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NUMERICAL MODELLING OF VAL D'ARÁN LANDSLIDE WITH MATERIAL POINT METHOD

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Abstract. *Flow-like landslides in mountainous areas can cause extensive damages due to their high velocity and long run-out distance. This work presents a real case of landslide occurred on 11 May 2018 in Val d'Arán (Catalonia, Spain). It involved about 50.000 m^3 of glacial and colluvial material, travelling about 250 m until the valley floor and climbing about 100 meters on the opposite hillside. With the aim to assess the capabilities of the Material Point Method (MPM) [1,2] plane strain analyses with the 2-phases 1-point formulation [3,4] are conducted on a representative section. First, the slope material is described with the Mohr-Coulomb criterion. Second, a constitutive model based on the critical state theory (Ta-Ger [5,6]), is adopted. The simulations results led to conclude that an advanced constitutive model, able to simulate the strength loss of the material during the movement, is required to reproduce flow-like landslides and to obtain realistic results in terms of long run-out distance.*

1 INTRODUCTION

Velocity and run-out of landslides are key factors determining the damage induced by landslide. Estimation of the initiation and post-failure behaviour is essential for evaluating the risk and quantifying the magnitude of consequences. The prediction of both run-out distances and velocity was investigated experimentally through flume laboratory tests [7]–[11] and numerically in the framework of the continuum [12]–[16] and discontinuous methods [17]. However, its numerical modelling is still challenging mainly because it involves large deformations, dynamic factors and requires a proper constitutive model able to reproduce the transitional behaviour between solid and fluid.

The landslide investigated in this work occurred on 11 May 2018 in Val d'Arán (Catalonia, Spain) after a period of significant rainfall. It involved about 50.000 m^3 of glacial and colluvial material, travelling about 280 m until the valley floor and climbing about 100 meters on the opposite hillside [18]. Based on field observation and laboratory tests conducted, both materials can be classified as clayey sands. Although the evolution of groundwater level and pore water pressures prior the failure is unknown, one of the hypotheses that could explain the failure triggering is the soil saturation induced by the water table rising. If the soil is susceptible to liquefaction, excess pore water pressure can be generated with the associated decrease of effective stress, affecting the velocity and post-failure behaviour of the landslide.

2 METHODOLOGY

The numerical method adopted in this study is the Material Point Method (MPM). It was developed to represent fluid dynamics [19] and extended to soil mechanics problems [1,2]. The method is intermediate between particle-based methods and finite element methods. The continuum media is described by a set of Lagrangian materials points that can move with the material and a computational mesh that remains fixed through the calculation and covers the whole domain. Each point represents a portion of the domain and carries all the information of the material while the governing equations are solved at the nodes of the computational background. This double discretization can simulate large deformations without problems associated with mesh distortion, which are typical in conventional finite element methods.

In this study, plane strain analyses with the MPM 2-phases 1-point formulation [3,4] are conducted on a representative section by using the Anura3D software, developed by the MPM Research Community (www.anura3d.com).

The failure triggering was probably due to the soil saturation induced by the water table rising. With the aim of evaluating the initiation of the movement, different hypotheses of phreatic levels are considered by modelling the slope material with the Mohr-Coulomb criterion. Then, the strength loss of the failed mass and its effect on the run-out distance are investigated by introducing a softening behaviour of the material. Finally, the limitations of the previous analyses are discussed and the advanced constitutive model Ta-Ger [5,6] is adopted to reproduce the flow-like landslide.

The objective is to ascertain if this model is able to track the triggering of the movement and the post-failure behaviour by reproducing the strength loss due to the propagation of pore water pressure, allowing the landslide mass to travel a long distance.

3 NUMERICAL MODEL

The geometry of the problem and the computational mesh are given in Figure 1. Plane strain conditions are imposed by means of the boundary conditions restricting out-of-plane deformation and horizontal displacements along the vertical contours. The computational mesh is generated by using a 3D mesh of linear tetrahedral elements with a size of 5 m. A thin slice of one element thickness is considered to simulate 2D conditions. Initially, four material points are distributed within each element in the position of Gauss points.

From a geological point of view, the slope is characterized by a layer of colluvium material on the top of a deposit of glacial origin with irregular thicknesses. The bedrock is located at a depth of about 25 m and is modelled as linear elastic as it is not involved in the failure. In order to simplify the geological model, the colluvial and glacial layers are represented as a unique material. This assumption can be accepted since the results of laboratory tests provided similar properties for both materials. In particular, a friction angle $\phi_{res}' = 33$ º, obtained from ring shear tests, is assumed in the simulations.

