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Technical Note

Production of frictional heat and hot vapour in a model of self-lubricating landslides

By

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1. Introduction

Since the work of Heim (1932) we know that the apparent friction resistance of large landslides is only poorly related to the frictional coefficient of the bulk rock. In small-scale experiments with granular flows it is found that $\mu \equiv \tan\phi_0 \approx \Delta H/R$ where μ is the friction coefficient of bulk rock (often expressed in terms of the friction angle ϕ_0), R is the horizontal run-out of the centre of mass, and ΔH is the vertical height of fall. In contrast, large landslides usually travel with a smaller effective friction than the bulk value, $\Delta H/R < \tan\phi_0$ (Scheidegger, 1973), which implies greater run-outs and velocities than expected. Hence, the idealized picture of a landslide as a gigantic granular flow does not properly account for its enhanced mobility.

Numerous suggestions have been put forward to explain the anomalous mobility of large landslides. Some researchers have suggested mechanisms based on lubrication by an air layer trapped underneath the landslide (Shreve, 1968), acoustic fluidization due to high-frequency acoustic waves travelling through the granular medium (Melosh, 1979), dispersive forces exerted by powder-sized grains (Hsü, 1975), mechanical fluidization (Davies, 1982; Campbell et al., 1995; Straub, 2001).

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Geological data show that during the flow of a landslide, the highest shear rates are concentrated within a thin shear layer located deep into the landslide, whereas the upper cap remains relatively undisturbed (see Shreve, 1968; Erismann and Abele, 2001). Evidence is provided by shallow geological structures remaining in place during the mass failure, which is suggestive of a passive transport on top of the shear layer (see for example Erismann and Abele, 2001). In this region, intense frictional heat may be produced, possibly leading to melting in non-carbonate rocks (Erismann, 1979; Sørensen and Bauer, 2003).

Water is common in failed landslide masses, and it often contributes to the initial failure. It is easy to calculate that the heat generated in the slippage plane is such that water (if present in the crushed rock), will be quickly brought to the boiling point and transform into vapour (see the Appendix). It has been suggested independently by Habib and Goguel that the consequent build of vapour pressure could act as a lubricant in the shear layer, thus increasing the landslide mobility (Habib, 1975; Goguel, 1976, 1978). The question is under what conditions this increase in pressure will be sufficient to reduce friction.

Some researchers have emphasized the role of water in landslide mobility (see for example Legros, 2002), and a few have developed analytical or numerical models to study the process of failure at relatively low temperature in particular field cases (Voight and Faust, 1982; Vardoulakis, 2000; Aharonov and Anders, 2006). However, no systematic work has assessed the viability and generality of vapour formation as a mechanism for reducing the friction during landslide flow, nor has the dependence on the important parametres, such as water content and permeability of the medium, been studied in detail. Purpose of this paper is to investigate the Goguel-Habib model of vapour lubrication by introducing a numerical model for the equation of motion of a model landslide coupled with the equations for the diffusion of vapour and heat at the sliding interface.

2. The model

For simplicity we envisage a landslide as a slab of constant thickness H. In accord to geological evidence, the landslide is composed of broken rock and moves rigidly (hence the illustration as a ‘‘slab’’) on top of a shear layer where frictional heat is produced. Without vapour generation the shear stress resistance at the level of detachment has the form of a Coulomb frictional term, $\tau = \rho\,\mathrm{gHcos}\,\beta \tan\phi_0$ where $\rho, \mathrm{g}, \beta, \phi_0$ are the density, gravity acceleration, slope angle and friction angle, respectively. If hot vapour at pressure P_0 builds up at the level of detachment, the effective shear stress reduces to a value $\tau = [\rho\,\mathrm{gHcos}\,\beta - P_0]\tan\phi_0$. In this case the equation of motion for the slab becomes

$$\frac{dU}{dt} = g\left[\sin\beta - \left(\cos\beta - \frac{P_0}{\rho g H}\right)\tan\phi_0\right] - \frac{1}{2}\frac{\rho_{\mathrm{air}}}{\rho} C_D\, V^{-1/3}\, U^2 \qquad (1)$$

where U is the velocity of the landslide along the slide path. The last term is the drag force exerted by air ($\mathrm{C_D}, \rho_{\mathrm{air}}$, V are a drag coefficient, the air density and the landslide volume). This contribution turns out to be very small.

