SIMULATING LANDSLIDES WITH THE MATERIAL POINT METHOD: POTENTIALITIES AND CHALLENGES

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Advances in numerical methods have provided useful tools to investigate the complex behavior of landslides, which can be a valuable support for landslide hazard assessment, planning, and design of mitigation measures. Among different methodologies, the Material Point Method (MPM) has been recently growing in popularity thanks to its ability to simulate large displacements and has been applied to simulate an increasing number of real cases. Despite the success, there are still several challenges to be addressed. This paper aims to discuss the current state of the art of the modelling of landslides with MPM highlighting its advantages and disadvantages to serve as guidelines for future applications and encourage the development of new solutions for current numerical challenges.

Keywords: Material Point Method, Landslides, numerical simulation

INTRODUCTION

Landslides are dangerous natural hazards that involve different types of material and mobility mechanisms. In the last decades, significant advancements have been made in the understanding of landslide mechanisms thanks to the developments of measurements and monitoring techniques, field and laboratory tests, and numerical studies.
One of the first methodologies proposed to investigate the stability of slopes is the Limit Equilibrium Method (LEM), which allows calculating a factor of safety (FS), commonly defined as the ratio between the maximum available shear strength and the mobilized shear stress. FS is generally calculated based on the equilibrium of driving and resistance forces, assuming an arbitrary shape of the failure surface and rigid-perfectly plastic soil behavior. Since the 50s, LEM has had a wide applicability thanks to its simplicity, and it is still valuable to evaluate the proximity of slope failure. In the 90s, Finite Element Methods (FEM) and Finite Difference Methods (FDM) were introduced in the field of slope stability. These methods can be used together with LEM or alone. In the first case, seepage analyses are performed to determine the pore pressure distribution in the slope to be used as input for LEM; in the second case, FS is calculated with the Strength Reduction Method (SRM), with the advantage that the failure surface is a result of the model and does not need to be defined a priori as in LEM. Advanced

multiphase formulations and constitutive models can be implemented in FEM and FDM. However, the results are limited to the onset of failure due to the numerical difficulties that arise when dealing with large deformations and consequent mesh tangling.

Several techniques have been proposed to overcome such difficulties, e.g., Discrete Element Method (DEM), Arbitrary Lagrangian Eulerian (ALE), Coupled Eulerian–Lagrangian (CEL), Particle Finite Element Method (PFEM), Finite Element Method with Lagrangian Integration Points (FEMLIP), Smooth Particle Hydrodynamics (SPH), Material Point Method (MPM), etc. These methods can simulate the post-failure behavior of the landslide, which is of great interest in evaluating the consequences of slope failure for risk assessment and mitigation. The popularity of MPM has increased substantially in the last decade, and the number of case studies analyzed with this method has increased sharply in the few years. This is probably due to the significant advancement of the numerical technique (e.g., the availability of multiphase formulations) and the accessibility of open-source codes.

This paper provides a brief overview of the method and discusses its applicability to real cases and its advantages and disadvantages. Overall, it aims to (a) serve as a guideline for future applications and (b) encourage the development of new solutions for current numerical challenges.

MATERIAL POINT METHOD

MPM has been developed since the 90s to simulate large displacements of history-dependent materials. It applies the principles of continuum mechanics, and the balance equations are discretized with the use of the finite element grid and the material points (MPs). The grid is typically fixed in space, and it is used to assemble and solve the field balance equations of motion. The MPs are used to discretize the continuum mass; they store all the dynamic properties of the body, as well as material properties and loads. Large displacements are simulated by MPs moving through the grid, thus overcoming issues with element distortions typical of FEM. The computational cycle is illustrated in Figure 1.

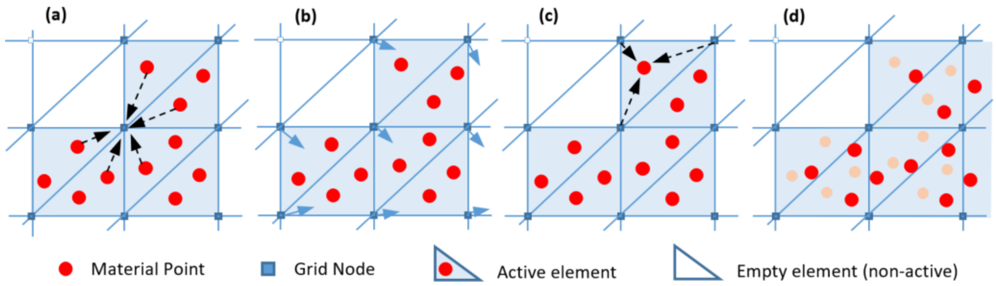

Figure 1 Computation scheme of MPM: a) map information to the nodes, (b) solve the governing equations of motions at the nodes, (c) update MP quantities (d) update MP position and housekeeping.

Soil is a mixture of solid, liquid, and gas phases, and several MPM formulations have been proposed to simulate the multiphase interactions, which can be schematically summarized in Tab. 1. The rows indicate the number of phases explicitly considered in the balance equations, e.g. one-phase means that the material is modelled as an equivalent continuum representing the mixture and two-phase means that the balance equations of two constituents (solid and liquid) are considered separately including their interactions. The columns indicate the number of sets of MPs used to discretize the continuum phases; e.g. single-point means that the MPs represent the mixture and move according to the displacement of the solid phase, double-point means that separate sets of MPs are used for the solid and liquid phases, and they move according to the displacements of the corresponding phase.

