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Effect of the heating of the intergranular water on the softening of a shear band

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Abstract. When a landslide takes place, it is believed that a shear band of loose granular media acts as a lubricant between the descending block of soil and the basis on repose. The mechanism involved is known as softening: the granular skeleton looses its stiffness and the shear stress on the block is lost. In the hypothesis of Habib, the friction between grains heats the pore water, increasing its pressure and reducing the effective stress by the Terzagi criterion. Vardoulakis had constructed models on this hypothesis including thermal diffusion and Darcy's law, plus a double dependence of the friction angle on the displacement and the velocity of the rolling block. Hereby we present a discrete element simulation of the process on a tilted shear band between two soil blocks: one bottom at rest and one upper at move. Soil blocks are assumed with uniform permeability and thermal conductivity. The shear band is modeled as a set of Voronoi polygons with elastic, frictional and damping forces between them. Pore water acts with hydrostatic pressure on the grains and on the upper and lower blocks, with a thermodynamic response that is reproduced by the Steam Tables provided by the International Association for the Properties of Water and Steam (IAPWS 97 report). At each time step, the forces on all grains are computed and all translational and rotational movements are integrated. Then, the heat is computed as the work done by all dissipative forces, distributing between water and grains according to their thermal capacities and increasing water temperature and pressure. Finally, this water pressure pushes the grains apart, reducing the shear stress on the upper block and speeding up the landslide. By this simulation procedure we obtain temperature increments on 10C^o that are strong enough to produce softening. Although the model is in two dimensions, it provides new insights on the study of catastrophic landslides evolutions.

Keywords: Shear Band, DEM, Thermo-poro dynamics
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INTRODUCTION

Landslides and avalanches are among the most disastrous events that occur naturally. They account for billions of dollars in damages each year. Although efforts in their study have been extensive, little is known about the triggering factors of a landslide. Water plays an important role since the pore pressure decrease the effective normal stress between grains in soils. This feature can be simply wrote as the Mohr Coulomb criterion with the Terzaghi effective stress,

$$\tau > \mu\,(\sigma - p), \tag{1}$$

with τ the shear stress, σ the normal stress and p the pore pressure. As can be seen, the pore pressure decreases the effective stress and hence increase the likelihood of a failure.

From the above analysis we can deduce that the pore pressure is an important factor for the appearance of avalanches. Moreover, this pressure is affected by the granular movement since due to the frictional force certain amount of energy is dissipated as heat. The vaporization hypothesis proposed by Habib [1] explains that the granular movement prior to the avalanche warm the pore water and increase its pressure. With the pressure increment, the failure criterium is reached sooner and the avalanche occurs. Further development was made by Vardoulakis [2] with a set of coupled differential equations of the pore pressure, water temperature and shear rate. In Fig. 1 the effect of a sliding block over a shear band of saturated granular material is showed.

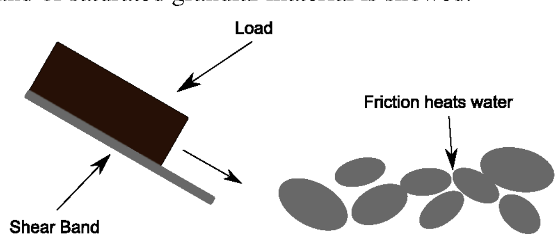

FIGURE 1. (Left) A sliding block over a thin band of granular material. (Right) The intergranular friction force due to the shearing provided by the load increases the pore pressure and reduces the threshold for a landslide appearance according to Eq. 1.

We propose in this paper a model based on the DEM [3] method of simulation for the purposes of investigating the por pressure hypothesis from a micromechanical point of view. The granular material is divided in a set of random Voronoi polygons that suffer elastic and frictional forces and also the force provided by the hydrostatic pressure of the water. The results from our simula-

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tions show some evidence for the vaporization hypothesis.

THE MODEL

The granular material is divided in a set of Voronoi polygons constructed as is shown in Fig 2 [4].To construct the polygons we need first a set of points randomly distributed on the plane, called the Voronoi points. For each point the polygon associated with it is defined as the set of points in the plane that are closer to the given point than to any other one. In other words,

$$V(p) = \{x \| dist(x,p) < dist(x,q)\}, \quad (2)$$

where $V(p)$ is the Voronoi polygon associated to the Voronoi point p, q is any other point and the function *dist* is the euclidian distance between two points in the plane. Of course, the boundaries of these polygons are lines that are equidistant to two points, and the vertices of these polygons are equidistant to three points. This feature provide us with an equation for the coordinates x,y for each vertices. If a line is drawn from one Voronoi point the another, this line will be perpendicular to the common side of the two corresponding polygons. Each polygon has three degrees of freedom: the two coordinates of the center of mass and the angular displacement from the equilibrium position.