The frictional heat produced per unit time and unit area flowing in the upper half of the sliding plane is calculated explicitly as

$$\dot{E}_{\mathrm{diss}} = e[(\rho g H \cos\beta - P_0)\tan\phi_0 U] \tag{2}$$

The factor e accounts for the fact that only half of the heat produced flows into the upper part of the sliding plane. Additionally, there may be dissipation processes not resulting in local heating. Energy may be transferred away from the sliding plane, for example in form of acoustic waves, and moreover some amount of energy is also used up in the disintegration of the mass, especially when grains become very small (King, 2001). It is thus difficult to estimate this parametre at the present stage; here a fixed value will be used in the calculations.

The calculated value for $\dot{E}_{\mathrm{diss}}$ enters as a boundary condition of the energy flux in the upper portion of the landslide as

$$\left(\frac{\partial T}{\partial y}\right)_{y=0} = -\frac{\dot{E}_{\mathrm{diss}}}{\chi} \tag{3}$$

where T is the temperature, χ is the thermal conductivity and y is the coordinate perpendicular to the interface between the slab and the ground ($y = 0$ at the interface). In the absence of water at the interface, the heat would propagate following a standard diffusion equation. However, as discussed earlier, most country rocks are normally rich in water. Hence, when the failure takes place, the rock disintegrates and the water is allocated more or less uniformly in the pores of the crashed granular aggregate. It is assumed that frictional heat diffusing through the material will bring water to the boiling point and then to dry hot vapour.

To account for the water-vapour phase transition in the early phase, the following prescription is used in the computer calculation. When the transition point is reached at some location, the local temperature is kept constant until the accumulated heat density has attained an amount $\lambda_m \rho_{0w}$ where ρ_{0w} is the initial water density and λ_m is the latent heat for water-vapour transformation. The effect is very small owing to the little water amounts considered (and corresponds to a cooling of the rocky material by less than 2–3°), but could become more important for greater water content.

The equation for the heat flow inside the granular medium is (see e.g. Bear, 1972; Pruess, 1997; Woods, 1999)

$$\frac{\partial T}{\partial t} - \frac{\chi}{\rho_s c_s (1-\Theta)} \frac{\partial^2 T}{\partial y^2} = -\frac{\rho_v c_v}{\rho_s c_s} u_v \frac{\partial T}{\partial y} \tag{4}$$

where c_s, c_v is the specific heat of the solid and vapour, respectively, Θ is the porosity, and the conductivity

$$u_v = -\frac{k_v}{\mu_v} \frac{\partial P}{\partial y} \tag{5}$$

represents the velocity of vapour in the porous medium as derived from Fick's law, k_v is the permeability of the medium, μ_v is vapour viscosity. The two terms in the heat flow in Eq. (4) account for conduction and advection, respectively.

From the equation of continuity, the density of vapour changes as

$$\frac{\partial \rho_v}{\partial t} = \frac{k_v}{\mu_v \Theta}\left[\frac{\partial P}{\partial y}\frac{\partial \rho_v}{\partial y} + \rho_v \frac{\partial^2 P}{\partial y^2}\right] \tag{6}$$

The relationship between pressure, density and temperature of the heated vapour is provided with sufficient accuracy by the equation of state for a perfect gas, $P = \kappa \rho_v T$ with $\kappa = 460\,\mathrm{J\,kg^{-1}\,K^{-1}}$. Finally note that the hypothesis of little water content implies that the saturation (i.e., the fraction of pores filled with water) will go rapidly to zero when vapour diffusion commences. For this reason the theory (Eqs. (4–6)) has been written for the relative permeability of vapour equal to one; for much higher water contents the theory should be extended to account for the coexistence of water and vapour gaseous phases, see Bear (1972) and Turcotte and Schubert (2001).

3. Results

A computer program was written to solve iteratively Eqs. (1–6) using a finite time step and a discrete vertical mesh for the coordinate y. The initial water density ρ_{0w}, the thickness of the simulated landslide, and the slope path are fixed for each simulation,

