Engineering Geology 212 (2016) 10–20

Contents lists available at ScienceDirect

Engineering Geology

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

Modelling the space–time evolution of bed entrainment for flow-like landslides

Sabatino Cuomo [a,*], Manuel Pastor [b], Vittoria Capobianco [a], Leonardo Cascini [a]

[a] Department of Civil Engineering, University of Salerno, Italy
[b] Department of Applied Mathematics, Universidad Politecnica de Madrid, Spain

ARTICLE INFO

Article history:
Received 14 December 2015
Received in revised form 14 June 2016
Accepted 27 July 2016
Available online 29 July 2016

Keywords:
Propagation
Landslide
Entrainment
SPH
Debris avalanche
Debris flow

ABSTRACT

The paper discusses the space–time evolution of bed entrainment for some typical flow-like landslides in three different test areas. First, the attention is focused on debris avalanches (DA), whose lateral spreading is highly affected by bed entrainment. Two cases of debris avalanches turning into debris flows (DF)—i.e., channelized flows—are then investigated to discuss the potential occurrence of complex bed entrainment scenarios. A quasi-3D (depth-integrated) coupled SPH (Smooth Particle Hydrodynamic) model is used. The numerical results show that i) the eroded thicknesses have maximum values in the intermediate portion of the debris avalanche path and ii) the computed time variations of eroded thicknesses and the entrainment rates are consistent with those indicated in recent literature for DAs at the studied areas. In addition, the computed scenarios are differentiated in terms of unitary flow discharge, identifying the typical behaviour of small volume DA, landslides propagating inside gullies as DFs, and combined DFs and DAs.

1. Introduction

Bed entrainment—also called erosion or basal erosion—is the process that causes an increase in the volume of flow-like landslides (Savage and Hutter, 1991; Pastor et al., 2009) owing to the inclusion of soil, debris and trees uprooted from the ground surface. In principle, the entrainment process can be simply analysed by referring to the entrainment rate (e_r), defined as the time derivative of the ground surface elevation (z), over which the landslide propagates. It is generally agreed that the entrainment is positive if z diminishes—i.e., $e_r = -\partial z/\partial t$. However, the entrainment rate (e_r) depends on several variables: the flow structure (i.e., percentage of solid and fluid in the mixture), the densities and sizes of the solid particles, the saturation degree of the base soil along the landslide path, the slope angle, and how close to failure the effective stresses are at the bed of the propagating mass. Based on these key factors, many formulations for the entrainment rate have been proposed in the literature, and a comprehensive review of the entrainment models has been provided by Pirulli and Pastor (2012) and Cascini et al. (2014).

Here, it is worth noting that most of the formulations indicate a direct proportionality between the entrainment rate (e_r) and the flow velocity (v) and/or the flow depth (h). Moreover, it is recognised that the occurrence of bed entrainment implies that i) velocity and height of the flowing mass are modified, ii) pore water pressure at the base of the flow is altered, and iii) the rheology (i.e., the features and mechanical behaviour) of the flow could be modified as well if the flowing mass and the entrained materials are very different. Indeed, the entrainment process is very complex, and former contributions have been proposed based on tests (flume, centrifuge, or full scale) of differently sized, generally smaller than 10 m^3, propagating volumes (Iverson et al., 2011; Hu et al., 2014) or numerical modelling of real debris flows (Cascini et al., 2014) or historical debris avalanches (Cuomo et al., 2014).

