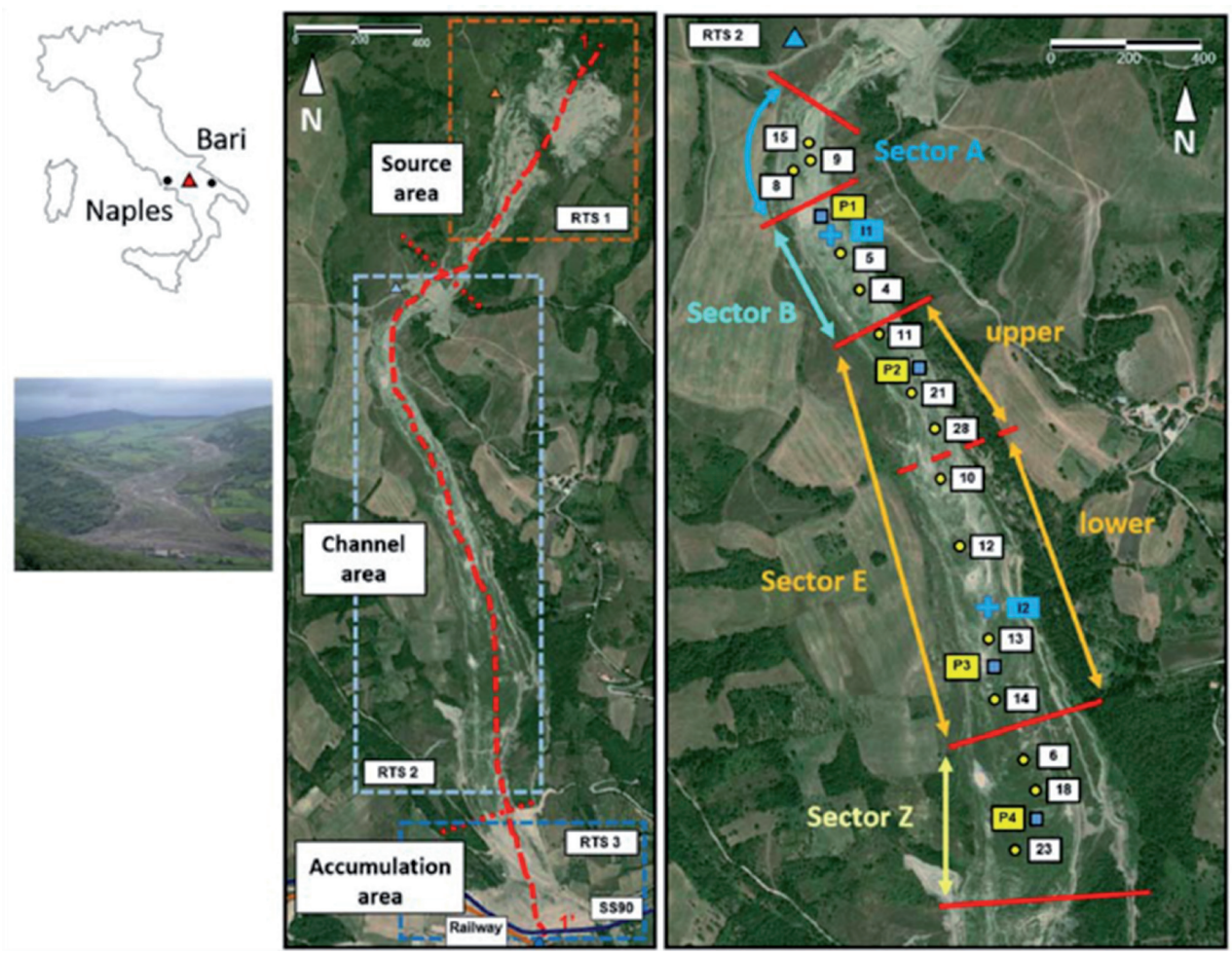


Fig. 2 - (a) Location of the Montaguto landslide (red triangle). (b) Front view of the landslide (Giordan et alii, 2013). (c) Aerial view of the Montaguto landslide with: the landslide areas monitored by the three robotized total stations (triangles), the indication of the landslide kinematical sectors, the national road (blue line) and the railway (brown line); the topographic targets (yellow circles), inclinometer tubes (cyan crosses) and piezometer cells (blue squares) installed along the landslide channel are also shown (from Lollino et alii, 2014)