For a given phreatic level, the material above is defined as dry material, while the one below is considered fully saturated. A more accurate analysis may be performed by modelling the slope as a 3-phase unsaturated material, however, in this work, a simplified simulation is presented.

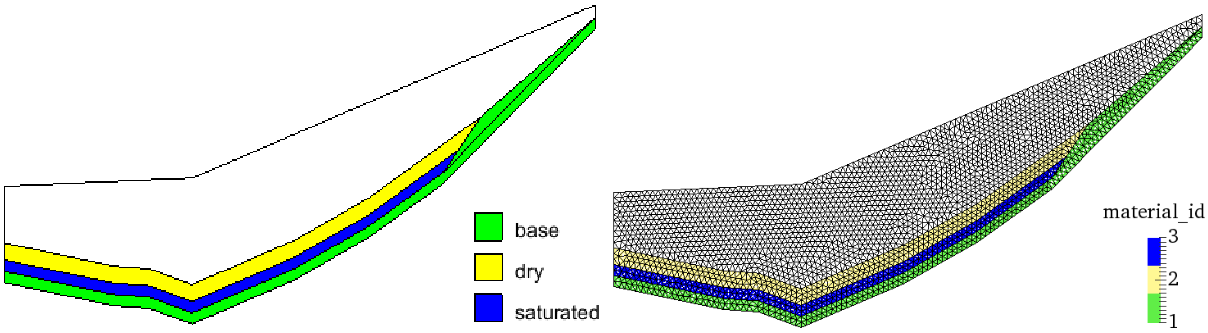

Figure 1: Geometry and computational mesh for the phreatic level located at -15 m of depths from the upper surface.

4 RESULTS

4.1 Drained analysis with Mohr-Coulomb

As a first approximation, the Mohr-Coulomb constitutive model is used to model the colluvial and glacial layers and drained conditions are considered for the saturated material, thus no excess pore water pressures are computed. The material properties are summarized in Table 1. The simulation is carried out in two stages. Stresses are initialized by applying a quasi-static gravity loading. A homogeneous local damping factor $\alpha = 0.75$ is applied to reach a quasi-static equilibrium state in a faster way allowing a considerable reduction in the computational time. In the second stage, the full dynamic behaviour of the soil is analysed and a small local damping factor $\alpha = 0.05$ is used in order to simulate the natural energy dissipation of the material.

Table 1. Mohr-Coulomb model parameters.

Parameter	Symbol	Unit	Value
Initial porosity	n	-	0.48
Young Modulus	E	kPa	10000
Poisson ratio	ν	-	0.33
Friction angle	ϕ'	∘	33
Cohesion	c'	kPa	5

Figure 2 shows the results of the numerical simulations for the different assumption in the depth of the phreatic levels. In drained conditions, the water table rising leads to an increase in the destabilizing forces but they are not sufficient to accelerate the slide and reach the observed run-out. This result seems to indicate that during the movement the resistance offered by the mobilized mass significantly reduced. In order to investigate this aspect, in the second simulation, the slope material is described with Mohr-Coulomb with strain softening model.

