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Run-out of landslides in brittle soils

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ABSTRACT

One of the factors causing the acceleration of landslides is the loss of strength of the soil involved in the potential unstable mechanism. The travelled distance and the landslide velocity, a key factor in risk analysis, will be determined by the loss of resistant forces. Brittle behaviour, commonly associated with cemented soils, overconsolidated plastic clay formations and sensitive clays, lead to the progressive failure phenomenon explained by the reduction of the strength with increasing strain. In the present study, this phenomenon has been analysed in the case of a saturated slope which becomes unstable by increasing the boundary pore water pressure. A Mohr–Coulomb model with strain softening behaviour induced by increasing deviatoric plastic strain is used. The paper focusses not only on the stability of the slope but also on the post failure behaviour (run-out and sliding velocity). A coupled hydro-mechanical formulation of the material point method has been used to simulate the whole instability process. The influence of the brittleness of the material on the triggering of instability and run-out is evaluated by means of a parametric study varying peak and residual strength. The onset of the failure and the failure geometry are controlled by both peak and residual values. Good correlations between run-outs and brittleness are found. The decay of the strength determines the acceleration of the landslides and the travelled distance.

1. Introduction

The dynamic behaviour of landslides receives increasing attention because landslide risk analysis and spatial identification of vulnerable areas require estimations of the slide run-out and the velocity of the unstable mass [1]. Special attention is given to reservoirs, lakes and fjords potentially affected by landslides on their margins [2–4]. In fact, slope instabilities may affect dams and their foundations and they may lead to partial or complete blockage of rivers, creating dangerous "natural" dams or the generation of a destructive wave due to the impact of the landslide against the stored water [5–7]. The potential damage caused by landslides can be determined by several factors related with the volume of the mobilised mass, the run-out, velocity and acceleration. One of the factors that control the acceleration of the slide is the loss of resistant forces associated with the drop of available soil strength. This phenomenon is typically observed in first time failure developed in "intact" sites in materials exhibiting a brittle behaviour. This is the case of hard soils and soft rocks, overconsolidated and cemented clayey soils with special relevance in the case of high plasticity soils. These materials exhibit a softening behaviour from a peak value, associated with a low value of shearing displacements, to a low residual strength when bonds are destroyed and clay particles orient in the direction of shearing. This reduction of strength leads to the propagation of the failure surface following a process of progressive failure.

When a point exceeds the maximum available strength, a degradation process initiates due to the strain softening associated with the constitutive response of the material. The unbalanced stresses are transferred to the surrounding areas which in turn may overstress neighbouring points in the process, leading eventually to residual strength conditions. This stress transfer phenomenon develops during slip surface propagation. This mechanism was first recognized by Terzaghi and Peck [8] and Taylor [9]. It was further discussed in the context of overconsolidated clays and clay shales by Skempton [10], Bjerrum [11] and Bishop [12]. Further contribution are made by Palmer and Rice [13], Stark and Eid [14], and Puzrin and Germanovich [15].

Several real cases involving progressive failure are collected and analysed in the literature [16–20]. Troncone [21] presents a 2D numerical analysis of well documented Senise large landslides in Southern Italy and a 3D extension in [22]. Other real cases of landslides involving progressive failure mechanism in the Iberian Peninsula have been collected in [23].

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Contributions mentioned above mainly concentrate on the analysis of the generation and evolution of the failure surface but the run-out stage, once instability occurs, is not explored. Modelling large displacement involves the use of alternative calculation techniques to the Lagranian approaches generally used in FEM. Soga et al. [24] reviews current numerical methods capable of analysing the slide motion. In this work, the Material Point Method (MPM) [25] is selected to analyse the stability of slopes and their post failure response in strain softening materials. MPM is a numerical technique able to simulate large displacements by means of combining two discretizations of the media: (a) a set of material points which move through and (b) a fixed computational grid. This dual description prevents mesh distortion problems and contacts between different bodies are automatically solved.

A fully coupled hydro-mechanical material point code was developed for saturated soils within the MPM Research Community framework [26–29]. A strain softening elastoplastic constitutive law was has been implemented with the purpose of analysing progressive failure phenomena that take place in materials exhibiting a reduction of the strength with increasing strain [30].

This MPM formulation was recently applied in Alonso et al. [31] to model the Selborne failure experiment [32]. Failure of the Selborne slope was triggered by forced water recharge. Field instrumentation data indicated that the failure was a progressive mechanism in overconsolidated brittle clays. The numerical MPM analysis presented in [31] provided consistent and accurate results in the prediction of the shape and position of the failure surface, the development of progressive failure and the slide motion after failure.