of upstream masses, drastically reduced the shear strength of the soil, allowing the flow to propagate on gentle slopes. The model indicates that Surge B, ch aracterized by a run-out of over 2000 meters, mobilized a friction angle close to the residual value (approx. 11-13°) and maintained high pore pressures due to the significant thickness of the mass (up to 15-20 meters), which increased the duration of the consolidation process.

The simulation of propagation using Smoothed Particle Hydrodynamics (SPH) methods further confirmed that the phenomenon cannot be modeled as a single block, but requires a multi-stage approach. The SPH simulations highlighted that the material in the source area was characterized by high viscosity and yield stress, likely due to the low water content in the upper parts of the slope, while the material in the channel and toe exhibited reduced rheological parameters, consistent with the degradation produced by the long transport and the greater availability of water in the valley (Cascini *et alii*, 2013).

The activation of the Montaguto earthflow is strictly related to hydro-climatological forcing. A long-term analysis (1927-2010) demonstrated that the main reactivation stages (1958, 2006) were preceded by hydrological years characterized by exceptional rainfall (Guerriero *et alii*, 2016).

Following the emergency occurred in 2010, which led to a new interruption of the infrastructure, a permanent monitoring network was installed to control the residual evolution of the landslide. This network, composed of robotic total stations (RTS), piezometers, and inclinometers (Fig. 2c), revealed that, despite the remediation works (drainage trenches and slope reprofiling), some local sectors of the landslide remained active. In particular, the central sector of the channel, identified as "Sector E" (Fig. 2c), continued to show significant movements, with velocities that in 2011 reached 20-30 cm/month, before gradually decreasing in the following years (Lollino *et alii*, 2017). Subsurface monitoring revealed the presence of a shear surface located at a depth of 7-8 meters and the existence of high pore water pressures within the landslide mass. In Sector E, piezometric levels were measured up to several meters above the ground surface, indicating a condition of undrained loading (Lollino *et alii*, 2020). This overpressure is attributed to the compression of the material of Sector E against the downstream sector (Sector Z), which acts as a stable barrier. The interaction between the moving mass and the stable downstream portion generates a mechanism of passive resistance that causes the rise in pore water pressures, which is supposed to be the reason for the instability of the central sector (Lollino *et alii*, 2017).

NUMERICAL MODELLING

The Material Point Method (MPM; Sulsky *et alii*, 1994, Yerro, 2015; Fern *et alii*, 2016) represents an advanced numericalmtechnique that has gained significant traction in the field of geotechnical engineering, particularly for the analysis of large deformation problems such as landslides, slope instabilities, and granular flows. This method effectively bridges the gap between Lagrangian and Eulerian approaches, combining the advantages of traditional mesh-based methods, such as the Finite Element Method (FEM), with those of mesh-free techniques, such as Smoothed Particle Hydrodynamics (SPH). The fundamental architecture of MPM is based on a dual discretisation of the continuum. First, the material domain is represented by a collection of Lagrangian material points (MPs), often referred to as particles, which carry all historical state variables, as mass, velocity, stress, strain and constitutive parameters.

Secondly, a background computational mesh, Eulerian and fixed in space, covers the entire computational domain. This background mesh is used to solve the governing equations of motion and perform spatial derivatives and then it is reset at the end of each time step, thereby avoiding the mesh distortion issues that affect Lagrangian FEM during large strain processes.

