EFFECT OF SHEAR BAND THICKNESS ON THE TERMO-HYDRO-MECHANICAL COUPLED ANALYSIS OF LANDSLIDES

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Thermal effects induced by the own motion of an unstable mass have been included in the analysis of the post-failure behavior in early works, most of them with the aim of looking for the causes of the rapid acceleration of Vajont landslide (Italy, 1963). Some limitations of these contributions, including recently published papers, lies in the fact that (a) the analyzed landslide geometries are simple and (b) the plastic work dissipation, inducing heat, is concentrated in a shear band defined by the contacts between rigid bodies. This contribution generalizes previous ideas and presents a numerical approach capable of including thermally induced pore water pressure in landslide analyses. Special attention is given to the effect of the shear band thickness, which becomes relevant in numerical simulations.

Keywords: rapid landslides, material point method, THM coupling, shear band thickness.

INTRODUCTION

Starting at the early contribution of Voight & Faust (1982), several authors have explained the acceleration of landslides invoking the frictional heating of the slip zone. By formulating mass, energy and momentum balances in the shear band the following phenomena are accounted for: once a soil mass becomes unstable, the pore water pressure in shear bands increases because of the frictional heat generated and the thermal expansion of the saturated soil. The associated decrease in effective stress leads to a loss of frictional resistance at the slip zone and, consequently, the acceleration of the sliding mass. A summary table on contributions to the analysis of thermally-induced catastrophic landslides is presented in Alonso et al. (2016). In all of these contributions simple geometries are analyzed and the approach followed consists of combining the dynamic equilibrium of the entire unstable mass with the coupled thermo-hydro-mechanical (THM) phenomena occurring in the shear band and the surrounding soil. These approaches imply that the application of the described phenomena cannot be generally applied. Note that in the prediction of a slope behavior, the position of the basal sliding surface is not known a priory and shear bands can be distributed inside sliding mass and not only in the assumed "basal" surface. The THM phenomena eventually develops in the entire domain. With the aim of overcoming such limitations, Pinyol et al. (2017) have recently presented a numerical approach capable of modelling the thermal pressurization effects on landslides in a general way.

A key aspect of the motion lies in the thickness of the shear band. This aspect is analyzed in detail here. To do that, analytical solutions for simple cases, under particular assumptions, are discussed. A planar landslide analyzed by means of the finite differences method (Alonso et al., 2016) is considered to take advantage of the fact that, in this approach, the shear band thickness is imposed and it does not depend on the numerical discretization. Finally, the consequences of shear band thickness in the numerical modelling in MPM is highlighted.

EFFECT OF SHEAR BAND THICKNESS

The effect of shear band thickness can be derived explicitly for the case of a block sliding on a horizontal surface at an imposed constant velocity (v) assuming adiabatic conditions and impervious material. The following differential equation (Eq. 1) can be obtained by formulating the governing equations (mass, heat and momentum balance equations and the Mohr-Coulomb failure criterion) and assuming that the source term in the heat balance equation is equal to the frictional work dissipated in the shear band where plastic strains localize:

$$\frac{\mathrm{d}u_w(t)}{\mathrm{d}t} = \frac{\beta \tan\varphi' v}{\left(m_v + n\alpha_w\right)\left(\rho c\right)_m 2e}\left[\sigma_n - u_w(t)\right] \tag{1}$$

where the unknow variable is the thermally induced excess pore water pressure in time, $u_w(t)$, σ_n is the total normal stress, $2e$ is the thickness of the shear band, m_v is the oedometric compressibility coefficient, n is the porosity, φ' is the effective frictional angle, $\beta = (1-n)\beta_s + n\beta_w$ is the volumetric thermal expansion coefficient for the mixture computed as a weighted average of the volumetric thermal expansion coefficients of solid particles (s) and water (w). The parameter $\left(\rho c\right)_m = \left(n\rho_w c_w + (1-n)\rho_s c_s\right)$ is the specific heat of the soil where ρ is the soil density and c indicates the specific heat.

Equation (1) can be solved analytically and the thermally induced excess pore water pressure is given by:

$$u_w(t) = \sigma_n\left[1 - \exp\left(-\frac{\beta \tan\varphi' v}{\left(m_v + n\alpha_w\right)\rho c_m 2e}t\right)\right] \tag{2}$$

Figure 1 shows the effect of the shear band thickness on the excess pore water pressure for the particular case defined in the figure. The effect of the shear band thickness is significant. Given a displacement rate, the shear band thickness determines the magnitude of the dissipated work per unit of volume which, in turn, determines the temperature increments. In this sense, highest increments of temperature and pore water pressure are expected inside the thinnest shear bands.

