Thermo-hydro-mechanical analysis of landslides under earthquake action

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Abstract

Landslides generated in low permeability saturated layers of clayey materials may develop high pore pressures due to the increase of temperature during the motion. The plastic work generated in a more or less localized shear band provides a heat input that causes temperature rise. Strength reduction in the band during an earthquake could increase the landslide speed and runout and this can cause catastrophic effects. Finite differences are used in this paper to solve the thermo-hydro-mechanical coupled problem of heat generation due plastic work, increment and dissipation of pore pressure, in a shear band or in a discontinuity for an infinite slope that slides on a saturated clay layer. At the same time Newmark sliding block analysis are conducted in order to measure the influence of parameters such as clay permeability, compressibility, and temperature pressurization coefficient on the velocity of the landslide. The yield acceleration of this slopes could be small and the final displacement estimated with a Newmark sliding block analysis could not cause catastrophic effects. However if the permeability of the sliding layer is low the behavior could be very different due to complete strength reduction. If thermo-hydro-mechanical effects are taken into account, the key parameters in the analysis are the pressurization coefficient, hydraulic diffusivity and the thickness of the heat and pressure generation zone.

1 INTRODUCTION

Thermo-hydro mechanical effects associated with failure in saturated low-permeability materials have been extensively studied by different authors: Lachenbruch (1980), Vardoulakis (2002), Alonso and Pinyol (2010), Pinyol and Alonso (2010), Alonso et al. (2016). The problem is strongly coupled because the heat generated by frictional forces increases the temperature of the sliding surface and due to differential expansion of water and soil skeleton pore pressure is generated, which in turn decreases the effective stress and therefore the resisting frictional force. Strength reduction in the band during an earthquake could increase the landslide speed and runout and this can cause catastrophic effects. Some historical cases of catastrophic high-speed landslides such as Vaiont's could be explained by the decrease in strength due to the increase in pore pressure generated by the mechanical work of the frictional forces, Alonso and Pinyol (2010).

In this paper, the displacement and velocity of a landslide, during the action of a destructive earthquake, are estimated using Newmark's sliding block method applied to an infinite slope that slides over a layer of saturated low-permeability clayey soil (Figure 1). It is assumed that the shear plastic strains are concentrated in a narrow shear band and the sliding mass move as a rigid body without considering any soil amplification response. Also it is considered that the shear strength of the band can be estimated using a residual friction angle for the clay.

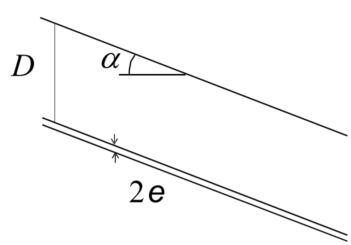

Figure 1 Infinite slope with shear band thickness.

The band thickness is very small compared with the problem scale. Large concentrated shear strains in the band are imposed by the sliding. The rate of work per band unit volume can be obtained from the shear stress and the rate of shear strain. In turn if the sliding surface is considered as a discontinuity in the clay layer, the rate of work input per unit surface can be also computed using the relative velocity. The rate of work input is a source term for the heat balance equation.

2 GOVERNING EQUATIONS

If we suppose that the localized zone in the clay layer has a thickness 2e and the plastic shear strain is constant in the band, the heat input is equal to the plastic work of the shear stress, so the increment of plastic work per band unit volume is:

$$h_b(t) = \tau_{xy}\ \dot{\gamma} \qquad (1)$$

$\dot{\gamma}$: shear strain rate
τ_{xy} : shear stresss.

2.1 Conservation of energy

Assuming that advective terms provide a negligible contribution to change the band temperature during the sliding motion Pinyol and Alonso (2010) the heat balance equation became:

$$h_b = \frac{D}{Dt}(\rho c\, T) - div[-\Gamma grad(T)] \qquad (2)$$

D/Dt is the material derivative with respect to time, T is temperature, ρc the effective heat capacity per unit volume of the soil fluid mixture and Γ the heat conduction coefficient.