Numerical stability in explicit MPM simulations is governed by the Courant-Friedrichs-Levy (CFL) condition, which dictates that the time step must be smaller than the time required for a sound wave to propagate across the smallest element in the mesh. The critical time step depends on the material stiffness, density, and the characteristic length of the elements. For materials with high st iffness or very fine meshes, the required time step can become extremely small, increasing the computational cost.

A critical aspect of MPM modelling is handling the multi-phase nature of the soil materials. Several formulations have been developed to address the interactions among solid-water-gas phases. The simplest is the one-phase single-point formulation, which models the soil as a single equivalent continuum. This approach is suitable for dry soils or saturated soils under fully drai ned or undrained conditions, for which the relative motion between water and soil is negligible. In undrained analysis using effective stress parameters, the bulk modulus of the pore water is used to compute excess pore pressures based on volumetric strains, assuming strain compatibility between the phases. However, for problems involving transient seepage, consolidation or liquefaction, where the interaction between solid skeleton and pore fluid is dynamic, a fully coupled two-phase formulation is needed.

In the context of this work, the open-source code ANURA3D (version 2024) has been adopted to simulate the Montaguto earthflow propagation here presented. The code requires a structured workflow involving pre-processing, calculation, and post-processing. Preprocessing involves defining the geometry, material properties, and initial conditions, using the software GiD. The calculation phase processes the input files (such as .GOM and .CPS files in Anura3D) to perform the time-stepping simulation; finally, the ParaView post-processing tool is used to visualize the massive amount of data generated, such as particle positions, velocities, and stress fields.

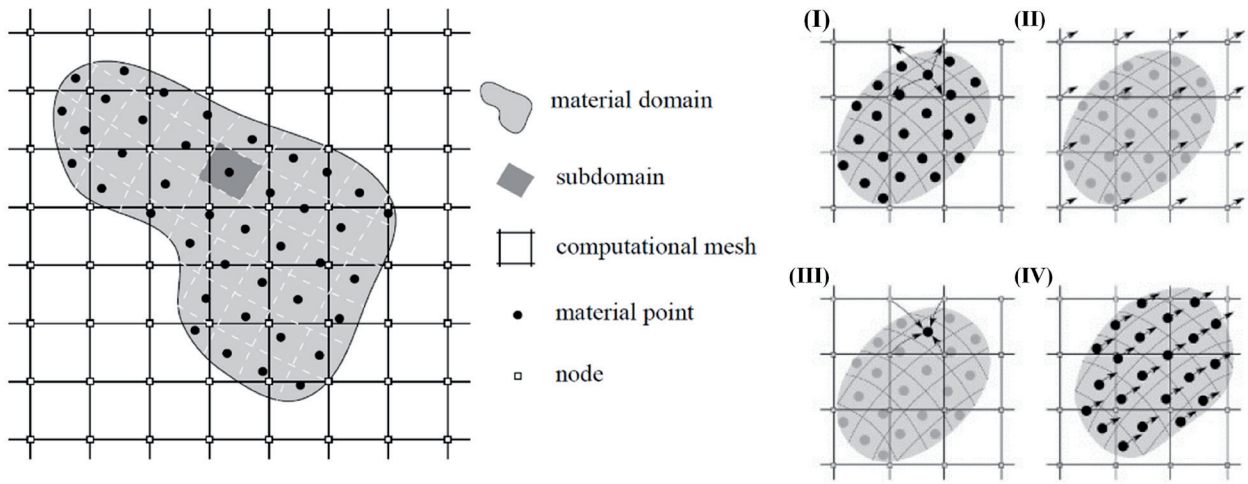


Fig. 3 - (a) Spatial discretisation of a continuum body with nodes of the computational mesh and material points (modified from Yerro, 2015); (b) MPM algorithm for a single calculation step of a time increment:(I) map information from MPs to nodes, (II) solve balance equations, (III) map velocity field to MPs, and (IV) update position of MPs (modified from Fern et alii, 2016)

