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

Anura3D
MPM Research Community

Paper number: mpm2019.40
www.anura3d.com
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Thermal effects in shear bands

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ABSTRACT

Thermal effects are invoked to explain rapid landslides. The main concept states that during motion frictional work dissipates in heat which leads to pore pressure increments which, in turn, reduces the effective strength. A relevant parameter in this process is the shear band thickness. For a given relative displacement, a thinner shear band involves higher values of mechanical work generated per unit of volume. This variable controls the temperature increments and the thermal induced excess pore water pressure. It leads to a pathological dependence of the results on the mesh when modelling this phenomenon by means of continuum numerical models such as MPM: In this paper this problem is explored and a solution to overcome mesh dependency is proposed and validated.

KEY WORDS: Thermal effects, shear localization, shear band thickness, frictional work, material point method.

INTRODUCTION

A mechanism invoked to explain fast sliding of landslides is the heating of shearing bands induced by mechanical energy dissipated during plastic deformations (Voight & Faust, 1982). This phenomenon consists in thermal induced dilatation of the materials by the increase of temperature, which leads to increments of pore water pressure reducing the effective frictional strength. The phenomenon is controlled by the frictional work dissipated per unit of volume. It leads to a strong dependency of the phenomena on the shear band thickness.

In Alonso et al. (2016) it is demonstrated that the effect of the shear band thickness is negligible when it is of the order of a few millimetres (typical values observed in the field). This is an interesting conclusion which suggest 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. 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).

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. Due to the dependency of the shear band thickness on the spatial discretization, 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. Taking into account the dimension of the landslide (from few meters to several kilometres) and the actual shear band thickness, a proper fine discretization will require an unworkable computational cost.

This problem was solved in MPM in Pinyol et al. (2018). To overcome the pathological dependency, a novel procedure was presented that consists in including a numerical shear band embedded on the plastically deformed elements. The thickness of these embedded shear bands are defined as a model parameters. This allows to calculate the equivalent frictional work per unit of volume that controls the heat generation. Local balance of heat and mass are defined between the embedded shear bands and the rest of the elements.

The procedure developed focuses on the calculation of the frictional work dissipated, given an incremental strain tensor calculated in the MPM computational element. A regularization procedure to avoid the dependence of the mesh on the results does not solve the problem. This paper presents a the methodology based on numerically embedded shear bands which allow a correct calculation of the dissipated heat, assuming the relative displacement in the elements of the MPM computational mesh are correctly calculated. The paper evaluates the effect of the shear band thickness on the results. The evaluation is carried out by simulating a confined sample subjected to a deviatoric stress by imposing a vertical displacement rate.

The calculations are carried out by means of a MPM numerical code recently extended to solve thermo-hydro-mechanical dynamic behaviour of saturated porous media (Pinyol et al., 2018). 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.

MPM COMPUTATIONAL MODEL

In order to analyse the dependence of the shear band thickness with the mesh element size for the thermal coupled problem, three different square meshes (1cm × 1cm; 5mm × 5mm; 2mm × 2mm), with four material points per element, initially located at Gauss points, were used to model a triaxial test of a column of soil 15 cm wide × 30 cm high. The soil sample is confined by a stress of 100MPa and then it is subjected to a vertical displacement from the top of 1 mm/s until failure. A weak point is introduced in the bottom left corner to localize the shear band developed. Figure 1 shows the geometry and boundary conditions of the problem described.