As the problem is one dimensional:

$q_h = -\Gamma \frac{\partial T}{\partial y}$ is the heat flux and the divergence is $div(q_h) = -\Gamma \frac{\partial^2 T}{\partial^2 y}$

The heat balance equation can be written in a form similar to Rice (2006).

$$\frac{\partial T}{\partial t} = \frac{\tau\ \dot{\gamma}}{\rho c} + \alpha_{th} \frac{\partial^2 T}{\partial^2 y} \qquad (3)$$

$$\alpha_{th} = \frac{\Gamma}{\rho c} \text{ : heat diffusivity [m}^2\text{/s]} \qquad (4)$$

For a shear strong discontinuity, the heat input per unit area due friction work in a plane discontinuity is:

$$h(t) = (\sigma_n - p) tan\varphi\ \ v$$

σ_n : Normal stress, p: pore pressure

v : Relative velocity, φ: clay friction angle

2.2 Fluid mass balance

From the fluid mass balance equation (5) obtained in Pinyol and Alonso (2010), the equation (6) can be written as in Rice (2006) without considering volumetric plastic strains (dilatance).

$$-[n\lambda_w + (n-1)\lambda_s]\frac{\partial T}{\partial t} + (n\beta_w + m_v)\frac{\partial p}{\partial t}$$

$$-\frac{K}{\gamma_w}\frac{\partial^2 p}{\partial^2 y} = 0 \quad (5)$$

β_w: fluid compressibility
λ_w: fluid thermal dilation coefficient
λ_s : solid thermal dilation coefficient
n : porosity
m_v: one dimensional compressibility coefficient of the clay

$q_f = -\frac{K}{\gamma_w}\frac{\partial p}{\partial y}$: Darcy fluid flow

K : clay permeability

$$\frac{\partial p}{\partial t} = \Lambda\,\frac{\partial T}{\partial t} + \alpha_h \frac{\partial^2 p}{\partial^2 y} \quad (6)$$

Λ: elastic pressurization coefficient [MPa/^{0}C]

$$\Lambda = \frac{n\lambda_w + (n-1)\lambda_s}{n\beta_w + m_v} \quad (7)$$

If the pore volume compressibility is $\beta_n = nm_v$, the pore volume dilation coefficient is λ_n and the change of porosity due temperature increment is $-n\lambda_n = (n-1)\lambda_s$ the pressurization coefficient can also be written as in Rice (2006).

$$\Lambda = \frac{\lambda_w - \lambda_n}{\beta_w + \beta_n}$$

$\alpha_h = \frac{1}{\beta}\frac{K}{\gamma_w}$: hydraulic diffusivity [m^2/s]

$\beta = n(\beta_w + \beta_n) = n\beta_w + m_v$: volumetric pore fluid storage coefficient

3 FINITE DIFFERENCES SOLUTION

In order to implement Newmark sliding block method it is simpler to use finite differences for discretizing the governing equations in time and space, instead of a convolution of the fundamental Green solutions for temperature and pore pressure. Taking account of the symmetry of the problem, equation (3), without considering the heat input, can be discretized as:

$$T_{i+1}(k) = T_i(k) + r_1 \begin{bmatrix} T_i(k-1) - 2T_i(k) \\ +T_i(k+1) \end{bmatrix} \quad (8)$$

$y = k\,\Delta y$ *k=0,1,2…*
$t = i\,\Delta t$ *i=0,1,2…*
Δt: time increment
Δy: coordinate increment
$r_1 = \alpha_{th}\,\Delta t/\,\Delta y^2$

The stability condition requires $r_1 \leq \frac{1}{2}\Delta t/\,\Delta y^2$

For the case of a discontinuity in the clay layer, the heat input is concentrated and can be introduced using the boundary condition for the temperature gradient at *y=0*, taking account that for each semi-infinite space the heat input is $h_i/2$.