Despite these advancements, challenges still remain, particularly regarding the accurate calibration of constitutive parameters for large deformations, the handling of very distinct scales in geological features as well as the computational cost compared to traditional methods. However, the capability of MPM to seamlessly simulate the entire process of a landslide, from the triggering phase through large deformation propagation to final deposition, makes it a uniquely powerful tool in modern geological engineering and risk assessment. The increasing number of real case studies, ranging from rainfall-induced failures to earthquake-triggered landslides, confirms the potential wide applicability for investigating complex catastrophic events.

Model Setup

As regards the Montaguto earthflow (Fig. 4), the model size was determined based on the in-situ topography, as measured during a LiDAR survey performed in 2006, with a 1m x 1m resolution; however, for computational efficiency, in this work the Digital Elevation Model was resampled to 5m × 5m. The whole length of the modelled section is 3300 m, with an average slope angle of 8°.

The analyses have been carried out using standard soil constitutive laws and accounting for the material strength properties gained from available laboratory soil testing (Lolllino *et alii*, 2014). A linear elastic perfectly-plastic model, with a Mohr–Coulomb strength criterion and a non associated flow rule (ψ = 0°), has been adopted for the debris layer, whereas the bedrock was modelled as a linear elastic solid, as it is not involved in the movement.

In particular, a cohesion value equal to c' = 1 kPa has been assigned to the debris soil, whereas a friction angle value corresponding to post-peak state (ϕ' = 23°) was implemented, as derived from direct shear tests performed on samples taken at depth from the earthflow mass. Table.1 summarises the mechanical parameters used in the MPM simulations.

The mesh adopted in the MPM simulations, shown in Fig. 4, is formed of triangular elements and is coarser at the domain bottom and finer in the upper part, close to the landslide area. The size of the model and its mesh have been chosen by carrying out a series of preliminary simulations seeking computational efficiency without compromising the development of the mass movement: to this purpose, the mesh is refined within the 10 m-thick debris layer and coarsened close to the bedrock. The model is intentionally not rectangular, as the bedrock material was cut at the bottom in parallel way to the topography, and the amount of empty space is reduced in order to reduce the required memory for the simulation. All the soil units characterizing the debris material have 25 MPs/element, while the bedrock material has 3 MP/element. The model has a total of 63877 MPs and 6042 elements. The boundary conditions are consistent with the standard " box conditions", which prevent horizontal displacements on the vertical sides of the model and vertical

Layer	solid density (kN/mc)	porosity	Saturation degree	K (m/s)	E′ (kPa)	ν	c′ (kPa)	ϕ′
Debris	26.50	0.4	100%	1e-2	2e4	0.3	1	23°
Bedrock	26.5	0.4	100%	1e-2	2e6	0.3	(linear elastic)	

Tab. 1 - Soil material properties adopted in the MPM analysis, after initialisation. K: hydraulic conductivity; E': Young Modulus; v: Poisson's ratio