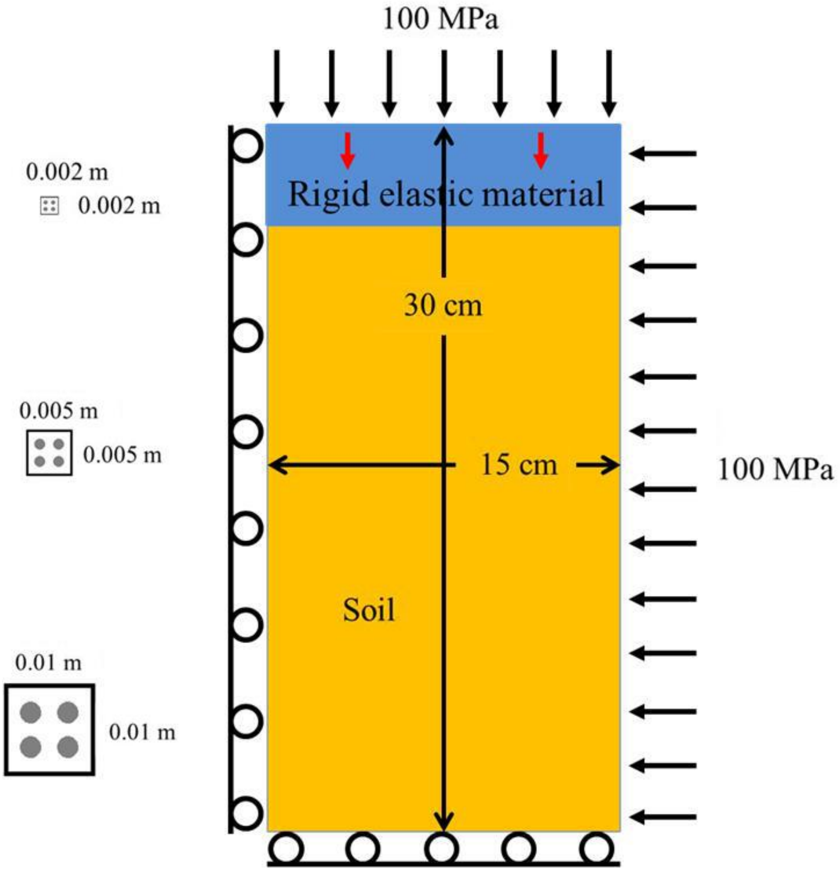

Figure 1 Geometry and boundary conditions for the test

The dry soil was simulated with a strain softening Mohr-Coulomb model with $\phi_{peak} = 15^\circ$ and $\phi_{res} = 10^\circ$. The transition from peak values to residual ones, was assumed to be an exponential function of the equivalent accumulated plastic strain $\varepsilon_{p_{eq}}$.

$$\phi = \phi_{res} + \left(\phi_{peak} - \phi_{res}\right) e^{-\eta \varepsilon_{Peq}} \tag{1}$$

Parameter η controls the rate of strain softening. The following values were adopted for η when changing the mesh size in order to regularize their response ($\eta_{1\text{cm}} = 20$; $\eta_{5\text{mm}} = 10$; $\eta_{2\text{mm}} = 4$). The rest of the parameters required in the simulation are indicated in Table 1.

The material is assumed to be dry and the evaluation focus on the temperature increments due to frictional heat dissipation. The test is reproduced under two hypotheses: (a) no embedded shear bands are included; (b) including embedded shear band 2 mm thick.

Table 1 Soil parameters

Parameters	Symbol	Value	Units
Solid particles density	ρ_S	2700	kg/m³
Thermal dilation coefficient	β_S	0.00003	1/°C
Specific heat	c_S	837 0.2	N·m/(kg·°C) cal/(kg·°C)
Porosity	n	0.2	-
Young's Modulus	E	10000	MPa
Poisson's ratio	ν	0.33	-

RESULTS AND DISCUSION

The initial failure surface develops five seconds after applying the deviatoric displacement of the top of the sample. As expected, the failure surface starts from the weak point located in the bottom left corner and propagates with an angle varying between 47° and 50° with respect to the horizontal axis. The same behaviour is observed for different mesh sizes. Differences among the three discretization manifest only in the width of the shear band developed. In all of the cases, the shear strains and the associated temperature generation localize in a band affecting one or two elements. After 10s, the shear band has fully formed and the average horizontal displacements of the developed wedge are around 5.5mm. The three meshes tests show similar results in terms of displacements (Fig. 2).

