Engineering Geology 157 (2013) 124–132

Contents lists available at SciVerse ScienceDirect

Engineering Geology

journal homepage: www.elsevier.com/locate/enggeo

The hypermobility of huge landslides and avalanches

Shiva P. Pudasaini [a,b,*], Stephen A. Miller [a]

[a] Department of Geodynamics and Geophysics, Steinmann Institute, University of Bonn, Meckenheimer Allee 176, D-53115, Bonn, Germany
[b] School of Science, Kathmandu University, P. O. Box: 6250, Kathmandu, Nepal

ARTICLE INFO

Article history:
Received 13 August 2012
Received in revised form 2 January 2013
Accepted 12 January 2013
Available online 4 February 2013

Keywords:
Hypermobility
Huge landslides and avalanches
Terrestrial and extraterrestrial avalanches
Extreme travel distances
Physical modeling and model validation
Fluidization

ABSTRACT

Catastrophic failure of large land masses, which generate landslides, rockfalls and debris avalanches, can have hazardous consequences extending far beyond the source. Observations show that the mobility of such events depends strongly on the volume for volumes larger than 10^6 m^3, with many different processes invoked to explain higher mobilities (hypermobility) for both terrestrial and extraterrestrial events. Although the mobility of large events has been extensively studied, there is no generally accepted mechanism for predicting extreme travel distances because the underlying physical processes are poorly understood. Here we show using physical and rheological arguments that the wide scatter observed for very large mass wasting events in all environments collapses to a single relationship between event volume or inundation area and mobility. Hypermobility is defined to be the reciprocal of the effective friction coefficient μ_e, where the scale-dependent μ_e is derived analytically as a function of the mechanical, volumetric and topographical parameters of the flow. The dominant term in the coefficient is the degree of fluidization involved in the flow; our results show that fluidization is limited in extraterrestrial events, that significant fluidization occurs in non-volcanic and volcanic events, and fluidization dominates submarine events. This analysis demonstrates that fluidization is associated with long run-out distances, and that the degree of fluidization can be predicted by the volume, and physical and topographic parameters. The methodology is simple, physically-based and validated with datasets of very large terrestrial and extraterrestrial avalanche events. We demonstrate that the effective Coulomb friction rheology and the hypermobility function are applicable to avalanche events of any size, providing an opportunity to simulate past and/or potential huge landslide and debris avalanche events, run-out distances, destructive impact and assessment of risk. The model can be used to estimate the overrun area and volume in terms of known mobility data.

1. Introduction

A major concern in mass flow dynamics is understanding the physical processes operating during large volume landslides, avalanches, debris flows and rock falls with exceptionally long run-out distances (here called hypermobility). The large volume events can generate extremely mobile gravity-driven debris avalanches capable of traveling horizontal runout distances (L) as far as 30 times their vertical fall height (H) at velocities up to 100 ms^{-1} (Legros, 2002). These events involve up to 10^{12} m^3 of debris, sometimes traveling hundreds of kilometers over topographic slopes as low as 1° (Shreve, 1966; Howard, 1973; Voight, 1978, 1988; Keefer, 1984; Beget and Kienle, 1992; Siebert, 1992; Dade and Huppert, 1998; Legros, 2002; Sosio et al., 2012). The final debris deposit can be tens to hundreds of meters thick over areas of tens of thousands square kilometers (Howard, 1973; Lucchitta, 1978, 1979; Voight, 1978; Crandell et al., 1984; Keefer, 1984; Francis et al., 1985; Siebert et al., 1987; McEwen, 1989; Beget and Kienle, 1992; Siebert, 1992; Stoopes and Sheridan, 1992; Dade and Huppert, 1998; Legros, 2002; Kelfoun and Druitt, 2005; Davies et al., 2010; Sosio et al., 2011). An extensive list of transport mechanisms has been proposed to explain reduced friction and the hypermobility of large avalanches, including fine powders at the base, interstitial fluids, pore fluid pressure, air pockets, dispersive grain flow, local steam generation, frictionites, lubrication, fluidization, entrainment, oscillation, and dynamic fragmentation (Kent, 1966; Shreve, 1966; Howard, 1973; Hsu, 1975; Lucchitta, 1978, 1979; McSaveney, 1978; Davies, 1982; McEwen, 1989; Iverson, 1997, 2005; Davies and McSaveney, 1999; Legros, 2002; Collins and Melosh, 2003; Campbell, 2006; Mangeney et al., 2007; Pudasaini and Hutter, 2007; Deganutti, 2008; Cagnoli and Quareni, 2009; McSaveney and Davies, 2009; Davies et al., 2010). Although many of these mechanisms are appropriate to some site-specific landslides and debris avalanches, no one dominant mechanism stands out as an explanation for the hypermobility.