To provide further insight on the topic, this paper will focus on real-scale landslides, particularly on debris avalanches and debris flows, and related cascading effects (Crosta et al., 2006; Hungr, 2008; Crosta et al., 2009; Pirulli and Pastor, 2012). debris avalanche (DA) is defined as "very rapid to extremely rapid shallow flow of partially or fully saturated debris on a steep slope, without confinement in an established channel" (Hungr et al., 2001). Avalanche formation is mostly related to bed entrainment (Cascini et al., 2013a, 2013b; Cuomo et al., 2014). Debris flows (DF) propagate in V-shaped channels in which a large amount of water is available during heavy rainstorms and the propagating mass fluidizes (Cascini et al., 2014). Fig. 1 provides a sketch for a DA (scenario "1", Fig. 1a); a DA evolving into a single DF (scenario "2", Fig. 1b); a single DA generating multiple DFs (scenario "3", Fig. 1c); and several DAs and DFs evolving in a single huge DF or in multiple surges delayed in time (scenario "4", Fig. 1d). As an example of scenario "1", the 1999 Nomash River debris avalanche (Vancouver Island, British Columbia, Canada) mobilized a triggered volume of 3×10^5 m^3, whereas the erosion processes yielded nearly the same volume, with an average erosion depth of 8 m measured along 25° to 35° steep slopes (Hungr and

* Corresponding author.
E-mail address: scuomo@unisa.it (S. Cuomo).