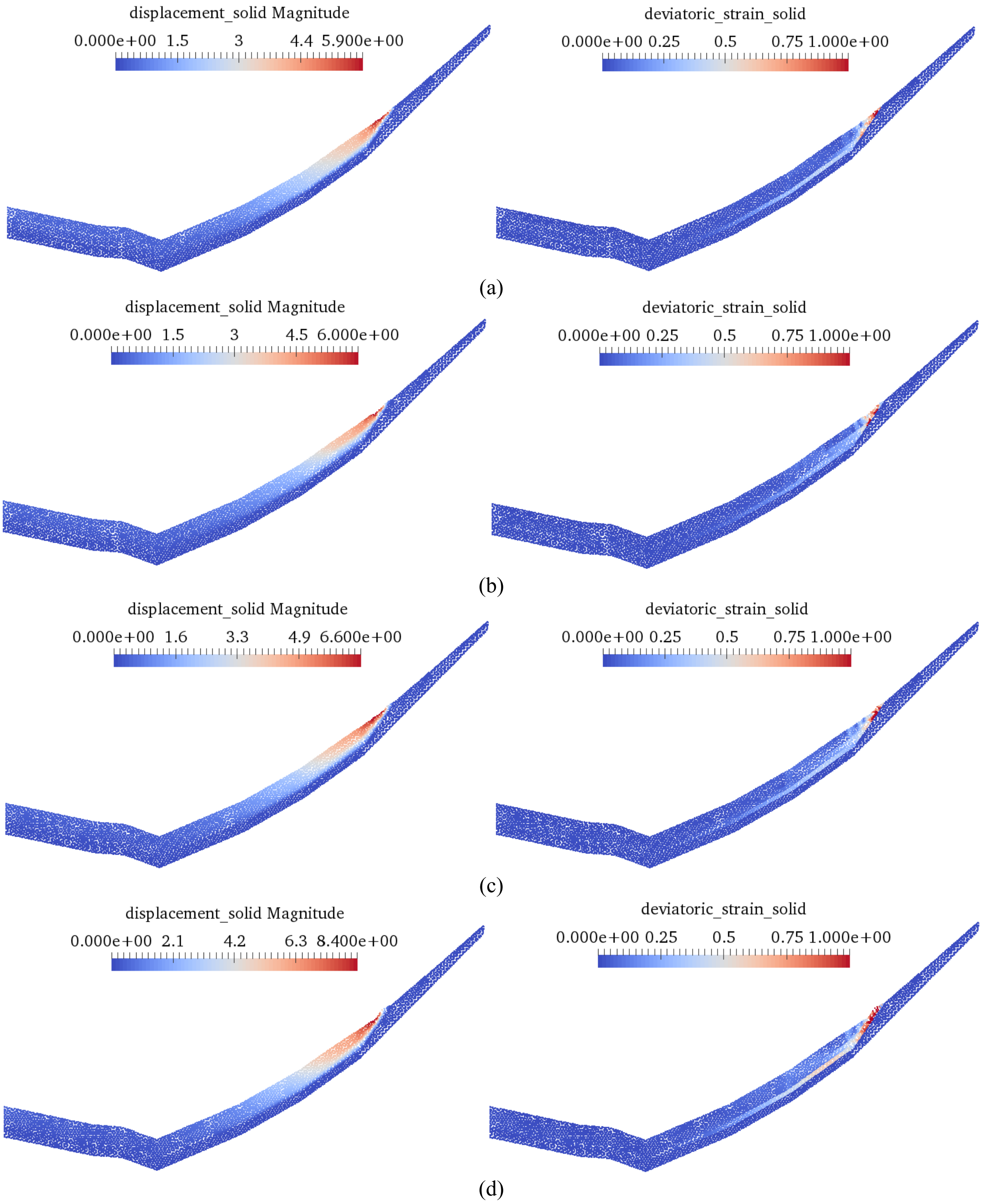

Figure 2: Total displacement and accumulated deviatoric strain results (after 10 seconds) for different depths of phreatic levels (PL) by using the Mohr-Coulomb model. (a) PL = −15m; (b) PL = −10m; (c) PL = −5m; (d) PL = 0 m.

4.2 Drained analysis with Mohr-Coulomb Strain Softening

The softening behaviour of the soil is introduced by reducing the effective strength parameters with the accumulated equivalent plastic strain. The strength loss of the material after the landslide triggering can generate a progressive failure phenomenon and facilitates the acceleration of the failed mass. For the case of phreatic level located at the surface, the residual values of cohesion and friction angle that needed to simulate the long run-out distance are shown in Table 2. The table also indicates the rest of the model parameters. The shape factor is an additional parameter that controls the rate of strength decrease with shear displacement. The simulation is carried out in two stages as described in the previous section.

Table 2: Mohr-Coulomb with Strain Softening model parameters.

Parameter	Symbol	Unit	Value
Initial porosity	n	-	0.48
Young Modulus	E	kPa	10000
Poisson ratio	ν	-	0.33
Peak friction angle	ϕ'_{peak}	°	33
Residual friction angle	ϕ'_{res}	°	10
Peak cohesion	c'_{peak}	kPa	5
Residual cohesion	c'_{res}	kPa	1
Shape factor	β	-	50

As shown in Figure 3, the post-failure mechanism and the long run-out can be quite well simulated by imposing a softening behaviour to the soil. However, the residual values of friction angle and cohesion that are needed are not compatible with the geotechnical characterization of the material.

