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Triggering conditions and mobility of debris flows associated to complex earthflows

J.-P. Malet[a,*], D. Laigle[b], A. Remaître[a], O. Maquaire[a]

[a]*School and Observatory of Earth Sciences, Institute of Global Physics, UMR 7516 CNRS-ULP, 5 rue René Descartes, F-67084 Strasbourg Cedex, France*

[b]*Cemagref - Snow Avalanche and Torrent Control Research Unit, B.P. 76, 2, rue de la Papeterie, F-38042, Saint-Martin d'Hères, France*

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Abstract

Landslides on black marl slopes of the French Alps are, in most cases, complex catastrophic failures in which the initial structural slides transform into slow-moving earthflows. Under specific hydrological conditions, these earthflows can transform into debris flows. Due to their sediment volume and their high mobility, debris flow induced by landslides are far much dangerous than these resulting from continuous erosive processes. A fundamental point to correctly delineate the area exposed to debris flows on the alluvial fans is therefore to understand why and how some earthflows transform into debris flow while most of them stabilize.

In this paper, a case of transformation from earthflow to debris flow is presented and analysed. An approach combining geomorphology, hydrology, geotechnics and rheology is adopted to model the debris flow initiation (failure stage) and its runout (postfailure stage). Using the Super-Sauze earthflow (Alpes-de-Haute-Provence, France) as a case study, the objective is to characterize the hydrological and mechanical conditions leading to debris flow initiation in such cohesive material.

Results show a very good agreement between the observed runout distances and these calculated using the debris flow modeling code Cemagref 1-D. The deposit thickness in the depositional area and the velocities of the debris flows are also well reproduced. Furthermore, a dynamic slope stability analysis shows that conditions in the debris source area under average pore water pressures and moisture contents are close to failure. A small excess of water can therefore initiate failure. Seepage analysis is used to estimate the volume of debris that can be released for several hydroclimatic conditions. The failed volumes are then introduced in the Cemagref 1-D runout code to propose debris flow hazard scenarios.

Results show that clayey earthflow can transform under 5-year return period rainfall conditions into 1-km runout debris flow of volumes ranging between 2000 to 5000 m^3. Slope failures induced by 25-year return period rainfall can trigger large debris flow events (30,000 to 50,000 m^3) that can reach the alluvial fan and cause damage.

Keywords: Earthflow; Debris flow; Modeling; Rheology; Runout; Hazard assessment

* Corresponding author. Now at: Faculty of Geosciences, University of Utrecht, The Netherlands.
E-mail address: J.Malet@geog.uu.nl (J.-P. Malet).

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1. Introduction

Mountain river valleys contain vast areas periodically exposed to catastrophic debris flows in case of strong meteorological precipitations or rapid snowmelt. This is particularly true for clay shales basins of southeast France known for their susceptibility to trigger muddy debris flows (Malet et al., 2004). These muddy debris flows are characterized by huge volumes of solid debris that are then deposited on alluvial fans. Schematically, these debris flows can initiate through two types of mechanisms. On one hand, initiation can occur in a torrential stream during an intense and localised thunderstorm after the concentration by runoff processes of loose material provided by shallow landslides affecting the watershed slopes or the breaking of a natural dam. On the other hand, initiation can occur through the liquefaction of slow-moving landslides experiencing a significant creep behaviour.

Classically, the transformation from a slide to a debris flow is depicted in three stages: (a) the failure localized along a surface within a creeping soil described using the Mohr–Coulomb plastic criterion; (b) the liquefaction of the bulk as a result of high pore water (fluid) pressure due to rapid infiltration in cracks; (c) acceleration and initiation of the debris flow. Presumably, as stated by several authors (Hungr, 1995; Iverson, 1997a; Iverson et al., 1997; Ancey, 2002), failure of the landslide mass is due to a combination of several mechanisms: rapid creep deformation, sudden increase in pore pressures and increase in load or erosion at the foot of the sliding mass. A high water content (higher than the liquid limit) is a necessary condition for the soil to be saturated and determines the liquefaction of the bulk. Saturation of the bulk causes intense surface runoff, complete saturation of the cracks and a sudden increase in the pore water pressures. Most debris flows occur during or after heavy and sustained rainfalls. In some cases, snowmelt can be sufficient to initiate debris flows, but for the remobilisation of unconsolidated landslide deposits, a combination of thawing soils, rainfall and snowmelt is often invoked. This is particularly true for impermeable clayey material.

Due to their sediment volume, debris flows induced by landslides are both far more dangerous than those resulting from continuous erosive processes and have an associated potential high hazard magnitude. In most cases, clayey earthflows experience significant creep behaviour (Picarelli, 2001), then decelerate and finally stop flowing after achieving a new hydromechanical equilibrium (Malet et al., 2004a). However, in a limited number of cases, earthflows may accelerate suddenly and give rises to debris flows. A fundamental point to correctly delineate the area exposed to debris flows on alluvial fans is therefore to understand why and how some earthflows transform into debris flow while most of them stabilize. As stressed by Crosta (2001), answering this question is difficult because it is the result of the action of several factors, such as (1) the hydrological and mechanical characteristics of the involved material, (2) the rapidity of the failure stage and postfailure stage (Vaunat and Leroueil, 2002), (3) the continuous changing of material properties (grain-size distribution, rheological characteristics) during flowing due to water feeding and channel-bed material scouring (Pierson and Costa, 1987; Hungr, 1995) or (4) the morphological characteristics of the flowing path (Hutchinson, 1988).

The Callovo–Oxfordian “Terres-Noires” of the Ubaye valley (southern Alps, France) are known for their numerous active landslides (Antoine et al., 1995; Maquaire et al., 2003). Three large earthflows (Poche, Super-Sauze and La Valette) have developed in this formation and have initiated more or less mobile mudflows or muddy debris flows in the recent years (LeMignon and Cojean, 2002), including a large range of volumes, for instance from 5000 to over than 60,000 m^3 at La Valette in 1988 (van Beek and van Asch, 1996). In this latter case, to prevent further catastrophic development on the urbanized alluvial fans, remedial measures were taken by the Service de Restauration des Terrains en Montagne, including groundwater drainage, displacements monitoring and the design of a sediment trap.

In this paper, two debris flow case histories of the complex Super-Sauze earthflow, representative of black marl landslides, are presented to evaluate the processes involved during the transition from failure to postfailure behaviour. The Super-Sauze earthflow affects the north facing slope of the Brec Second crest where the combination of steep slopes (up to 35°), downslope stratigraphic dip and the lack of vegetation make this basin one of the most landslide and debris