Figure 3 shows the computed increments of temperature for the three different meshes at 10s, for the case in which embedded shear bands are not included in the formulation. It is clearly observed that the increment of temperature increases when reducing the element mesh size. It is almost null for the coarse mesh, around 5° for the element mesh size of 0.005mm × 0.005mm and goes up to 15°—20° for the smallest element mesh size. These results show the expected behaviour of dependence of the increase of temperature with the discretization mesh.

The second analysis was performed including the embedded shear band formulation proposed by Pinyol et al. (2018) and Alvarado (2018). In these cases, the thickness of the embedded shear band is independent of the mesh discretization and it is defined as an input parameter, in this case, equal to 2 mm. Figure 4 shows the temperature developed in the shear surface for the three meshes. It can be observed that the increment of temperature is similar for the three cases and it is in the range 15° — 20°, proving that the results are independent of the mesh discretization. Note that the results for the smaller mesh (0.002mm × 0.002mm) does not change compared with the previous case because the element mesh size matches the thickness of shear band selected for the analysis.

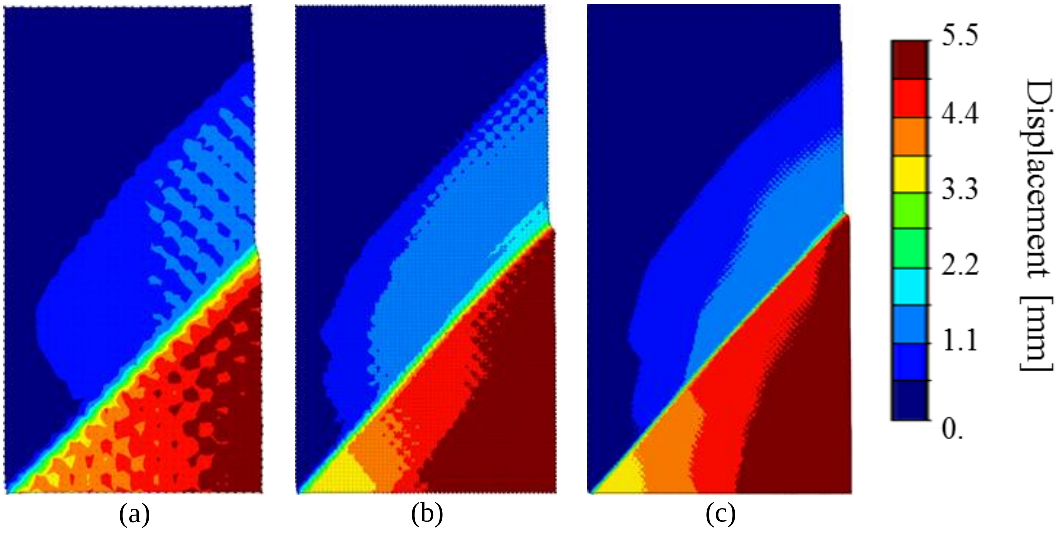

Figure 2 Horizontal displacements for t = 10s. (a) Mesh 0.01, (b) Mesh 0.005, (c) Mesh 0.002

