The Influence of Shear Heating on the Development of Creeping Landslides

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Abstract

Large-scale landslides may exhibit a creeping phase possibly followed by catastrophic failure. An example of a landslide that exhibited such behaviour was the Vaiont landslide that occurred in Italy, 1963, where the final phase of catastrophic collapse was preceded by several months of creep. Shear heating of the slip plane is a possible mechanism that has been invoked to explain the severity of the final collapse, however its possible effect on the creeping phase has not been fully investigated. In this context we present a model for the creeping movement of a landslide idealized as a rigid mass sliding on a thin clay layer. Heat production and excess pore pressure generation due to frictional heating, as well as their diffusion, are taken into account. The behaviour of the clay is modelled using rate process theory, which is a general theory quantifying time-dependent soil deformation on the basis of micromechanical considerations. As a first step, uniform infinite slopes are considered and the model is used to explore factors that influence the transition from an initial phase of creep to a final catastrophic phase.

Keywords

Rate process • Frictional heating • Creeping landslides

264.1 Introduction

Despite their importance, the mechanisms due to which some slides acquire high velocity leading to catastrophic failure are not fully understood. Frictional heating has been identified as a possible cause (Anderson 1980; Habib 1975; Vardoulakis 2000, 2002; Veveakis et al. 2007), assuming that heat produced due to friction leads to rising temperature, build-up of pore pressure and possible thermoplastic collapse of the soil and allows the slide to accelerate.

Few landslide models that take into account the effect of frictional heating exist in the literature (Alonso et al. 2010; Cecinato and Zervos 2012; Cecinato et al. 2008, 2011; Vardoulakis 2000, 2002; Veveakis et al. 2007). Most of these, however, are concerned with the final stage of catastrophic movement and ignore the very slow, creep-like movement often observed over a long period of time. In this paper we are concerned with the transition from a regime of creep-like movement to final catastrophic collapse. The advantage of the presented landslide model is that, it incorporates the time dependent behavior of soils using the concept of rate process theory, where the concept of thermal activation is inherently included. In the following, in Sect. 264.2 we present the landslide equations and the numerical implementation. Some computational results and discussion and conclusions are presented in Sects. 264.3 and 264.4 respectively.

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264.2 Landslide Model and Numerical Implementation

In this section we derive a landslide model based on that developed by Vardoulakis (2002). All deformation is assumed concentrated on a thin clay layer overlain by the sliding mass.

Temperature (θ) inside the shear band is governed by a diffusion equation:

$$\frac{\partial \theta}{\partial t} = \kappa_m \frac{\partial^2 \theta}{\partial z^2} + \frac{D}{j(\rho C)_m} \tag{264.1}$$

where κ_m the thermal diffusivity of the soil and the last term is a dissipation term, where D is the amount work converted into heat and $j(\rho C)_m$ is the thermal constant of the soil water mixture. The excess pore pressure (u) is governed by a similar diffusion equation:

$$\frac{\partial u}{\partial t} = \frac{\partial}{\partial z}\left(c_v \frac{\partial u}{\partial z}\right) + \lambda_m \frac{\partial \theta}{\partial t} \tag{264.2}$$

where c_v is the temperature-dependent consolidation coefficient and λ_m the pressurization coefficient, which quantifies heat-induced excess pore pressure. The dynamics of the sliding mass can be described as:

$$\frac{dv_d}{dt} = g\left(\sin(\psi) - \frac{\tau}{\gamma H}\right) \tag{264.3}$$

where g is the acceleration of gravity, ψ is the angle of the slope and τ the (uniform) shear stress within the shear band. γ and H are the unit weight of the soil and the thickness of the sliding mass respectively.

Rate process theory considers the movement of "flow units" such as atoms or molecules and was developed by Eyring (1936). It has been applied to soils by Kuhn and Mitchell (1993), Mitchell et al. (1968), Mitchell (1964) and Feda (1989) among others. The movement of flow units is opposed by an energy barrier called activation energy, U_0; if enough energy to exceed U_0 is supplied by an external source, the unit will move causing deformation. This energy source can be e.g. a heat source or an applied stress. The shear strain rate is written as (Feda 1989):

$$\dot{\gamma} = F_1(\theta) \exp\left(F_2(\theta)\frac{\tau}{S}\right) \tag{264.4}$$

where $F_1(\theta) = \frac{k}{h}\exp\left(-\frac{U_0}{R\theta}\right), F_2(\theta) = \frac{\lambda}{2k\theta}$, S the number of bonds per unit area (or number of flow units), which depends on the normal effective stress $\sigma_n^{'}$, and τ the applied shear stress. k is Boltzmann's constant $(1.38 \times 10^{-23} JK^{-1})$, θ the absolute temperature (K) and h is Planck's constant $(6.624 \times 10^{-34}\,\mathrm{Js}^{-1})$. Assuming a linear velocity profile inside the shear band, the velocity of the sliding mass is $v_d = \dot{\gamma} d_b$ where d_b is the shear band thickness. Solving Eq. 264.4 for τ and substituting into Eq. 264.3 gives the dynamic equation as follows:

$$\frac{dv_d}{dt} + \frac{g}{\gamma HA} S\, In(v_d) = g\sin(\psi) + \frac{g}{\gamma HA} S\, In(F_1(\theta)d_b) \tag{264.5}$$

and the heat dissipation term D as:

$$D = \frac{S}{A} In\left(\frac{v_d}{d_b F_1(\theta)}\right)\frac{v_d}{d_b} \tag{264.6}$$