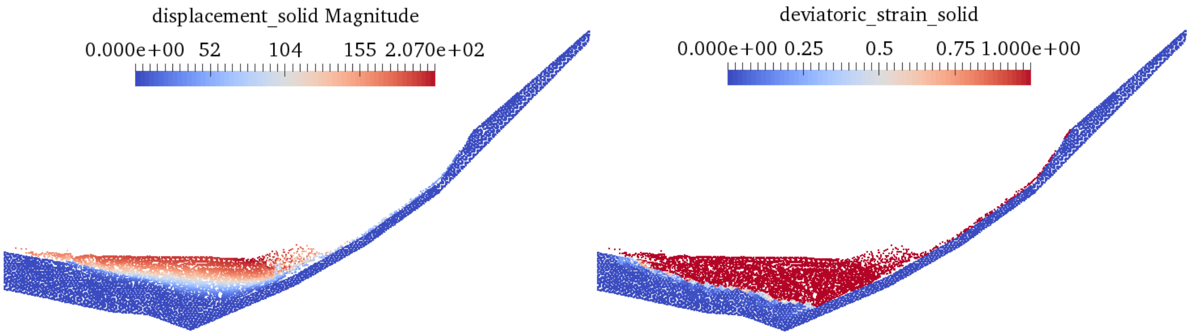

Figure 3: Total displacement and accumulated deviatoric strain results (after 40 seconds) for the case of the phreatic level at the surface by using the Mohr-Coulomb with strain softening model.

4.3 Undrained analysis in effective stresses with Ta-Ger

In the last simulation, the strength loss of the material is attributed to the excess pore water pressure generated during motion, which induces an effective stress decrease and, consequently, loss of frictional strength [20]. The loss of strength is being modelled in order to understand the long run-out observed. In the numerical calculation, the water table raising is assumed so fast that there is a significant generation of excess pore pressure, but negligible relative movement between solid and fluid phase, therefore pore pressure dissipation is neglected. The slope material is described with the Ta-Ger constitutive model [5,6]. It is an elastoplastic model based on the critical state theory and developed with the aim of reproducing the behaviour of soil under different types of loading, drainage conditions and initial stresses, without the need to recalibrate its parameters. A material that exhibits a contractive behaviour is considered.

In order to characterize the mobilized soil, drained and undrained triaxial compression tests are simulated for samples consolidated isotropically to 100, 150 and 200 kPa prior to shearing. The model parameters are summarized in Table 3. Figure 4 shows the results of the simulation in drained and undrained conditions. It can be observed that, when the drainage conditions are prevented and the soil is contractive, the mean effective stress decreases as a consequence of growing positive excess pore water pressure. The reduction in mean effective stress is accompanied by the reduction in deviatoric stress and hence the sample softens.