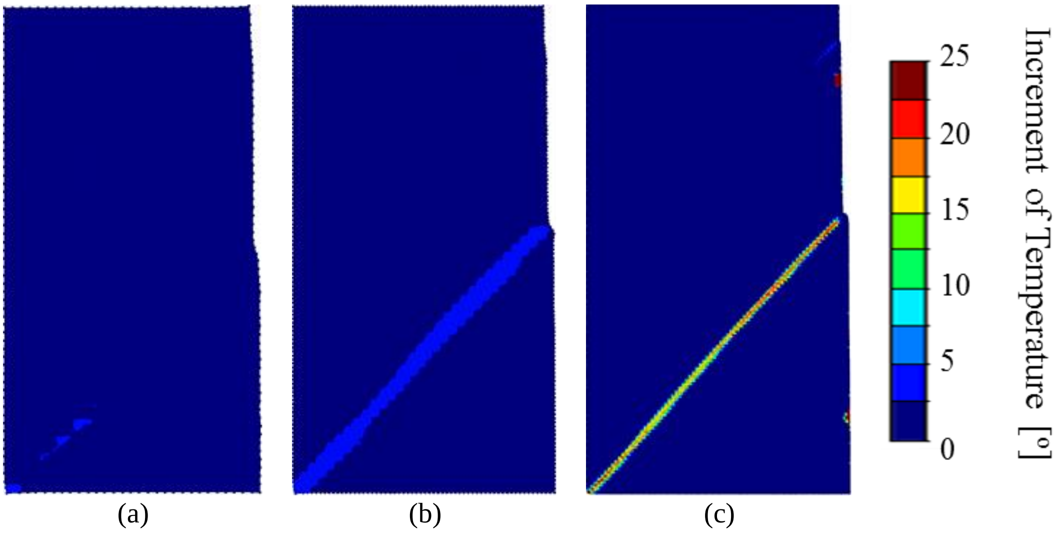

Figure 3 Temperature increments for t = 10s, without embedded shear bands. (a) Mesh 0.01, (b) Mesh 0.005, (c) Mesh 0.002

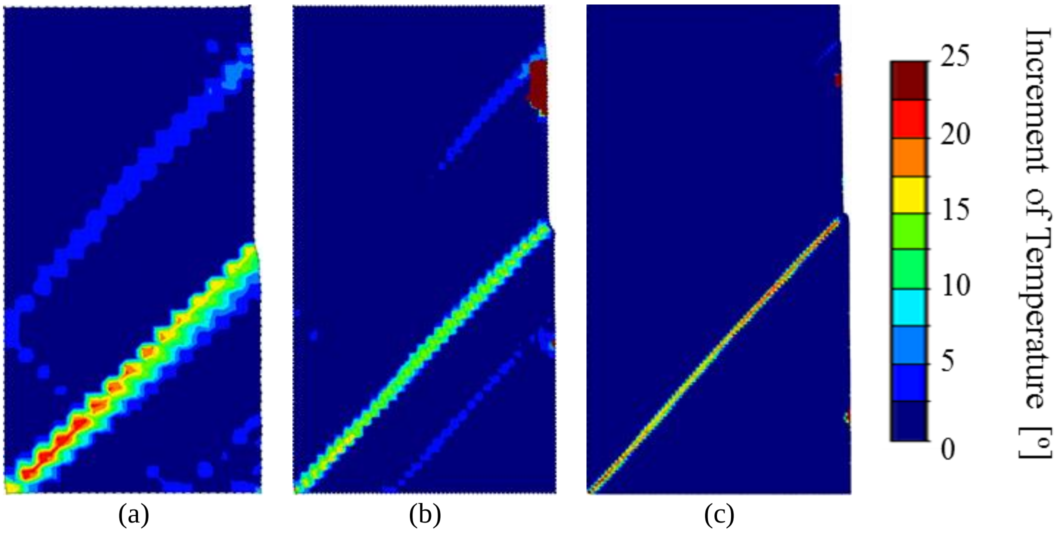

Figure 4 Temperature increments for t = 10s, with embedded shear bands. (a) Mesh 0.01, (b) Mesh 0.005, (c) Mesh 0.002

CONCLUSIONS

The shear band thickness is a key parameter in the analysis of landslides when thermal effects are developed. The effect of the shear band thickness is negligible when it lies in the millimetre 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. To overcome such limitation when modelling this thermo-hydro-mechanical coupled problem, a novel procedure has been evaluated in this paper. The modelling of a triaxial test shows that the MPM-THM formulation including embedded shear bands simulates successfully the heat generation due to frictional work overcoming the pathological dependence observed in a simpler formulation.

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.

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