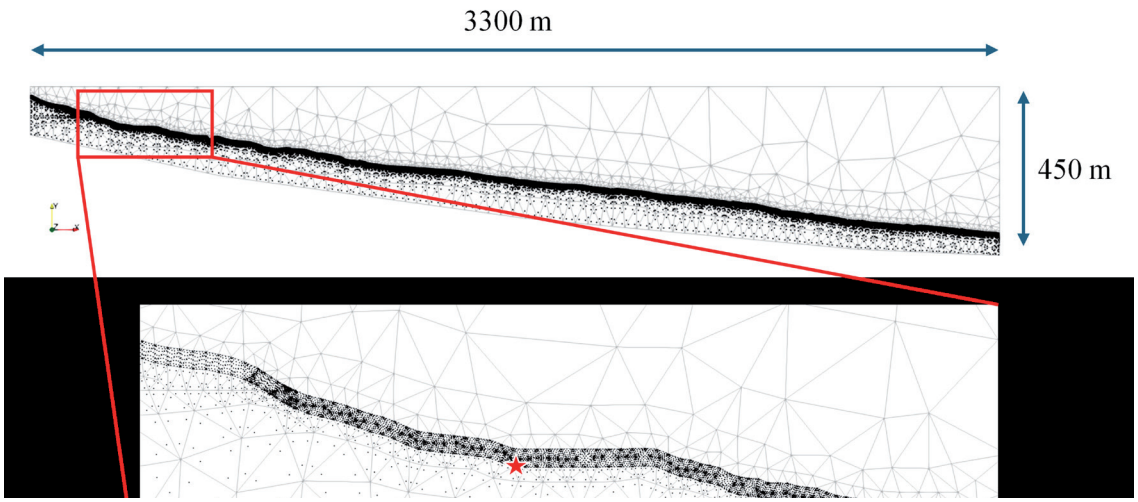


Fig. 4 - Computational mesh and initial distribution of material points in the implemented section of the Montaguto earthflow, with detail of the upper part of the slope. The red star indicates the location of the reference point

displacements at the base. No other boundary conditions are used. The computational mesh is composed by triangular elements with a minimum size of 5 m in the debris material, while in the bedrock the minimum size is larger.

The calculation process can be summarized in two main steps, as follows:

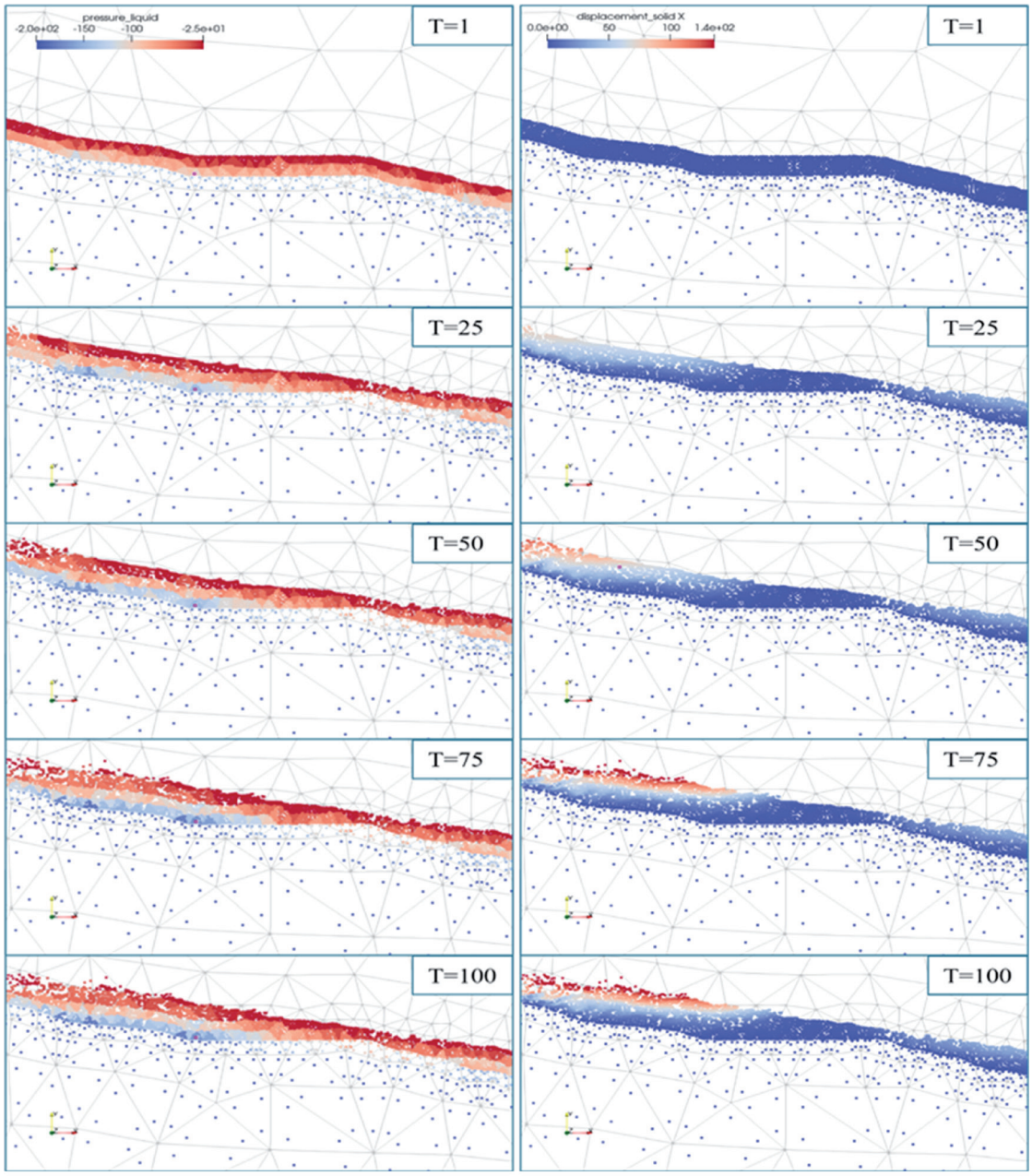
- firstly, the stresses were initialized by applying gravity loading from a quasi-static calculation, using soil elastic properties in order to obtain slope stability. In this stage, failure is not reached. The homogeneous local damping was set to 0.75, given that stress initialization should be a quasi-static problem, and the approach of applying artificial local damping is utilized to increase the speed of numerical convergence;
- in the second calculation stage, the failure is triggered by switching the material parameters to the actual geotechnical properties of debris material, as summarized in Table.1. A total amount of one hundred stages ("T" in Fig. 5), of different loading steps of 0.5 seconds each, was assigned to simulate the mass movement. A local damping of 0.05 is employed in this stage to facilitate dynamic analysis.