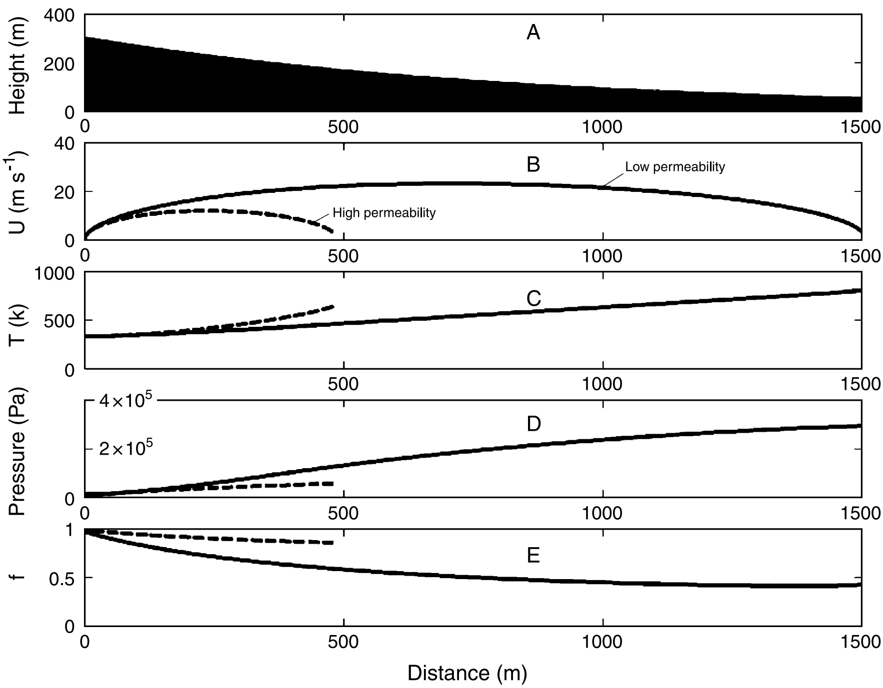

Fig. 1. Results of the slab model. From the top: A: the artificial sliding profile, B: the velocity of the centre of mass of the slab, C: the maximum temperature, D: the maximum vapour pressure, E: the parametre f (see text). All the quantities are plotted as a function of the horizontal distance reached by the centre of mass of the simulated landslide. The input parametres are $H = 20\,\mathrm{m}$; $\tan\phi_0 = 0.3$; $e = 0.3$; $\Theta = 0.3$; $\rho_{0w} = 4\,\mathrm{kg\,m^{-3}}$; $C_D = 0.4$; $V = 120{,}000\,\mathrm{m^3}$. Permeability: $k_V = 10^{-12}\,\mathrm{m^2}$ (*dashed*) and $k_V = 10^{-17}\,\mathrm{m^2}$ (*full line*)

whereas the initial temperature slightly decreases with height. Figure 1 shows the results of two simulations for a 20 m high block with two different permeability values. With relatively high permeability value ($k_V = 10^{-12}\,m^2$, dashed line) vapour is capable of percolating through the granular medium, whereas with low permeability ($k_V = 10^{-17}\,m^2$, full line) vapour density evolves very slowly.

Panels A and B show, respectively the artificial slope path used in the calculations and the velocity as a function of the position. With high permeability the block receives very little lubrication and so the motion is similar to the one of a pure frictional material. In contrast, when permeability is low, the block benefits from a substantial pressure increase at the interface with the bed, allowing it to move much longer and with higher speed. The temperature close to the interface (panel C) increases more rapidly with high permeability, where lubrication is small and friction becomes greater.

The pressure (panel D) dissipates rapidly in the case of greater permeability. If the permeability is small, the density remains constant and thus a temperature increase determines a pressure growth. Finally, panel E shows the fractional change in frictional resistance due to the lubrication effect $f = \Delta\tau/\tau_0 = 1 - P_0/[\rho g H \cos\beta]$. When the permeability is high, this ratio remains always very close to unity, signifying a minor role of lubrication. Note that the apparent friction coefficient found in the simulation ($(\Delta H/R)_{\mathrm{simulated}} \approx 0.2$) falls in the range of observed values for long-runout landslides (Scheidegger, 1973), even though such low values are usually reported for exceptionally large landslides of greater thickness.

Figure 2 shows the vapour pressure distribution in proximity of the interface for the two same cases as before, and further elucidates the physical basis for the lubrica-