Classical mobility approaches (Dade and Huppert, 1998; Calder et al., 1999; Legros, 2002) do not explain the mass-dependence of the

* Corresponding author at: Department of Geodynamics and Geophysics, Steinmann Institute, University of Bonn, Meckenheimer Allee 176, D-53115, Bonn, Germany. Tel.: +49 228 73 24 66.
E-mail address: pudasaini@geo.uni-bonn.de (S.P. Pudasaini).

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http://dx.doi.org/10.1016/j.enggeo.2013.01.012

hypermobility of large avalanche events. Coulomb friction rheology is effective in modeling small volumes (see, e.g., Iverson, 1997; Denlinger and Iverson, 2001; Pitman et al., 2003; Pudasaini and Hutter, 2003; Pudasaini and Kroener, 2008; Pudasaini et al., 2005, 2008; Pudasaini and Domnik, 2009; McDougall and Hungr, 2004; Ancey, 2005; Pitman and Le, 2005; Jop et al., 2006; Mangeney et al., 2007), but modeling large mass flows is inhibited because the appropriate values for the effective friction coefficient and effective stress are unknown and unconstrained (Dade and Huppert, 1998; Legros, 2002; Pudasaini and Hutter, 2007). Furthermore, a realistic rheological model should systematically include the physical, volumetric and topographical effects, and most importantly, determine whether and how the flow rheology depends on the mass. For a moving mass, H/L represents the (scale-free) coefficient of Coulomb sliding friction (Dade and Huppert, 1998; Legros, 2002). The inverse quantity, L/H is the measure of the mobility of the debris avalanches. This mobility is the basic parameter for estimating the areas at risk from debris avalanches, however, field data (see, e.g., Dade and Huppert, 1998; Legros, 2002; Deganutti, 2008; Sosio et al., 2011, 2012) show that simple Coulomb friction fails to predict the large event mobility because the volume of large events must be coupled with the topography of the inundation area and other physical parameters. Since the friction coefficient is substantially reduced during debris avalanches with exceptionally long travel distances, it must explicitly include a length scale, such as volume, inundation area, and topographic constraints. The friction coefficient must also include the intrinsic (true) frictional behavior of the material. In a well-known paper, Dade and Huppert (1998) propose relationships between an assumed uniform triangular inundation area with a constant shear stress (τ) and the loss of potential energy. They estimate a single average value of τ over datasets of all event types through a regression analysis between energy and area, suggesting a unit value of the geometric parameter $\lambda_{dh} = A/L^2$ (for definition, see Section 2). A drawback in this approach is that estimates of the amount of the work done by the debris during its slide are too high since τ is applied to the whole overrun area (A) and then multiplied by L. This leads to much higher values of the effective friction forces than their empirical estimation. Fig. 1 (McDougall and Hungr, 2004) shows that a physically more reasonable approach is to apply τ only to the (transient) debris covered area A_t (because τ is zero outside of A_t), and then multiplying by the total horizontal travel length L. The Dade and Huppert model is restricted to a horizontal triangular (angular) emplacement of the flow as described through the plan-shape geometric parameter λ_{dh}, and contains τ (considered a constant) as a fitting parameter that does not necessarily contain a mechanical significance (Dade and Huppert, 1998). Legros (2002) applied the energy equation to this angular geometry and showed that the predicted velocities were substantially higher than observed in real landslides. Additionally, the assumption that τ is independent of the overburden pressure can be questioned for frictional materials. We mention that, Kelfoun and Druitt (2005) reproduced the Socompa volcanic debris deposit by using a constant basal stress. Recently, Davies et al. (2010) proposed a model for the basal shear stress in terms of the normal stress on the top of the fragmenting layer of the volcanic debris and fragmentation induced dispersive pressure. The model is applied to explain dynamic fragmentation on Socompa volcanic debris avalanche.