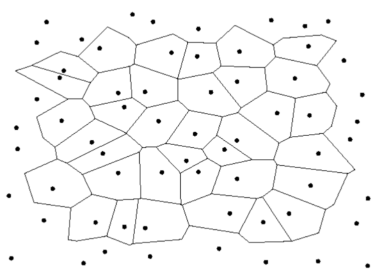

FIGURE 2. A typical set of Voronoi polygons and points.

When two polygons intersect with each other, an elastic repulsive force appears between them. This force is proportional to their overlapping area, is perpendicular to the line that joins the intersections of the two perimeters, and acts in the middle point of this line, as shown in Fig. 3. The exact value for this force is,

$$\vec{F}_g = \frac{YA_{ol}}{L_c}\hat{\mathbf{n}} \quad , \quad (3)$$

where Y is the granular Young modulus of the material, A_{ol} is the overlapping area, L_c is a characteristic length, given by $1/L_c = 0.5(1/r_i + 1/r_j)$ [3], with r_i the radius of the circle with the same area of the i-th polygon, and $\hat{\mathbf{n}}$ is a vector perpendicular to the intersection line of Fig. 3 with repulsive sign.

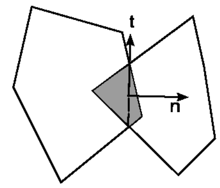

FIGURE 3. Here we show the action of the granular repulsive force. The vertical line goes between the two points that define the intersection of the polygons. We define the two unitary vectors $\hat{\mathbf{n}}$ and $\hat{\mathbf{t}}$ normal and tangential to the intersection line. They are also the directions of the normal repulsive force and the frictional force. The normal force is proportional to the overlapping area of the two polygons (in gray).

Finally the intergranular frictional force is modeled by the Coulomb force,

$$\vec{F}_f = \mu F_g \hat{\mathbf{t}}, \quad (4)$$

with F_g given by Eq. 3. Other dissipative forces are added in order to ensure numerical stability of the simulation [8]. The pore pressure adds another force to a given polygon proportional to its value p and to the area of contact with the water

$$\vec{F}_p = phl\hat{\mathbf{l}}, \quad (5)$$

where the product of the fixed tick h of each polygon and the side l that is in contact with water gives us the area of contact and the vector $\hat{\mathbf{l}}$ is normal to the side in contact with the water. Fig. 4 shows the shear band assumed by our model. The upper rectangle represent the load over the granular material. The space not occupied by the grains is filled with water and its pressure provides the force over the polygons given by Eq. 5. The gravity acts on the load effectively shearing the granular material. Since it is assumed that the shear band is far more larger than its thick, a polygon leaving the space trough the right frontier appears again at the left boundary (periodic boundary condition).

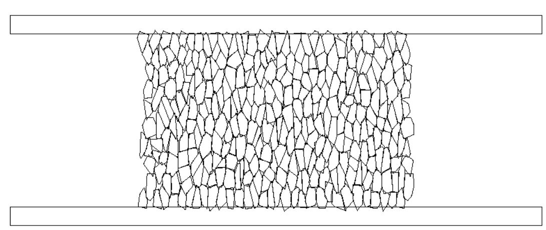

FIGURE 4. A 10x30 polygon array as the ones used in our simulations representing the shear band.

The water pore pressure is given by the steam tables of the IAPWS 97 [5] report. Only two thermodynamic variables are needed and we choose the specific internal energy and the volume of water. The last one is easily provided by our simulation since we are assuming a totally saturated material (see Fig. 4). The internal energy is obtained from the first law of thermodynamics,

$$dU = dQ - pdV \qquad (6)$$

with p the water pore pressure, dV the change in the volume filled with water and dQ the amount of heat dissipated by the frictional force (Eq 4) for the given time step.

Finally with all te forces defined Newton's second law is integrated with the optimized velocity verlet algorithm [6] both for the translational coordinates and for the angular displacement.

METHODOLOGY

For our simulation we used the parameters shown in table 1:

TABLE 1. Set of parameters used in our simulation.

Parameter	Value
Time step	1e-6 s
Granular density	3000 kg/m^3
Granular modulus Y	160 MPa
Average length of a polygon side	1 mm
Friction Coefficient μ	0.5
Initial load	4 MPa
Slope angle	30^o
Initial pore pressure	100000 Pa
Initial temperature	20 ^{o}C

After the set of polygons is constructed they fall under the action of gravity (with zero slope angle) until they reach an equilibrium position and their kinetic energy is dissipated due to the action of friction. Then the load is gently placed above the granular band as shown in Fig. 4. Once the system is in equilibrium the gravity is redefined with two components: $g_x = g\sin(\delta)$ and $g_y = -g\cos(\delta)$ with δ equal to the slope angle.

