2^{nd} International Conference on the Material Point Method for Modelling Soil-Water-Structure Interaction

Anura3D
MPM Research Community

Paper number: mpm2019.39
www.anura3d.com
www.mpm2019.eu

Thermal and strain rate effects on landslide. A real case

Núria Mercè Pinyol[1, 2*], Mauricio Alvarado [1], Eduardo E. Alonso[2]

[1]Centre Internacional de Metodes Numerics en Enginyeria, Barcelona, Spain
[2] Department of Civil and Environmental Engineering. Universitat Politècnica de Catalunya, Barcelona, Spain

[*] E-mail: nuria.pinyol@upc.edu

ABSTRACT

In this paper, the case of Canelles landslide (2006 Catalonia, Spain) is revisited with the aim of giving a comprehensive explanation of the observed behaviour and to investigate its future evolution. Rate effects and thermal interactions are invoked to explain the observed and expected behaviour of the landslide. Rate effects contribute to increase the shear strength during the motion and they counteract the weakening effect of thermally induced water pressurization in shear bands. The analysis is carried out by means of the material point method for a non-isothermal problems and saturated conditions.

KEY WORDS: Landslides, strain rate effects, thermal interaction, frictional work, large displacements, material point method, real case.

INTRODUCTION

Risk assessment of potentially unstable soil and rock masses depends on the post failure behaviour in terms of run-out and velocity. What is observed in the field is that landslide may exhibit widely different velocities ranging from extremely slow to extremely rapid. Several factors determine the evolution of the motion, i.e. external actions, kinematic restrictions and constitutive response of the involved material. They may depend on the range of strains and thermal interaction due to frictional work dissipation. This is a challenging and complex problem involving large deformations and dynamic equilibrium. This is probably the reason explaining that landslide risk is often assessed by means of empirical tools and procedures relying on statistical methodologies and survey analysis.

With the aim of providing an explanation of the creeping motion observed in numerous well documented active landslides, in contrast to the accelerated motion predicted by simple frictional laws, some approaches introduce the effect of the shearing velocity (or shear strain rate) on the resistance forces. The effect of the velocity is incorporated in the expression of the friction angle and, therefore, the velocity dependent contribution on the strength is affected by the applied normal stress.

In this paper, thermal and strain rate effects are invoked to explain the behaviour observed in the large Canelles landslide. As described in Pinyol et al. (2012), in 2006 a large unstable mass was identified in a valley of one of the largest reservoirs in Spain. In 2006, after a relatively rapid drawdown of the reservoir water level, the landslide was reactivated. The motion was identified by means of the development of a long continuous crack (around 2 km), indicating a landslide crest displacement, varying between 0.1 to 0.3 m. The analysis described here is carried out by means of the Material Point Method, which is selected because of its capabilities to reproduce the entire response of landslides, including triggering and post failure behaviour.

CANELLES LANDSLIDE REVISITED

The instability observed in Canelles landslide in 2006 was analysed by Pinyol et al. (2012) by means of two dimensional finite element analysis of a representative section. The geological and geotechnical study carried out allowed the identification of the geometry and magnitude of the mobilized mass. The position of the sliding surface was located in a continuous and relatively thin red high plasticity claystone unit. According to the study, the instability was induced by a rapid drawdown of the reservoir that partially submerged the toe of the slope.

The case is reviewed in this paper with the aim of analysing the post failure behaviour of the landslide including thermal and strain rate dependence of the frictional strength. The analysis was carried out in a MPM code which includes the thermo-hydro-mechanical formulation (Pinyol et al., 2018; Alvarado, 2018).

The stability of the slope was evaluated by means of limit equilibrium analysis, taking into account the pore water pressure distribution computed along time. It was checked that the pore water pressure computed in the summer of 2006, after a strong drawdown, could explain the failure detected in the field by a continuous crack. The landslide never accelerated. However, the risk of the Canelles landslide acceleration concerned the authorities responsible of the reservoir operation. It is well known that the sudden acceleration of Vajont landslide (Hendron & Patton, 1985) was preceded by a long period of creeping motion.