In this paper, we construct a model for determining the mean basal shear stress and a mass- or volume-dependent hypermobility and compare the model to available datasets.

2. The model

2.1. Basal shear stress

We derive the model equations for the mean basal shear stress, effective Coulomb friction coefficient and the hypermobility. We begin

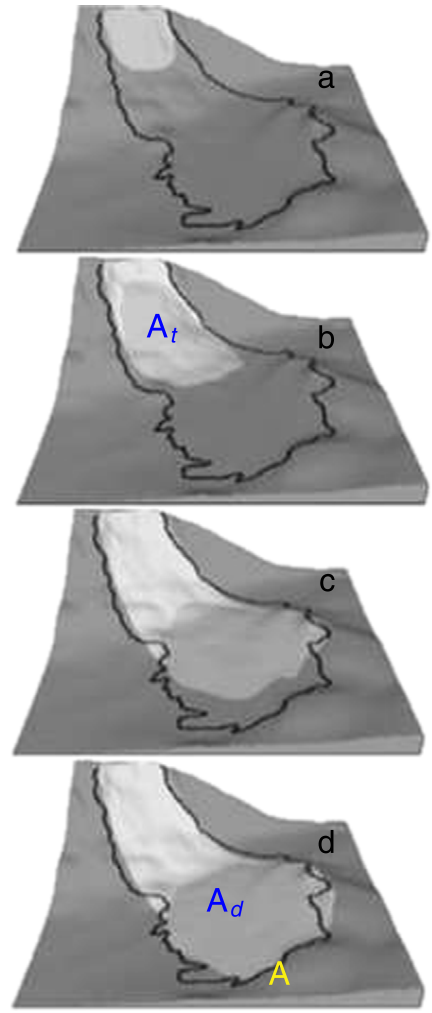

Fig. 1. Illustration showing how $A_t \ll A$, using the Frank slide (1903) as an example, where the 30 million m^3 slide partially buried the town of Frank, Alberta. The descending mass is in light gray. White area is the passage of the slide. The solid dark line indicates the measured trimline of the inundation area (A) of the flow. The simulation time was $t = 0$, 20, 40, 60 s, respectively, for panels a, b, c, d (McDougall and Hungr, 2004). Panels a and d show the initial mass and the final deposition. The area beneath the deposited mass is called A_d. Panels b and c are the transient sliding mass and the area beneath them is denoted by A_t.

with the local dynamical basal shear stress (Iverson, 1997; Iverson and Denlinger, 2001; Pudasaini et al., 2005)

$$\tau_l = \mu_c(1-\Lambda)\,\rho g\,(\cos\zeta + a_c)\,h(t;x,y), \tag{1}$$

where μ_c is the Coulomb friction coefficient, ρ is the bulk density, g is gravity acceleration, ζ is the slope angle of the basal surface, a_c accounts for topographically induced centrifugal forces, h is the flow depth in the direction normal to the sliding surface, t is time, and x and y are the downslope and cross-slope coordinates, respectively. Λ is associated with the degree of fluidization. That is, Λ is the ratio between the pore fluid pressure at the bed and the total normal pressure of the debris mass in the normal direction (Iverson and Denlinger, 2001; Pudasaini et al., 2005). This information can be substantial to (estimate and) predict the hypermobility of large debris avalanches (Berti et al., 1999; Major and Iverson, 1999; Iverson and Vallance, 2001; Berti and Simoni, 2005; McArdell et al., 2007). For more discussion on this, see Section 3. However, Λ can be mathematically analogous to the fluid volume fraction (Pudasaini et al., 2005; Pudasaini, 2012), or any other possible mechanism (see, Section 1) that reduces the basal shear resistance such as dynamic fragmentation (McSaveney