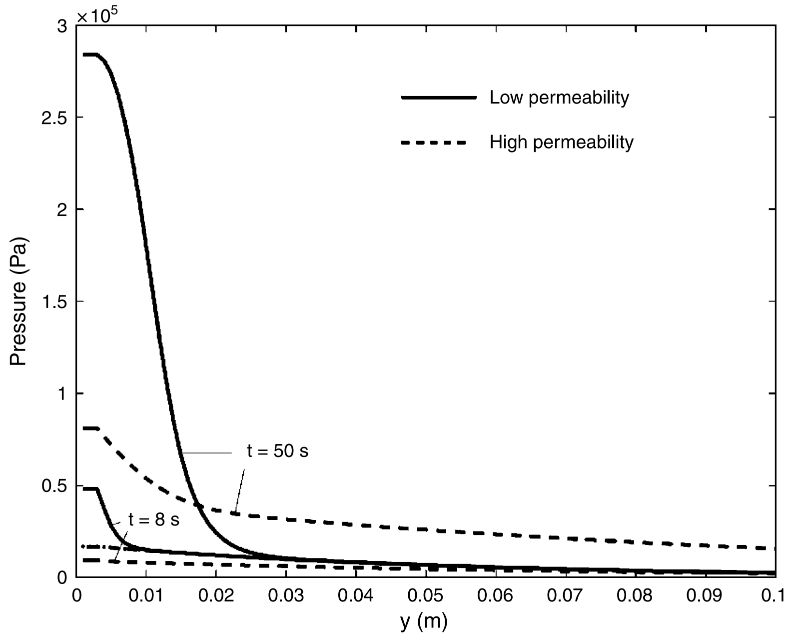

Fig. 2. Pressure profiles at the interface of the sliding mass after 8 s and 50 s

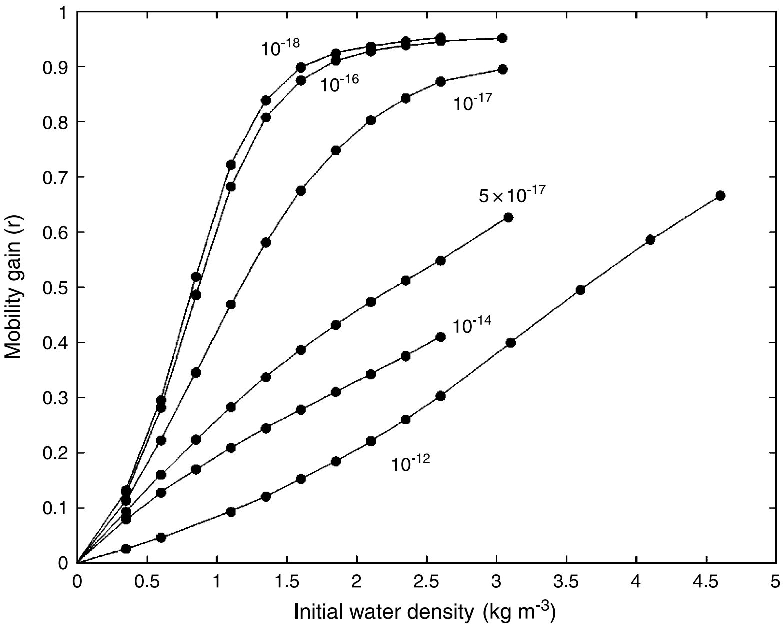

Fig. 3. Calculated values of the ratio $r = 1 - \tan\phi/\tan\phi_0$ as a function of initial water density ρ_{0W} for the reported values of the permeability

tion effect. One can notice the loss of pressure for the case with high permeability (dashed) due to the vapour percolation in the granular medium. With low permeability (full line), the vapour density remains constant; frictional heating raises the vapour temperature and the pressure P_0 builds up. As a consequence, the effective pressure $\rho g H \cos\beta - P_0$ diminishes (see Eq. (1)) and the frictional resistance plummets. It should be noted that in Eq. (4) the advective term on the right hand side contributes to less than 1% to the temperature derivative, which is thus dominated by the conduction.

The permeability k_V and the initial water density ρ_{0w} are both quite uncertain. To assess their role in the model, calculations were performed varying these parametres in conjunction. The results are gathered in Fig. 3, where the ordinate scale reports the quantity $r = 1 - \phi/\phi_0$ as a function of ρ_{0w} for different values of k_V. An efficient vapour lubrication effect is signalled by $r \approx 1$ where ϕ is the apparent friction coefficient calculated as the ratio of vertical to horizontal displacement of the slab (in the absence of lubricating effect ϕ coincides with ϕ_0). Clearly, the results in Fig. 3 confirm that both ρ_{0w} and k_V play an important role. With the input parametres used here, vapour lubrication takes place if the crushed rock contains at least $\sim 2\,\mathrm{kg\,m^{-3}}$ of water, even with permeability as high as $10^{-14}\,\mathrm{m}^2$. With permeability of $10^{-17}\,\mathrm{m}^2$ or less, vapour will enhance mobility even with a very modest amount of water. Calculations with greater permeability result in a very small or even negative value for r, which signifies the absence of the lubrication effect (the negative values can be ascribed to the effect of the drag force). Note also that the water content is independent of the porosity of the crushed rock. This is because water impregnated the intact rock before the failure (and so it may be related to rock porosity *before* the landslide took place), whereas the porosity Φ entering into Eqs. (4) and (6) derives from the properties of the crushed rock.