The strain rate law that defines the creeping behaviour is included by means of variations in friction angle of a Mohr-Coulomb model, according to equation 1, where $\overline{\phi}'$ is the maximum increment of the effective friction angle due to strain rate effect and ϕ'_{res} is the minimum effective residual friction angle associated with shearing at slow strain rate.

$$\phi' = \phi'_{res} + \overline{\phi}'\left(1 - \mathrm{e}^{-\alpha\dot{\varepsilon}_d^p}\right) \tag{1}$$

The water filling the reservoir is also modelled (Figure 1). The water material is characterized as elastic body defined by its real volumetric compressibility coefficient (2000 MPa) and imposing a shearing modulus close to zero. This procedure allows the simulation of the water effect on the slope, including the initial forces of the water during the motion. This dynamic effect of the water motion was not included in Pinyol et al. (2012).

Thermal effects on solid and water densities due to the heat generated by the dissipation of the frictional work in shear bands is included in the calculation by means of the follow constitutive laws:

$$\rho_S = \rho_S^0 \exp\left[-\beta_S\left(\theta - \theta^0\right)\right] \tag{2}$$

$$\rho_L = \rho_L^0 \exp\left[\alpha_L\left(p_L - p_L^0\right) - \beta_L\left(\theta - \theta^0\right)\right] \tag{3}$$

where ρ_S^0 and ρ_L^0 are the solid and liquid density at reference temperature θ^0 and liquid pressure p_L^0. The parameter α_L defines the liquid phase compressibility and β_S, β_L are the volumetric thermal expansion coefficients for solid and liquid phase, respectively. Notice that the liquid density variation induced by changes of the pore water pressure is also included. On the contrary, the compressibility of the solid particles against changes in stress is assumed negligible. Table 1 shows the parameters included in the calculation.

Table 1 Constitutive parameters for the materials

Parameters	Symbol	Value
Water		
Density	ρ_L	1000 kg/m^3
Bulk modulus	α_L	2200 MPa
Thermal dilation coefficient	β_L	0.00034 1/°C
Specific heat	c_L	4186 N•m/(kg•°C) 1 cal/(kg•°C)

	Solid particles	
Density	ρ_S	2700 kg/m^3
Thermal dilation coefficient	β_S	0.000031/°C
Specific heat	c_S	837 N•m/(kg•°C) 0.2 cal/(kg•°C)
	Clay Soil	
Porosity	n	0.2
Permeability	k	1.00E-8 m/s
Young's Modulus	E	500 MPa
Poisson's ratio	□	0.3
	Siltstones and limestone	
Porosity	n	0.3
Permeability	k	1.00E-6 m/s
Young's Modulus	E	2500 MPa
Poisson's ratio	□	0.3

MPM COMPUTATIONAL MODEL

A representative two-dimensional cross-section of Canelles landslide reported in Pinyol et al. (2012) was discretized as in shown in Figure 1 for the purpose of the MPM analysis. The computational mesh (a regular cartesian mesh with element size of 4x2 m) defines the computational domain. The initial location of the material points (four per element distributed in the position corresponding to integration points of a four-point Gaussian quadrature) describe the initial geometry of the slope before the failure observed in 2006.

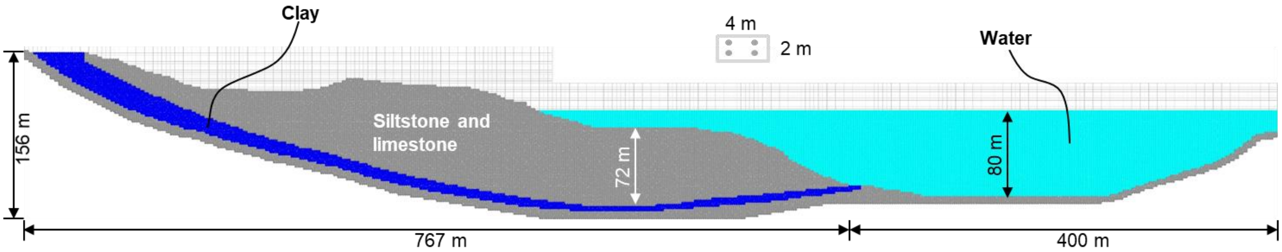


Figure 1 MPM discretization of Canelles landslide: computational mesh and material points