The non-linear heat and pore pressure equations were discretized using a Backward–Time Centered–Space (BTCS) implicit scheme which is unconditionally stable. The initial and boundary conditions were taken as follows;

$$\theta(\pm\alpha, t) = \theta_{ref} = 12.5\,^{\circ}\mathrm{C} \qquad \theta(z,0) = \theta_{ref} = 12.5\,^{\circ}\mathrm{C}$$
$$u(\pm\alpha, t) = 0 \qquad u(z,0) = 0$$

The initial condition for the velocity was calculated using the initial shear stress τ_0 at the onset of sliding as: $v_d(0) = F_1(\theta)\exp\left(F_2(\theta)\frac{\tau_0}{S}\right)d_b$.

The system of equations was solved with the stress state obtained from the Vaiont slide (Hendron and Patton 1985). The average slope angle was taken as 22°. The spatial domain for the diffusion equations was set to 20 times the shear band thickness. As a base line case, an analysis was carried out using the parameters given in Mitchell et al. (1968) ($U_0 = 128.5\,\mathrm{kJ/mol}, S_0 = 1.1 \times 10^9\, bonds/(\mathrm{m}^2\mathrm{Pa})$ and $\lambda = 2.8 \times 10^{-10}\,\mathrm{m}$). The shear band thickness (assumed as 1.4 mm), heat and pore pressure equation parameters ($\kappa_m = 1.45 \times 10^{-7}\,\mathrm{m}^2/\mathrm{s}$, $c_v = 7.5 \times 10^{-8}\,\mathrm{m}^2/\mathrm{s}$, $j(\rho C)_m = 2.84\,\mathrm{MPa}/^{\circ}\mathrm{C}$ and $\lambda_m = 0.012\,\mathrm{MPa}/^{\circ}\mathrm{C}$) were taken in line with Vardoulakis (2002). An investigation of the sensitivity of the results with respect to "standard" geotechnical parameters is reserved for a future study. In the following, we investigate sensitivity with respect to the non-standard rate process parameters by varying them within reasonable ranges.

264.3 Results and Discussion

Figure 264.1 present the time evolution of excess pore pressure at the middle of the shear band and the slide velocity for the baseline case. The maximum temperature rise is practically zero (2 × 10^{-4} °C) and so is the maximum excess pore pressure (1 Pa, dropping to zero after 8000 s). The velocity plot shows that, after a transient period, the block is

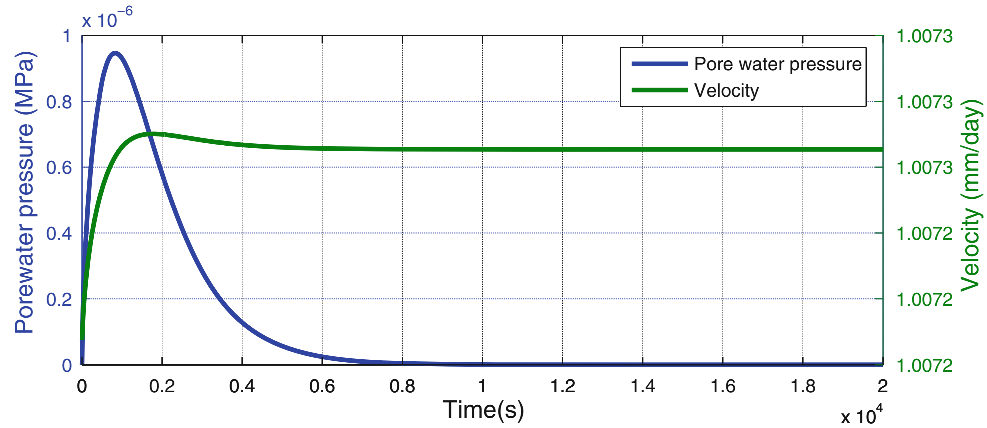

Fig. 264.1 Excess pore pressure at mid- shear band, velocity of the sliding mass; baseline case