$$T_{i+1}(-1) = T_i(1) + \Delta y\; h_i/\Gamma \quad (9)$$

h_i: heat increment at time step *i*

When we consider a uniform yielded shear band the heat is input using the following source term per unit band volume:

$$\frac{h_i}{2\rho ce}\Delta t$$

which is considered in the finite difference equation (10) only within the shear band:

$$T_{i+1}(k) = T_i(k) + \frac{h_i}{2\rho ce}\Delta t + r_1 \begin{bmatrix} T_i(k-1) - 2 * T_i(k) \\ +T_i(k+1) \end{bmatrix} \quad (10)$$

The finite differences equation which discretize eq. (6) is:

$$p_{i+1}(k) = p_i(k) + \Lambda[T_{i+1}(k) - T_i(k)]\,\Delta t + r_2(p_i(k-1) - 2p_i(k) + p_i(k+1)) \quad (11)$$

$$r_2 = \alpha_h * \Delta t/\,\Delta y^2 \quad (12)$$

Also $r_2 \leq \frac{1}{2}\Delta t/\,\Delta y^2$ for stability of the solution

The thickness of the zones of temperature and pressure increment are small enough to consider only a few coordinate increments Δy for the finite differences solution.

Figure 2 compares the pressure evolution in time at *y=0*, normalized with the initial effective stress σ_0, calculated with finite differences for the discontinuity plane case for two different hydraulic diffusivities. This example corresponds to an infinite slope with factor of safety equal one and parameters of Table 1. An initial small velocity of 10^{-4} m/s is imposed to initiate the sliding without considering earthquake action. Both results are similar in shape and it is important to note the time scaling of pressure evolution as a function of hydraulic diffusivities. Greater hydraulic diffusivity imply more time needed for reaching zero strength.

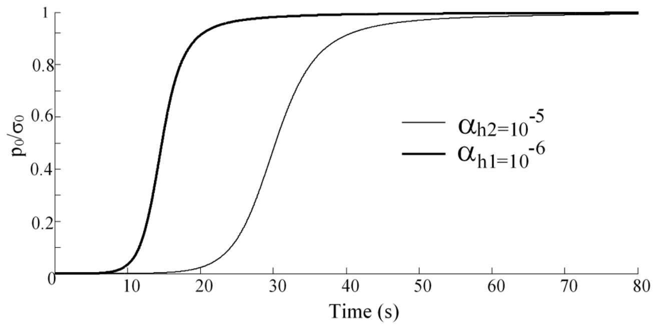

Figure 2. Comparison of normalized pressure calculated with finite differences for two hydraulic diffusivities

The time scale of full pressure development between both results (eq. (12)) can be obtained from equation 16, which is a convolution of the fundamental solution obtained by Lee and Delaney (1987).

$$\frac{t_2^*}{t_1^*} = \left(\frac{C_1}{C_2}\right)^{\frac{2}{3}} \tag{13}$$

$$C_1 = \frac{\Lambda\sqrt{\alpha_{h1}} - \sqrt{\alpha_{th}}}{\alpha_{h1} - \alpha_{th}} \tag{14}$$

$$C_2 = \frac{\Lambda\sqrt{\alpha_{h2}} - \sqrt{\alpha_{th}}}{\alpha_{h2} - \alpha_{th}} \tag{15}$$

$$p(0,t) = \frac{\Lambda\left(\sqrt{\alpha_h} - \sqrt{\alpha_{th}}\right)}{2\rho c\,(\alpha_h - \alpha_{th})} \int_0^t \frac{h(\tau)}{\sqrt{\pi(t-\tau)}} d\tau \tag{16}$$

The pressurization coefficient Λ and heat diffusivity α_{th} are assumed constant. Heat diffusivity, defined by equation (4), is not so variable for different soil-water mixtures, as the hydraulic diffusivity, which depends on permeability and compressibility of the layer. The pressurization coefficient (eq.(7)) depends mainly on the compressibility. If different values are used for this parameter also the time scale for full pressure development can be obtained with eq. (12).