The initial stress state is defined by imposing the gravity load gradually. Since the purpose of this paper is the analysis of the sliding motion once the instability was induced by a rapid reservoir drawdown, the initial conditions in terms of the pore water pressure distribution and water reservoir level corresponds to the conditions explaining the slide reactivation calculated by means of the finite differences analysis in Pinyol et al. (2012). The calculation involved the simulation of four-year period of the reservoir operation and average rainfall. This pore water pressure distribution has not been calculated in MPM because it requires an expensive and time consuming calculation in the MPM code due to the explicit time integration of the code and the small required time step. Therefore the initial pore water pressure distribution inside of the slope, introduced as initial values in the material points, are the values calculated by means of the FEM code (Code_Bright) in the summer of 2006 at the end of the drawdown (Pinyol et al., 2012).

Several cases were analysed under different hypotheses regarding the physical phenomena controlling the motion:

- Case 1: Thermal interaction without strain-rate hardening. This case corresponds to the hypothesis assumed by Pinyol et al. (2012) in the analysis of the risk of rapid motion. In this case, thermal balance equations and its interaction with the motion were activated in the code and the effective strength of the soil decreases with the increase in pore water pressure due to the increase in temperature.

- Case 2: Thermal interaction including strain-rate hardening. This case includes thermal and strain rate effects in the constitutive response of the soil strength using the following parameters ($\phi'_{res} = 11.5°, \bar{\phi}' = 2°$ and $\alpha = 10^7 1/s$).

- Case 3: No thermal interaction without strain-rate hardening. In this case, thermal interaction were not include in the analysis by imposing null temperature increments. The friction angle of the clayey layer is assumed constant and equal to the low residual value ($\phi'_{res} = 11.5°, \bar{\phi}' = 0°$).

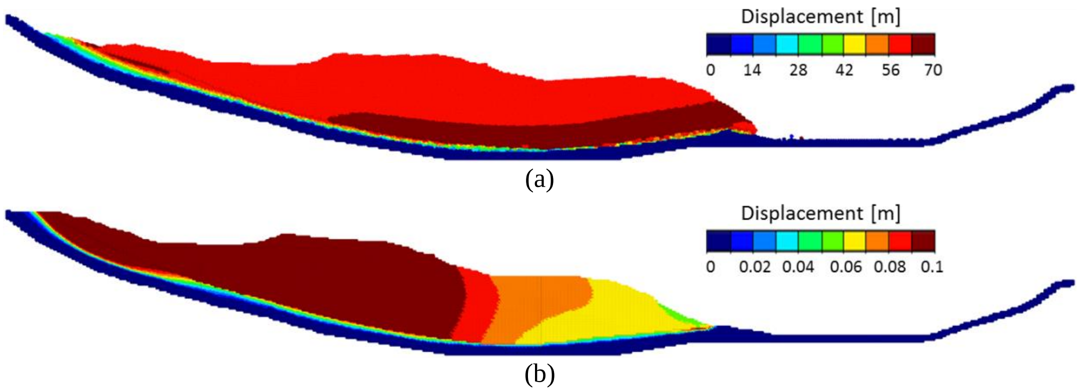
- Case 4: No thermal interaction including strain-rate hardening. The effect of the strain rate on the frictional strength of the clay is included with equation 1 ($\phi'_{res} = 11.5°, \bar{\phi}' = 2°$ and $\alpha = 10^7 1/s$).

RESULTS AND DISCUSSION

If thermal effects are considered without affecting the soil strength via strain rate effects, the landslide accelerates due to the increase in pore water pressure that is produced by the dissipation of energy in heat during the plastic deformations that take place immediately after the initial triggering of the landslide. This result indicates the existence of a risk of acceleration due to the accumulation of thermal-induced excess pore water pressures. However, despite this ‘prediction’, the actual slide displacement after its reactivation was no more than a few centimetres.