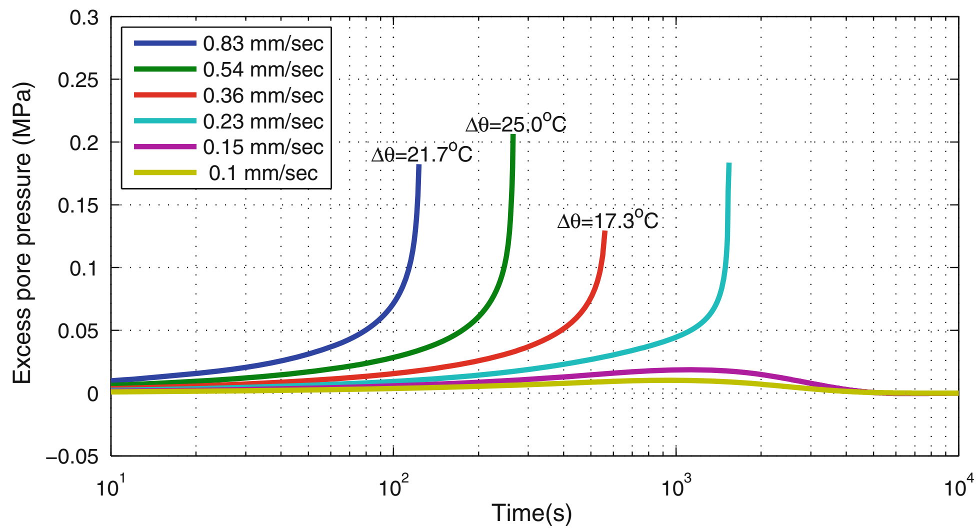

Fig. 264.2 Excess pore pressure at mid- shear band for different initial velocities

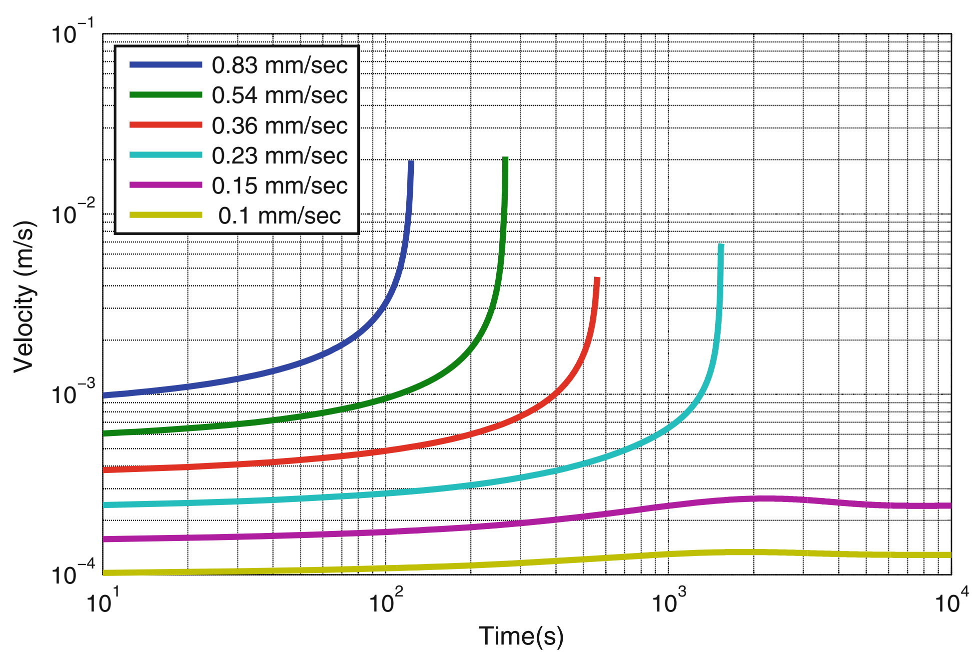

Fig. 264.3 Velocity plot for different initial velocities

predicted to reach a steady state of creep at 1 mm/day; this is in the range of realistic velocities for a creeping slide.

To investigate the possible transition to a catastrophic phase the activation energy was varied; this meant a different initial velocity, consistent with Eq. 264.4. The pore pressure at the middle of the shear band for a range of initial velocities is presented in Fig. 264.2 with the corresponding temperature rise. It can be clearly seen that, for the parameters used here, an initial velocity above 0.2 mm/s leads to a catastrophic phase as shown in Fig. 264.3.

The activation energy and the number of bonds per unit area have significant impact on the predicted initial velocity. For low initial velocity, i.e. higher activation energy and number of bonds, the model predicts a steady state as any heat generated dissipates without a significant temperature increase. Higher initial velocity, however, leads to temperature build-up and causes the slope to accelerate.

264.4 Conclusion

Rate process theory offers a possible framework for describing the transition between creep and catastrophic failure of a landslide. The results presented show a threshold velocity separating the creep and collapse regimes, beyond which positive thermal feedback leads to the final failure. The results presented here were found to be sensitive to the values of the rate process parameters used.

In the creep phase temperature effects are less important, as energy dissipation and heat production are low. Therefore frictional heating on its own is not predicted to cause the collapse of a slope; other external actions, such as dynamic loading or pore pressure increase, need to be invoked to push the velocity over the threshold. Once the threshold is exceeded, however, frictional heating is predicted to facilitate catastrophic collapse.

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