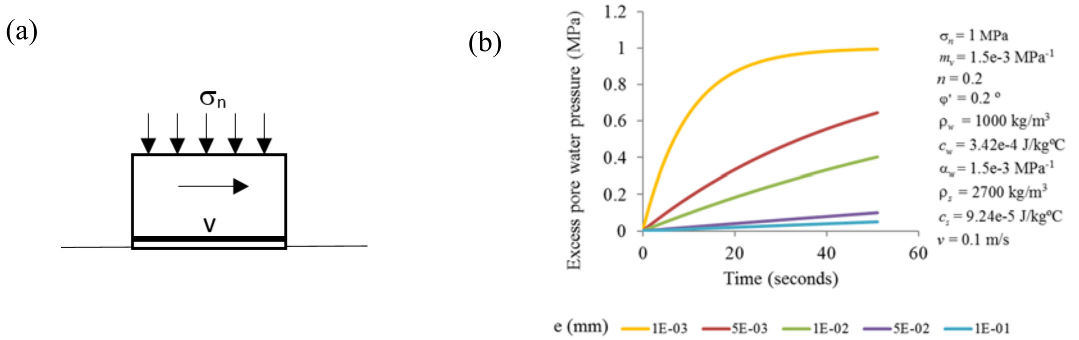


Fig. 1 (a) Sliding block at imposed constant velocity; (b) Effect of the shear band thickness.

Similar results are obtained when a more general case is analyzed in which temperature and pore water pressure dissipation is allowed. This is the case of the planar landslide shown in Figure 2 for two values of permeability (k=10^{-7} and 10^{-11} m/s). These results have been computed following the procedure presented in Alonso et al. (2016). The low dissipation of the excess pore water pressure for permeability k=10^{-11}m/s leads to higher velocities if compared with the case in which the excess pore water pressure dissipation is stronger (for k=10^{-7}m/s). Notice that the isothermal case is also plotted in Figure 2a. It is observed that the effect of the shear band thickness becomes relevant for values higher than 1 cm. This result suggests that it is not necessary to specify the exact thickness of the shear band (always difficult to identify in the field) when it is very thin (say in the order of mm or fraction of mm).