Our simulations ran with arrays of 6x30,8x30,10x30 and 15x30 polygons. Since the characteristic size of one polygon is 1mm then we have the following values for the band thickness: 0.6,0.8,1 and 1.5 cm. If is is assumed that the upper block of Fig. 4 provides 4 MPa of normal stress and it has the same density of the granular material it should have a thickness of about 200 m. This great difference between the sliding block and shear band thickness is reported and used in several macroscopical models ([2],[7]).

RESULTS

For a 10x30 array of polygons the corresponding water temperature is obtained from the simulation. As seen in Fig 5 the water temperature increases 14 K approximately. In contrast with the findings of Vardoulakis [2] which are in the order of 100K our temperature increment is small.

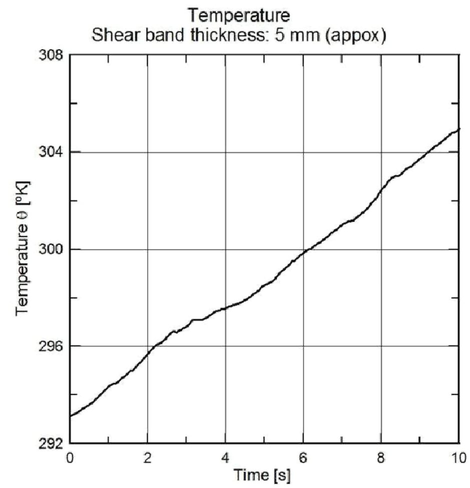

FIGURE 5. Water temperature obtained from a 10x30 polygon array simulation.

However the most important thermodynamic variable is the pore pressure. We show the results from simulations in the four different sizes that are considered in Fig 6. As can be seen the pore pressure behavior is extremely sensitive to the shear band thickness. Actually it increases each time we decrease the number of layers.

This could demonstrate the hypothesis of a thin shear band necessary for the proper increase in pore pressure. With our model we can also measure the of the upper block (Fig. 7) and it can be seen that after a certain time the friction is overcome and the block falls with an continually increased acceleration with time.

Of course these acceleration is due to the reduction in the shear stress associated with the friction. We can reproduce then the trigger event of a catastrophic landslide.

CONCLUSIONS

With a model based on the discrete element method we simulated the behavior of a granular band under shearing due to a sliding block. Although the role of the pore pressure in the friction force reduction is widely accepted, the increment of this pressure due to the excess heat produced by the strain process inside the shear band is an unproved hypothesis. Micromechanical simulations show that this is possible. However we have not consider

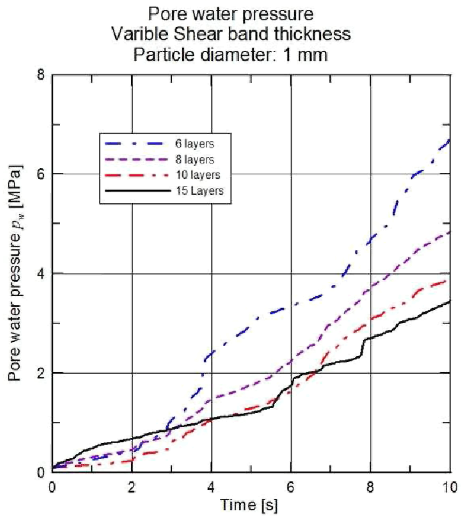

FIGURE 6. Total pore pressure (initial plus excess pressure) obtained for several shear band thickness given in number of granular layers. Since each grain has a characteristic size of 1mm, each simulation correspond to a shear band thickness of 0.6,0.8,1 and 1.5 cm respectively

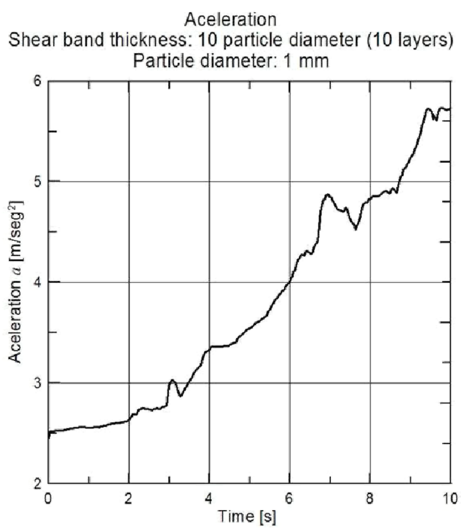

FIGURE 7. Acceleration of the load with time

the diffusion due to Darcy's law. Despite this we have seen smaller responses in both temperature and pore pressure that the ones predicted with the macroscopical models.

Remarkably the pore pressure is sensible to the number of granular layer of the shear band which could prove that truly just a thin section of shearing material is producing the exceeds pore pressure that lifts the sliding block and starts the landslide.

Further development on the model could include the dissipation of pore pressure and larger resolutions for the polygon array.

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