Table 1 Available MPM formulations

		Number of phase MP set	
		Single-point	Double-point
Number of phase governing equations	One-phase		-
	Two-phase		
	Three-phase		

POTENTIALITIES AND CHALLENGES

MPM has been applied to a great number of case studies; a complete review of the existing literature exceeds the purpose of this extended abstract. In contrast, we intend to summarize the main features used in the published case studies that allowed to capture the post-failure evolution of the landslide and provide suggestions for future works.

The first aspect to consider is the importance of multiphase interactions in the behavior of the landslide. This is relevant in most of the cases; however, it can be accounted for in a simplified manner; indeed, the one-phase single-point formulation has been successfully used in those cases where fully drained or fully undrained behavior of the material could be assumed (Yerro, Soga and Bray, 2018; Troncone *et al.*, 2023). This is often valid in clays and weathered rocks, even if the failure is triggered by changes in pore water pressure. The two-phase single-point formulation for saturated and unsaturated soils can account for the coupled interaction between solid and fluid phases, eventually considering also the presence of gas in a simplified way. This is necessary when changes in porewater pressure are crucial to explain the sliding phenomenon, for example, in landslides triggered by infiltration or seepage forces (Ceccato *et al.*, 2020; Mei *et al.*, 2020; Cuomo, Di Perna and Martinelli, 2021). Thermal effects may also be included (Pinyol *et al.*, 2018). The use of this approach is computationally more expensive and requires additional input parameters to simulate the hydraulic response, which may be difficult to estimate. An even more advanced way of simulating unsaturated soils is the use of the three-phase single-point formulation, which explicitly considers the balance equations of the gas phase(Yerro, Alonso and Pinyol, 2015). This approach is powerful, but the increase in complexity may be unnecessary in most applications. The two-phase double-point formulation allows to simulate not only the pore water, but also the free water and it is necessary if the impact of the landslide in the water basin is of interest or if the presence of the free water may modify the process significantly, such as in submarine landslides (Du *et al.*, 2021).

Another crucial aspect is the constitutive behavior of the material. Very advanced history-dependent materials could theoretically be used easily in MPM, but large displacements and stress oscillations due to grid crossing may pose numerical challenges. In many cases, simple elastic-perfectly plastic models are used successfully, but landslides in brittle materials such as quick or stiff clays require the use of strain-softening models (Yerro, Alonso and Pinyol, 2016).

Strain-softening models are mesh dependent, thus special care must be applied in the selection of the parameters and regularization techniques should be adopted. Many landslides are characterized by the liquefaction of the material, which explains the long runout distances. This aspect is still very difficult to capture, and only limited experience in real cases is available (Di Carluccio *et al.*, 2022), thus, further research is encouraged in this direction. Another relevant constitutive feature of rock and stiff clays is material anisotropy; while it could be included easily in small deformation problems, it poses a significant challenge at large displacement when the material is remoulded, and it has never been considered in MPM landslide simulation. The presence of fissures, joints, or very thin heterogeneities is difficult to simulate accurately due to the need for very small mesh elements, which may increase unacceptably the computational cost. Moreover, with the movement of MPs through the grid, elements can contain MPs of different materials; thus, a smearing effect occurs during the mapping of properties from the MPs to the nodes. The sliding along a predefined slip surface or a shear band can be simulated with the contact algorithm. This solution has been applied successfully in many real cases, and several advancements in the contact formulation have been proposed (Zhang *et al.*, 2023).

When the propagation of the seismic waves is of interest for the simulation of earthquake-induced landslides, special boundary conditions and accurate integration schemes are necessary (Alsardi and Yerro, 2022). Only limited research is available in this field, but it deserves more attention in the future.

Most of the published case studies are modelled in 2D for simplicity and to reduce computational cost. Full 3D simulations may require high computational effort; thus, computationally efficient codes are necessary. To improve computational efficientcy, a possible solution is the use of MPM in combination with other numerical methods such as FEM, FDM, or SEM (Spectral Element Method) (Feng *et al.*, 2022). At the scale of the slope, FEM or FDM are used for the pre-failure stage, and the results are used as an input for the subsequent MPM failure propagation and runout analyses (Lu *et al.*, 2023). At a regional scale, SEM is used to model elastic wave propagation from a seismic source to a local site with complex topography, and the results are used as BC for the MPM model of the slope. Special procedures are necessary to ensure the compatibility between the methods.

CONCLUSIONS

In the last years, the Material Point Method has been demonstrated to be capable of simulating the post-failure behavior of a number of real landslides, and the available codes have been enriched with several features to capture the essential aspects of the phenomenon. Despite the higher complexity and computational cost of the simulations, compared to traditional LEM and FEM, its ability to model progressive failure, long runout distances, and other cascading effects is fundamental to advancing the current understanding of landslides and improving risk assessment and management. We believe that the use of MPM will increase further in the future, possibly becoming a standard practice for landslide modelling, as occurred for LEM and FEM in the past.

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