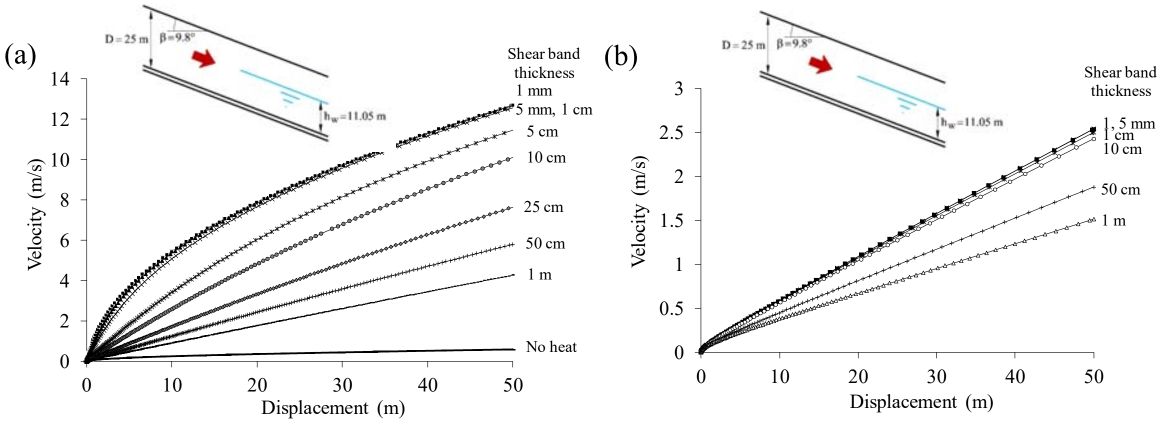


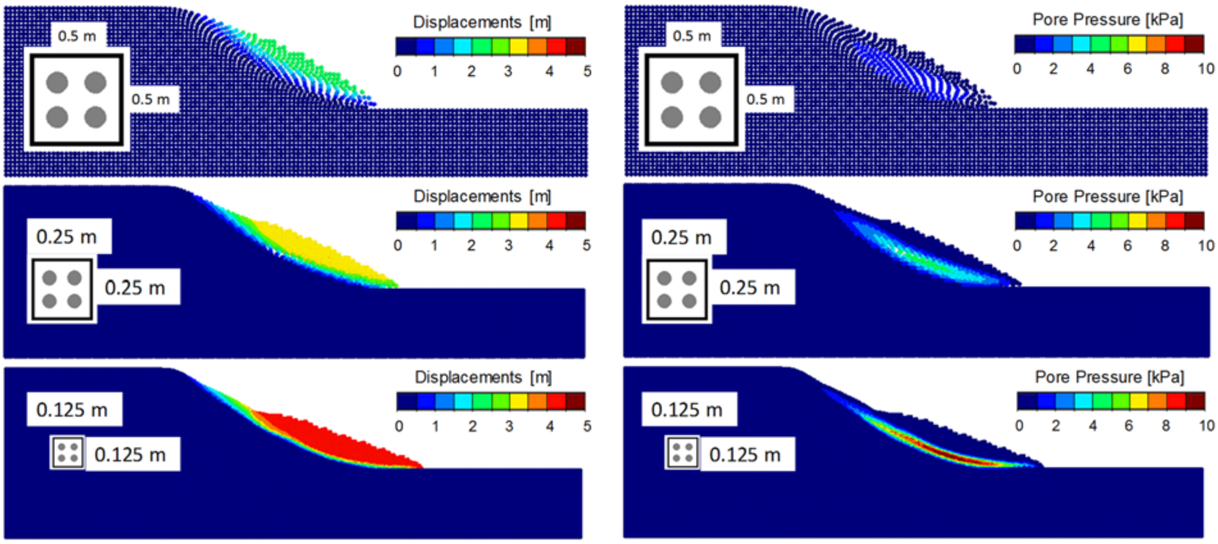
Fig. 2 Planar landslide. Effect of the shear band thickness on the velocity. (a) k =10^{-11} m/s and (b) k =10^{-7} m/s.

MPM NUMERICAL MODELLING

The thermo-hydro-mechanical dynamic behaviour of saturated porous media has been integrated into the framework of the material point method (MPM) (Sulsky et al. 1994) with the aim of providing a general numerical tool to simulate thermal interaction in landslide (Pinyol et al., 2017). The *u-p* formulation (Zienkiewicz et al. 1980) was extended to non-isothermal conditions by including the energy balance equation and assuming that the plastic mechanical work dissipates in heat.

The thickness of the shear band mainly depends on the grain size distributions of soils (Vardoulakis 1980; Scarpelli & Wood 1982; Alshibli & Hasan 2008). However, in numerical approaches such as FEM, FDM and MPM, the size of the shear bands developed depends on the element size and on the inclination of the band with respect to the mesh. The effect of the shear band is evaluated here for the case of a homogeneous slope 6 m high, inclined 36.9º and characterized with the Mohr-Coulomb failure criteria (28º of friction angle and 2 kPa of cohesion) and a permeability equal to 10^{-11}m/s. The motion is triggered by reducing the cohesion to 1 kPa. In order to evaluate the dependence on the size of mesh elements, the domain has been discretized using three alternative elements size: 0.5x0.5 m, 0.25x0.25 m and 0.125x0.125 m. In all the cases, four material points have been initially distributed per element.

The results in terms of displacement and excess pore water pressure are plotted in Figure 3. The motion observed in case of the coarse mesh is similar to the motion observed without including the heating effects (not plotetd in the figure). The shear band thickness associated with the element size is too large to induce a significant generation of excess pore water pressure capable of accelerating the slope. On the contrary, the strength reduces significantly due to the accumulation of the excess pore water pressure in the case of the finest mesh and consequently the acceleration and the run-out increase.



(a) (b)

Fig. 2 MPM results. Effect of the mesh element size.

CONCLUSIONS

The shear band thickness is a key parameter in the motion of landslides when thermal effects take a relevant role. The effect of the shear band thickness is negligible when it lies in the millimeter range. However, larger changes in the magnitude of the shear band thickness lead to highly different landslide responses (the thicker the shear band, the smaller the landslides acceleration). This feature is important in numerical simulations of slope motions in which the shear band thickness depends on the mesh size. A proper simulation using standard continuous numerical methods as FEM, DFM or MPM require the discretization of the domain where shear bands will be generated using an element size similar in size to the expected shear band thickness.

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