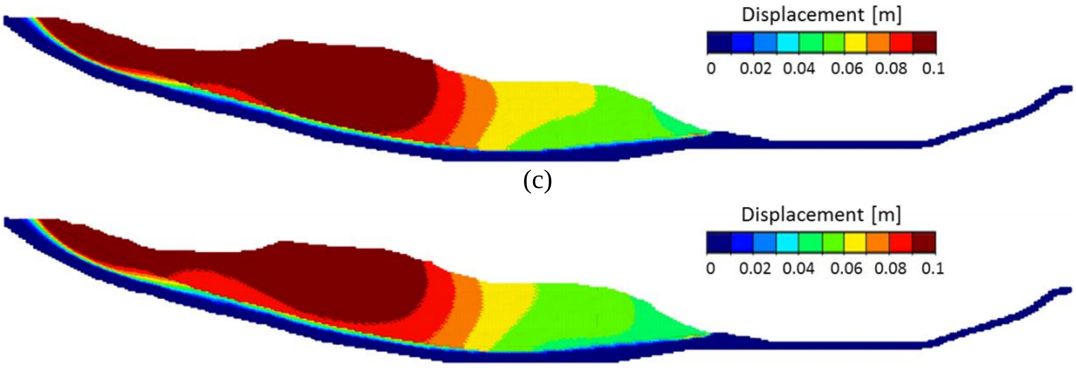
When strain rate effects are included, the velocity of the motion after initial instability is reduced and the excess of pore water pressure produced by the heating effect is dissipated. It results in a new stable condition for the landslide after a few centimetres of displacement. Figure 2 shows the final geometry of the landslide in equilibrium after calculation.

Case 3 and 4 are also evaluated. The final displacement of the toe is slightly smaller than the value calculated in Case 2 in which thermal interaction is included. According to these MPM results, the thermal interaction has effect on the velocity even at low velocity in case of low permeability materials. This conclusion, which was also raised in the analysis of Alonso et al. (2016), for simple geometries involving one-dimensional conditions, is also found by using a continuous MPM solution of a realistic geometry, based on a real case.



(a)

(b)



(c)

(d)

Figure 2 Accumulated displacement at the end of the motion. (a) Case 1, (b) Case 2, (c) Case 3 and (d) Case 4

CONCLUSIONS

The coupled behaviour of thermal and strain rate effects were analysed by means of the MPM modelling of Canelles landslide. The landslide was discretised according to Pinyol et al. (2012) as a large mass sliding over a clay layer. The thermal effects are included in a general coupled thermo-hydro-mechanical formulation (Pinyol et al., 2018 and Alvarado, 2018). Strain rate effects are included by means of a strain rate-dependent Mohr-Coulomb model. The formulation has been applied to a well-documented real case.

The results obtained show that strain rate effects could be of high importance in the behaviour of landslides and could help to explain the small displacements observed in Canelles landslide after its instability, even if thermal effects are included in the analysis.

ACKNOWLEDGEMENTS

The authors acknowledge the financial support to CIMNE by the CERCA Programme/Generalitat de Catalunya and AEI and FEBER. The first and the second authors also acknowledge the scholarship BES-2014-068284 and fellowship IJCI-2015-26342, respectively, from the Spanish Government and AEI (Agencia Estatal de Investigación), FEBER.

REFERENCES

Alonso EE, Zervos A & Pinyol NM. (2016). Thermo-poro-mechanical analysis of landslides: from creeping behaviour to catastrophic failure. Géotechnique 66(3), 202–219.

Alvarado M. (2018). *Landslide motion assessment including thermal including thermal interaction, An MPM approach.* PhD thesis, Department of Civil and Environmental Engineering, Universitat Politécnica de Catalunya, Barcelona, Spain.

Hendron AJ & Patton FD. (1985). The Vaiont slide, a geotechnical analysis based on new geological observations of the failure surface. *Vol. II. Technical Report GL-85-5*. Washington, DC, USA: US Army Corps of Engineers.

Pinyol NM, Alonso EE, Corominas J & Moya J. (2012). Canelles landslide: modelling rapid drawdown and fast potential sliding. *Landslides*, 9(1): 33–51.

Pinyol NM, Alvarado M, Alonso EE & Zabala F. (2018). Thermal effects in landslide mobility. *Géotechnique.* 68(6): 528–545.