For all the analyses, a double-phase, saturated material-fully coupled MPM formulation is considered; hence, pore water pressures are calculated according to the stress initialisation stage in the whole domain.

RESULTS AND DISCUSSION

Fig. 5 shows the results of a numerical simulation that assumes a progressive reduction of the soil shear strength parameters. The analysis well captures the transition from a stable condition (T = 1) to a flow-like evolution (T = 100), demonstrating the capability of MPM to handle large deformations. In particular, Fig. 5a highlights the evolution of pore water pressures within the debris layer, with the development of excess pore water pressures as a consequence of the undrained loading induced by debris material coming from the upper part of the slope. Fig. 5b instead shows the kinematical evolution of the same landslide sector in terms of both the progressive extension of the area affected by instability and the corresponding increase in horizontal displacement, which is supposed to be related to the aforementioned pore pressure increase. This result seems to be in good agreement with the process interpretation provided by some authors (Picarelli *et alii*, 2005; Lollino *et alii*, 2020) as regards the earthflow dynamics.

Finally, a sensitivity analysis was carried out to explore the influence of some material properties, as the soil stiffness and the soil hydraulic conductivity, on the earthflow behaviour. As shown in Fig. 6 and Fig. 7, starting from a hydrostatic distribution, excess pore pressures develop as a consequence of the undrained compression of the soil due to either the landslide movement itself or the overloading of a debris surge above the reference point (see Fig. 4). Specifically, in Fig. 6 two main events of excess pore pressure development can be recognised: the first one, between timesteps T = 0 and T = 25, and the second one, between T = 55 and T = 75. In the middle of such phases, pore water pressures remain approximately constant. Moreover, the calculated excess pore water pressures increase as the debris layer's stiffness decreases. As regards the effect of the hydraulic conductivity on the evolution of



(a) (b)