Table 1- Parameters for the comparison of Figure 2

Quantity	Unit	Description
ρc=2.7	MPa/^{0}C	Heat capacity per unit volume of the soil-water mixture
Λ =0.01	MPa/^{0}C	Pressurization coefficient
α_{th}=0.15 e^{-6}	m^2/s	Heat diffusivity
α_{h1}=10^{-6} α_{h2}=10^{-5}	m^2/s	Hydraulic diffusivity
ϕ=12	degree	Clay friction angle
α=12	degree	Slope angle

4 NEWMARK SLIDING BLOCK METHOD WITH THM ANALYSIS

Active forces for dynamic equilibrium of a rigid block on a sliding surface are shown in Figure 3. The sliding surface of inclination α can be a discontinuity or a yielding shear band in a saturated clay layer. In the following it is considered that there is no pre-existent pore pressure.

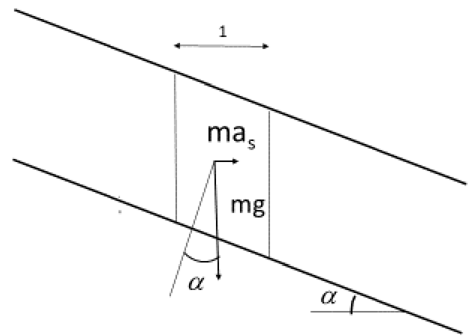

Figure 3. Forces for an infinite slope.

m: mass per unit of sliding surface; $a_{s\,i}$: seismic acceleration for step *i*

$p_{0\,i}$: pore pressure (y=0) in the sliding surface for step *i*

normal effective stress :

$$mg\cos\propto - ma_{s\,i}\sin\propto - p_{0\,i} \tag{17}$$

active force: $mg\sin\propto + ma_{s\,i}\cos\propto$ (18)

friction force: $friction_i = (mg\cos\propto - ma_i\sin\propto - p_0)\tan\emptyset$ (19)

resultant force:

$$fresult_{\ i} = mg\sin\propto + ma_{s\,i}\cos\propto - (mg\cos\propto - ma_{s\,i}\sin\propto - p_0)\tan\emptyset \tag{20}$$

If *fresult* $_i$ > 0 the movement starts and the velocity of the sliding for a step *i+1* is:

$$v_{i+1} = v_i + \frac{fresult_{\ i}}{mass}\Delta t \tag{21}$$

And the heat increment in the finite differences solution is:

$$h_i = friction_i\ v_i \tag{22}$$

The displacements calculation proceed as follow: for a step *i* the resultant force is determined with Eq. (20), velocity with Eq.(21), the heat increment is obtained with Eq.(22), then this quantity is introduced in the differences equations

(9) or (10) according to the case. Temperature is obtained from Eq. (8), or Eq. (10), and pressure from Eq. (11). According to Newmark method the displacements are calculated integrating the velocity until the velocity became zero.

5 ANALYSIS EXAMPLE

An example analysis for an infinite sliding slope is described below in order to quantify the effect of selected parameters. Figure 4 shows the results with the parameters of Table 2, considering that the slip surface is a plane of discontinuity and varying the value of the hydraulic diffusivity α_h.This parameter is practically identical to the consolidation coefficient C_v of the clay layer because the compressibility of water β_w is very low (see eq. (23)). The consolidation coefficient vary strongly with the clay plasticity index and the shrinkage index, (Sridharan and Nagaraj (2004)), mineralogy (Robinson and Allam (1998)), and less with the effective vertical confinement stress since the permeability and the compressibility coefficient decrease at the same time with the consolidation stress.