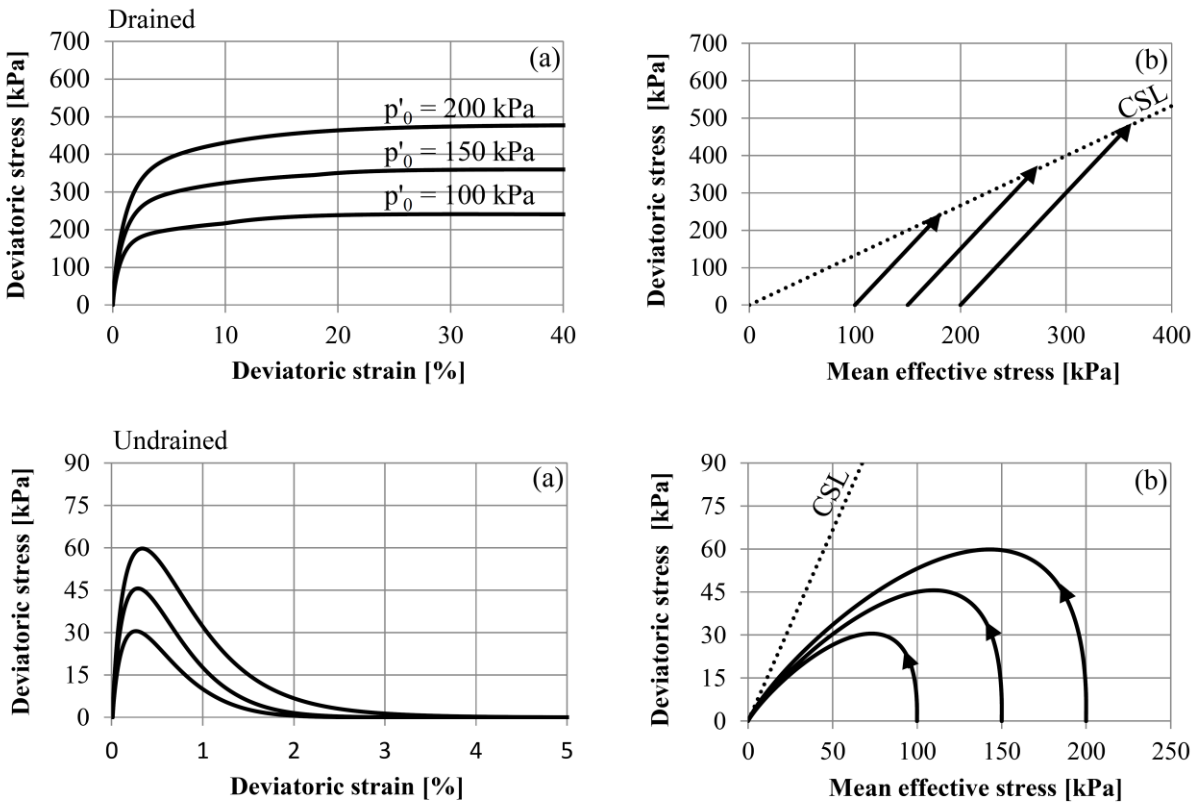

Figure 4: Drained and undrained triaxial compression simulations at different confining pressures. (a) Deviatoric stress-deviatoric strain relationship; (b) stress path in the triaxial plane.

The simulation is carried out in two phases: (1) Stresses are initialized by quasi-static gravity loading ($\alpha = 0.75$); (2) the full dynamic behaviour of the soil is analysed and undrained conditions are imposed to the material ($\alpha = 0.05$).

Table 3: Ta-Ger model parameters.

Parameter	Symbol	Unit	Value
Shear modulus constant	G_0	-	2500
Shear modulus exponent	m	-	0.4
Poisson ratio	ν	-	0.33
Friction angle at critical state	ϕ'_{cs}	°	33
Hardening exponent	n	-	0.5
Initial value of bounding stress ratio	M_{s0}	-	1.11
Bounding and Phase transformation coefficient	c	-	6
Initial void index	e_0	-	0.93
Minimum void index	e_{min}	-	0.597
Maximum void index	e_{max}	-	0.977

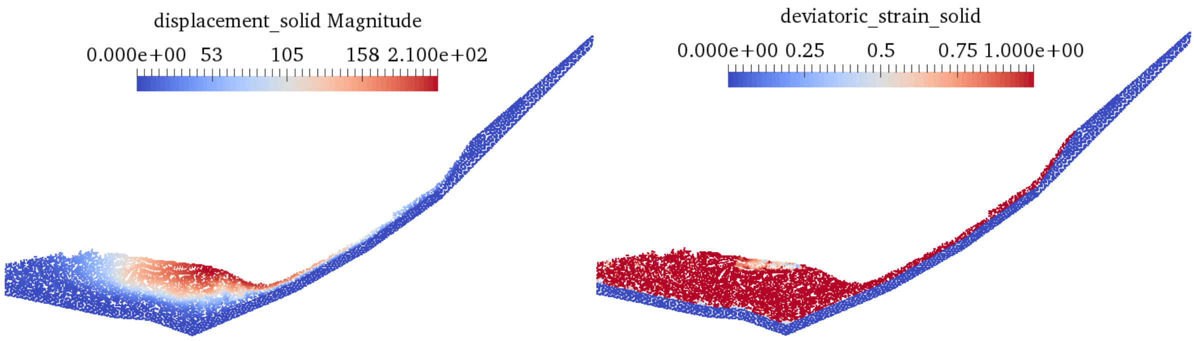

Figure 5: Total displacement and accumulated deviatoric strain results (after 20 seconds) for the case of the phreatic level at the surface by using Ta-Ger model with undrained conditions.

Figure 5 shows the total displacement and accumulated deviatoric strain at the end of the simulation period for the case of the phreatic level located at the surface. The dynamics of the movement and the large run-out is well reproduced. It can be seen that the generation of excess pore water pressure is fundamental to trigger the mechanism of flow-like landslides.

5 CONCLUSIONS

A flow-like landslide can be generated by several mechanisms such as the saturation of the soil involved in the failure and its susceptibility to liquefaction. The high velocity of the failed mass and the long run-out distances characterize its post-failure behaviour.

Table 4: Results comparison (the run-out observed in the field is 380 m).

Phreatic level	MC		MCSS		Ta-Ger	
	Run-out	Duration	Run-out	Duration	Run-out	Duration
-15 m	5.9 m	10 s				
-10 m	6.0 m	10 s				
-5 m	6.6 m	10 s				
0 m	8.4 m	10 s	207 m	40 s	210	20 s

The classical elasto-plastic constitutive models such as the Mohr-Coulomb and the Mohr-Coulomb with strain softening are not able to reproduce the real behaviour of the soil including the strength loss due to the propagation of the pore water pressures in the post-failure stage.

The hypothesis of a generation of excess pore pressures in undrained conditions, together with the advanced constitutive model Ta-Ger, allowed to capture the general characteristic of the flow-like failure and the large run-out.

In Table 4 are summarized the results of the simulations in terms of run-out and duration of the movement.

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