The aim of the paper is to explore the response of saturated slopes in brittle materials. It focusses on exploring the material properties controlling the run-out distance and velocity of the unstable mass in brittle materials. First, a synthetic slope is presented in which the shear stress distribution and the progression of failure mechanism are discussed. Afterwards, by means a parametric analysis, the brittle behaviour of the material soil (defined in terms of brittleness index I_B) is shown to be a key factor of the slope response. The results are discussed with the aim of deriving practical conclusions.

2. Basis of MPM formulation

The MPM [33] discretizes the continuum as a set of subdomains. In the standard approach, presented by Sulsky et al. [25], the mass of each subdomain is considered to be concentrated in a point, the material point (Fig. 1). Other properties such as velocities, strains and stresses, are also carried by the material points.

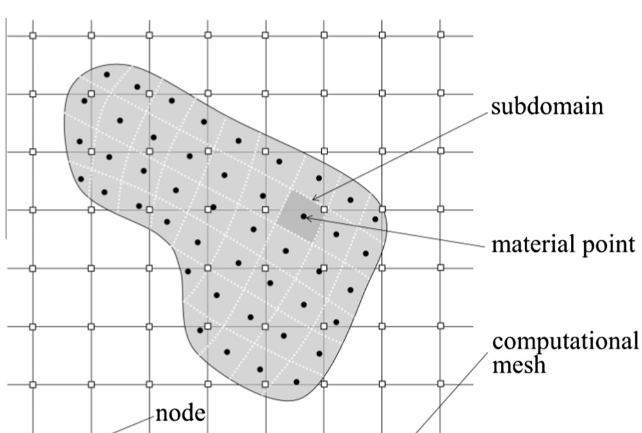

Fig. 1. Scheme of the spatial discretization used in MPM formulation.

This information is projected on to a background mesh where governing equation are solved. The support computational mesh covers the full domain of the problem and remains fixed during calculation. Calculations on the mesh serve to update the material point properties and location. Linear interpolation shape functions are used to provide the relationship between material points and nodes at any point of the domain. This approach allows MPM to combine the advantages of Eulerian and Lagrangian formulations.

The MPM formulation for a mechanical problem was presented by Sulsky and Schreyer [34]. Different authors have extended the MPM to solve coupled hydro-mechanical problems under saturated conditions [20,27,35]. More recently, Yerro et al. [28] extended MPM for unsaturated soils.

The numerical approach considered in this work to simulate saturated soils is based on [27]. It assumes that each material point represents a portion of the soil, moves attached to the solid skeleton and carries information of solid and liquid phases. Solid and liquid accelerations are calculated in the computational mesh solving the dynamic momentum balances of both phases. Velocities, displacements and strains are obtained in the material points; and liquid mass balance equation is established in the material points to provide liquid pressures. An explicit Euler–Cromer scheme [36] is used to update displacements and velocities from calculated accelerations.

In order to avoid non-physical vibrations, it is common to include a damping term in the balance equations. The approach adopted here was presented by Cundall [37]. It introduces a damping force proportional to the corresponding out-of-balance force (proportional factor α) and opposite to the phase velocity. In dynamic problems, the proportional factor should be very small (0–5%) in order to approximate the correct solution and avoid an overdamped system.

The standard MPM approach [25,33] in which the mass of each material point is assumed to be concentrated at the corresponding material point, suffers from spurious oscillations when material points cross from one element to another one. It is caused by a jump discontinuity in the gradient of low-order shape functions that are used for the integration. In order to reduce this numerical problem, a simple technique of low computational cost is introduced in this work [38]. It arises from considering that the stress on each element is constant and corresponds to the average of the stresses of the material points located within a given cell. Other authors proposed more accurate techniques. For instance, Bardenhagen and Kober [39] proposed to distribute the mass of each material point in a certain region. This idea results in a family of methods known as Generalized Interpolation Material Point (GIMP) methods. More recently, MPM has been extended to convected particle domain interpolation methods (CPDI1 and CPDI2) which are developed to improve the tracking of material point domains [40,41].

3. Constitutive modelling

In this paper the basic non-associated Mohr–Coulomb law is generalized to introduce strain softening plasticity with the aim of modelling a strength loss after peak strength conditions. In order to reduce the singularities of Mohr–Coulomb yield surface (edges and tip) that involve some numerical problems during the elastoplastic integration, the modifications proposed by Abbo and Sloan [42] have been implemented.

Following previous contributions [43–46,18], the softening behaviour is accounted for by reducing the strength parameters (friction angle φ', and cohesion c') exponentially with the accumulated deviatoric plastic strain ε_d^p according to the following softening rules:

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