Fig. 5 - Initial (T=1) and intermediate (T=25, 50, 75, 100) distribution of: (a) pore water pressure (in kPa); (b) displacements along x axis (in m/s). K=1e-2 m/s; E'=20 000 kPa

pore water pressures, Fig. 7 indicates how the K value affects such process: as a matter of fact, when K decreases from 1e-2 m/s to 1e-4 m/s, a different trend in pore water pressure is observed. In particular, when K = 1e-4 m/s, a clear peak of pore water pressure, of about 200 kPa, can be observed in the timesteps between 10 and 20, with a progressive dissipation in the following calculation stages. For the case of K = 1e-2 m/s, a slower increase in pore pressure is instead calculated, reaching a maximum value of 170 kPa in the timesteps between 60 and 100.

CONCLUSIONS

A 2D MPM model was developed based on the detailed geological and geotechnical characterization available for the Montaguto landslide. The material behaviour is simulated using

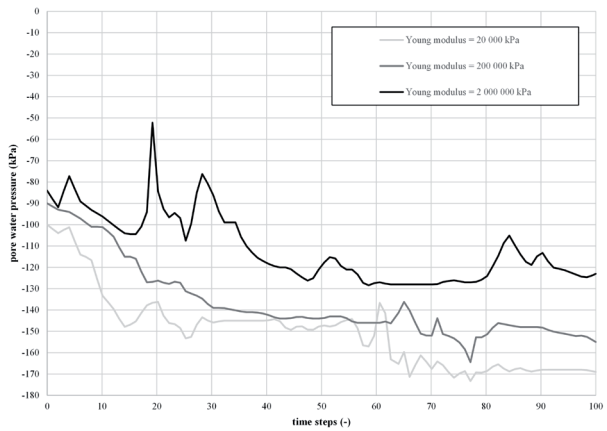


Fig. 6 - Comparison of the pore water pressure calculated during the analyses, at the reference point (located as in Fig. 4), for different values of the Young modulus of the debris

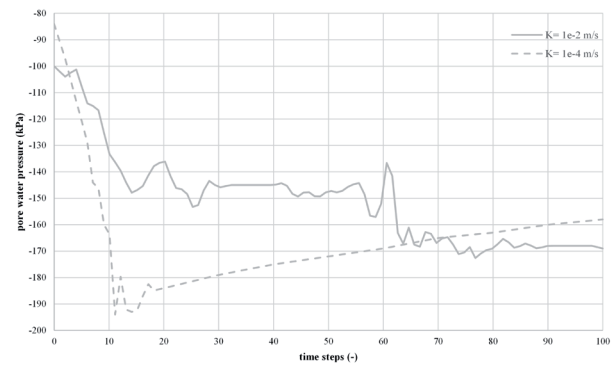


Fig. 7 - Comparison of the pore water pressure calculated during the analyses, at the reference point (located as in Fig. 4), for different values of hydraulic conductivity K (E'=20 000 kPa)

an appropriate elasto-plastic constitutive model, calibrated against the monitoring data and the laboratory tests. The model focuses on simulating the reactivation phase of the earthflow, the evolution of the pore water pressures and the kinematical features of the landslide.

The numerical results successfully reproduce the key kinematic features of the Montaguto earthflow, mainly represented by the development of excess pore water pressures within the landslide mass as a consequence of undrained loading processes. The calculated displacement patterns and the pore water pressure distributions are in good agreement with the process interpretation derived from the monitoring data. Sensitivity analyses were carried out to evaluate the influence of soil material parameters on the process evolution.

The findings demonstrate the high potential and robustness of MPM as a tool for simulating the full life cycle of complex earthflows, from slow creep to rapid acceleration and runout. Such a modelling approach can provide a significant advancement over traditional methods, offering a powerful tool for enhanced hazard assessment, scenario-based forecasting, and the design of effective mitigation strategies for critical infrastructure protection in earthflow-prone areas.

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