http://dx.doi.org/10.1016/j.enggeo.2016.07.011
0013-7952/

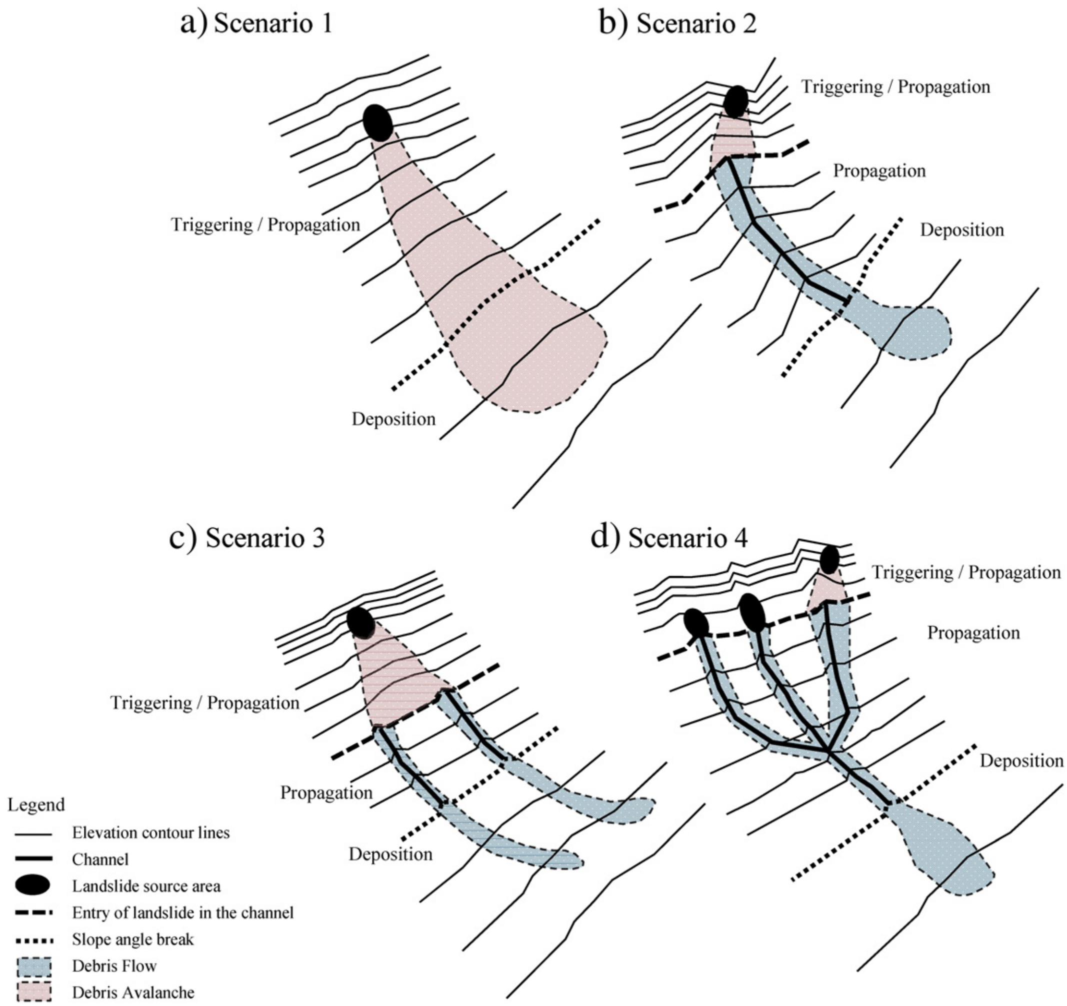

Fig. 1. Schematic of typical propagation scenarios for flow-like landslides: a) scenario "1", b) scenario "2", c) scenario "3", d) scenario "4".

Evans, 2004; Hungr et al., 2005). Regarding scenario "2", the 1995 Izoard pass debris flow (southern French Alps) was characterised by an erosion thickness up to 5 m at the top of a 25° to 30° steep channel (Lake et al., 1998). An interesting debris avalanche, which bifurcated into two debris flows (scenario "3"), occurred in Tsing Shan (Hong Kong) in 1990. Bed entrainment greatly increased the landslide volume, from 150 to 1600 m^3, because of the very steep slope (approximately 40°) and the abundance of colluvial material along the slope (King, 2001a, 2001b; Pastor et al., 2007, 2014). Regarding scenario "4", this is typical in high mountain ridges of China (Tang et al., 2011; Hu et al., 2014) and Canada (Hungr and Evans, 2004).

Considering that examples of space–time evaluations of entrainment thicknesses and propagation heights for real case histories of scenarios 1–4 are still missing in the current literature, this paper addresses this scientific gap. With this aim, a quasi-3D (depth-integrated) coupled SPH (Smooth Particle Hydrodynamic) model is used (Pastor et al., 2009; Blanc and Pastor, 2012a,b) to analyse three specific test areas of Southern Italy, in which unsaturated air-fall volcanic (pyroclastic) soils lie on a steep carbonate relief and are very prone to failure. As further contribution to the current literature, this paper clarifies the importance of the propagation scenarios on the space-time evolution of bed entrainment, focusing the attention on the correlation between eroded thicknesses and topography of landslides path.

The paper is structured as follows. First, the main features of the selected physically based model are highlighted, and the case history of Southern Italy is illustrated with special reference to the field evidence and soil mechanical properties. The numerical modelling of three different events, classifiable as scenarios 1, 3 and 4, is then proposed together with a discussion of the current and future possibilities to properly model a flow-like landslide.

2. SPH model

Propagation analysis is performed through the "GeoFlow_SPH" model, which is a depth-integrated hydro-mechanical coupled model proposed by Pastor et al. (2009), based on the fundamental contributions of Hutchinson (1986) and Pastor et al. (2002). The propagating mass is schematized as a mixture of a solid skeleton saturated with water. The unknowns are the velocity of the soil skeleton (v) and the pore water pressure (p_w). Both variables are defined as the sum of two components related to i) propagation and ii) consolidation along the normal direction to the ground surface.

The governing equations are i) the balance of mass of the mixture (which also includes the entrainment rate term), combined with the balance of linear momentum of the pore water, ii) the balance of the linear momentum of the mixture, iii) a kinematic relation between the deformation-rate tensor and velocity field, and iv) the rheological equation relating the soil-stress tensor to the deformation-rate tensor. Further details are provided by Pastor et al. (2009, 2014); Cascini et al. (2014), and Cuomo et al. (2014). It is worth recalling that the vertical distribution of pore water pressure is approximated using a quarter-cosinus shape function, with a zero value at the surface and zero gradient at the basal surface (Pastor et al., 2009). The reason is that with consolidation being ruled by a parabolic equation, shorter wavelengths are