Table 2- Parameters for the example of Newmark Method THM analysis of Figure 5

Quantity	Unit	Description
ρc=2.7	MPa/^{0}C	Heat capacity per unit volume of the mixture
(1) Λ =0.01	MPa/^{0}C	Pressurization coefficient
α_{th}=0.15 e-6	m^2/s	Heat diffusivity
ϕ=18	degree	Clay friction angle
α=12	degree	Slope angle
a_y=0.10	g	Initial yield acceleration

(1) Pressurization coefficient adopted from literature, Lima et al.(2010), Delage(2013)

$$\alpha_h = \frac{1}{n\beta_w + m_v}\frac{K}{\gamma_w} \cong \frac{1}{m_v}\frac{K}{\gamma_w} = C_v \qquad (23)$$

Two values of hydraulic diffusivity α_h have been selected from the range of values of the consolidation coefficient reported in the literature, Delage (2013). Figure 4 shows the accelerogram selected for this example, which corresponds to the CHY080 record of the Taiwan earthquake (PEER(2020)) the yield acceleration (a_f=0.10g), and the velocity and displacement for

$\alpha_{h1} = 10^{-5}\,\frac{m^2}{s}$ and $\alpha_{h2} = 10^{-6}\,\frac{m^2}{s}$. In the first case the displacement obtained is 2.15m and in the second, the slope is unstable at the end of the earthquake producing a catastrophic slide. Figure 5 compares the temporal development of pore pressure, normalized with the initial effective stress on the slip surface, for both cases. In the second case the pore pressure reaches the effective pressure during the earthquake and reduce the frictional strength to zero without time for pore pressure dissipation due to the lower permeability of the clay.

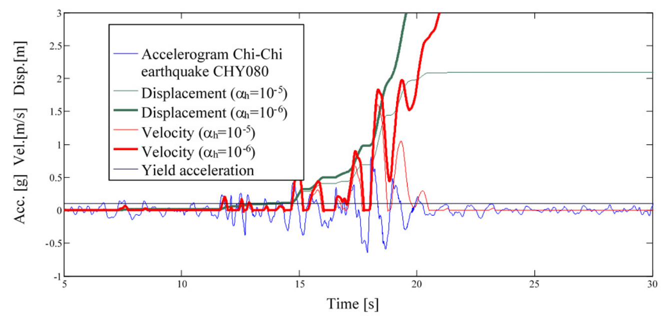

Figure 4.Velocity and displacement for different hydraulic diffusivities (af=0.10g)

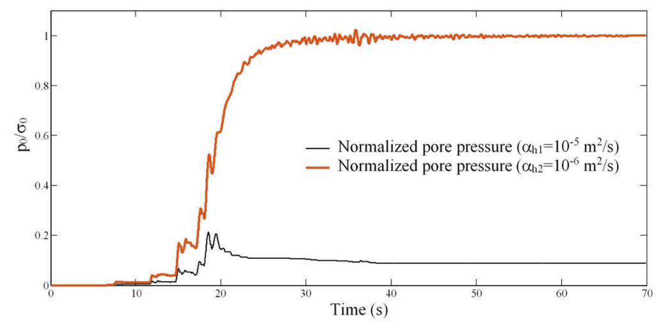

Figure 5.Normalized pore pressure increase for different hydraulic diffusivities (a_f=0.10g).

6 CONCLUSIONS

A methodology has been developed to take into account thermo-hydro mechanical coupling with a sliding block analysis of an infinite slope during an earthquake. Preliminary results indicate that the possibility of triggering a catastrophic sliding of a slope over a saturated clay layer during an earthquake depends strongly on the diffusivity of the clay which is directly related to the consolidation coefficient. The lower the permeability of the clay or the higher the volumetric compressibility, the longer the pore pressure dissipation time and greater the possibility of catastrophic sliding. The coefficient of pressurization, which can take values for different materials between 0.01 and 1 MPa/ºC (Delage (2016)) also directly influences the pore pressure development as indicate Eq. (16), in this case the greater the volumetric compressibility of the clay, the lower the coefficient of pressurization.

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