What value of permeability should we consider for the crushed rock? The hydraulic conductivity in the large landslide deposits of Val Pola (mostly gneissic material) has been recently determined by Crosta et al. (2007). Measured values vary between $10^{-6}\,\mathrm{m\,s^{-1}}$ and $10^{-3}\,\mathrm{m\,s^{-1}}$, corresponding to permeability $10^{-13}\,\mathrm{m^2} < k_V < 10^{-10}\,\mathrm{m^2}$, with wide deviation from the average and a systematic decrease with depth due to reduce of grain size. Concerning the dependence on the rock type, a softer rock will disintegrate to smaller grains, which results in lower permeability. The grain size of broken rock scales approximately like $d \propto W^2$ where W is Bond's index, a measure for rock resistance to breaking (Locat et al., 2006; Crosta et al., 2007; De Blasio, 2005) and hence the permeability goes like $k_V \propto W^4$.

Thus the permeability of a landslide deposit composed of limestone can be expected to be ≈ 0.16 smaller than for a hard rock like gneiss, the other conditions being the same (possible variations of the Bond index between different kinds of limestone and gneiss is neglected in this estimate). The difference in composition is thus likely to give an extra order of magnitude variation in the permeability. Tentatively, permeability values may be expected to range between $k_V \approx 10^{-12}$–$10^{-14}\,\mathrm{m^2}$ up to 10^{-10}–$10^{-9}\,\mathrm{m^2}$. According to the present calculations, efficient vapour lubrication is likely to occur only for the lowest values. A further uncertainty is worth mentioning. The estimated values of permeability are based on the properties of the deposit, whereas the permeability in the slippage plane might be substantially different.

To conclude, it has been shown that the vapour lubrication effect is theoretically possible in a travelling landslide only if the permeability is very small and the water quantity sufficiently high. More systematic calculations should assess the role of the different parametres and include the landslide disintegration and stretching. Future field surveys of landslide deposits should also focus on systematic measurements of the water content and permeability (Crosta et al., 2007).

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Appendix

This appendix presents a plain estimate of the frictional heat involved in the shear zone of a travelling landslide and of the time needed to reach the temperature of water vapourization. The frictional heat flux (energy produced per unit surface and unit time) at the base of the sliding slab is $\mathrm{J} \approx \mathrm{e}\rho\mathrm{gH}\cos\beta\tan\phi_0\mathrm{U}$ where g is the gravity acceleration, ρ is the density, H is the thickness of the landslide, and β is the slope angle. After a time τ from the start of the slippage, the heat has travelled a length of about $\delta \approx [\chi\tau/(\rho\mathrm{C})]^{1/2}$ on each side of the sliding plane, where C, χ are the specific heat and the thermal conductivity, respectively. Thus the average temperature after a time τ is about $\langle\Delta\mathrm{T}\rangle \approx \frac{1}{\delta\mathrm{C}\rho}\int_0^\tau \mathrm{J}\,\mathrm{dt} = \frac{1}{2}\mathrm{e}\,\mathrm{g}^2\mathrm{H}\cos\beta\tan\phi_0(\sin\beta - \cos\beta\tan\phi_0)\left(\frac{\rho}{\chi\mathrm{C}}\right)^{1/2}\tau^{3/2}$. With the values

$$H = 20\,\mathrm{m};\quad \tan\phi_0 = 0.3;\quad \beta = 45°;\quad \chi = 2.5\,\mathrm{W\,m^{-1}\,K^{-1}};\quad C = 10^3\,\mathrm{J\,kg^{-1}\,K^{-1}};$$
$$\rho = 2.7\times10^3\,\mathrm{kg\ m^{-3}};\quad e = 0.3$$

it is found that the time needed to increase the temperature by $\langle\Delta\mathrm{T}\rangle = 100\,\mathrm{K}$ is about 2–3 s. The energy flux after this elapsed time is of the order $\approx 2\times10^4\,\mathrm{W\,m^{-2}}$.