Engineering Geology 205 (2016) 1–11

Contents lists available at ScienceDirect

Engineering Geology

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

Dynamic simulation of the motion of partially-coherent landslides

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ARTICLE INFO

Article history:
Received 20 August 2015
Received in revised form 11 December 2015
Accepted 16 February 2016
Available online 17 February 2016

Keywords:
Landslide Runout Analysis
Rock slide
Rock avalanche
Goldau
Mystery Creek
Landslide dynamics

ABSTRACT

Rock avalanches are catastrophic landslides that threaten people and property worldwide. The only way to mitigate the hazard posed by these events is to anticipate their impact area and velocity before they occur. Fluid dynamic models are one tool used to perform this kind of analysis. When these models are applied to some rock avalanche case histories, it has been found that the impact area is often over-predicted. This is due to the fact that the models assume that the landslide fluidizes immediately, when in reality the landslide begins as a sliding of a relatively rigid block, which progressively fragments during motion and only gradually turns flow-like. This work details the derivation, implementation, validation and verification of Dan3D Flex, a dynamic model that can simulate the initially rigid phase of rock avalanche motion. This model has been interfaced with an existing equivalent fluid model to allow for all stages of rock avalanche motion to be simulated. Dan3D Flex only requires one additional parameter which can be constrained based on an examination of the pre-failure topography. The back analysis of two rock avalanche case histories is presented to demonstrate the utility of the new model.

1. Introduction

Rock avalanches and other long-runout landslides can threaten elements at risk that are far from the source area. Prediction of their dynamic behaviour, including the extent of the impact area and distribution of velocity and depth is an essential task for risk assessment. Most practical runout analyses are conducted using empirical models (Hungr et al., 2005). However, the use of numerical models of landslide dynamics is rapidly increasing.

A large number of models have been introduced in the literature over the last two decades. A summary was assembled during the landslide runout benchmarking exercise run in 2007 by the Geotechnical Engineering Office in Hong Kong (see Hungr et al., 2007), dividing models into the following groups, based on several criteria:

Dimensions:

a) *Two-dimensional models* assume zero deformation in the y-direction (perpendicular to movement), similar to plane strain conditions such as flow in a prismatic channel with zero side friction.
b) *Pseudo-3D models* take into consideration user-specified flow width variations in the volume-conservation equation, while neglecting momentum flux in the y-direction (Hungr, 1995).
c) *Three-dimensional models* track both volume continuity and momentum in three dimensions.

Hydraulics literature often labels dimensionality in mathematical terms, based on the governing equations. In such convention, depth integrated 3D models are labelled two-dimensional. This convention will not be used in the present article.

Basic approach:

1) *Differential models* are based on a complete solution of the partial differential equations of fluid continuum motion. In this category belong advanced fluid dynamic models such as LS-Dyna (Kwan et al., 2015), OpenFOAM (Boetticher et al., 2011) and TOCHNOG (Crosta et al., 2003). These programs have extensive capabilities to deal with complex geometries, but are highly demanding on computational capacity and input data.
2) *Depth-integrated models* derive from methods of unsteady flow routing, routinely used in shallow-flow hydraulics (e.g. Chow, 1959). Some are simply extensions of the Navier Stokes solutions for non-Newtonian fluid flows (e.g. FLO-2D, O'Brien et al., 1993). Savage and Hutter (1989) introduced non-hydrostatic stress distribution within the stream column, whereby the interior of the flowing mass is considered to be a frictional medium in a state of shear flow. The internal deformation is controlled by an internal friction angle, while basal shear occurs with a different angle of friction (the "SH model"). Hungr (1995) extended the SH model to consider the possibility that basal shearing is nonfrictional and depends on a selectable rheological kernel. Several three-dimensional models based on the SH theory appeared subsequently (e.g. Chen and Lee, 2002; McDougall, 2006; Pirulli, 2005). Hungr (2008) proposed a stress correction for cases of deeper flows that violate the assumption of shallow flow that is implicit in the SH model.

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http://dx.doi.org/10.1016/j.enggeo.2016.02.006
0013-7952/

3) *Discrete particle models* represent the failed material as an assemblage of spheres or other objects (e.g. Imre et al., 2010; Campbell and Brennen, 1985; Poisel et al., 2008). Assumed processes controlling mechanical interaction between the particles are very important.

Some dynamic models attempt to incorporate a full mathematical description of a constitutive relationship, derived from micro-mechanics of an assumed granular material or mixture (e.g. Iverson and George, 2014). Most, however take a semi-empirical approach, termed "equivalent fluid model" by Hungr (1995). Here, the constitutive relationship controlling the basal flow resistance is assumed to be based on a simple rheological relation, controlled by a few parameters whose values are determined by back-analysis of real cases. Most models include fixed basal resistance rheologies: Frictional (Savage and Hutter, 1989), Bingham (Jeyapalan, 1981; Dent and Lang, 1983; Voight and Sousa, 1994; Huang et al., 2012; Dai et al., 2014), Herschel–Bulkley (Coussot and Proust, 1996; Imran et al., 2001), or the Voellmy rheology (Christen et al., 2010). Some models allow a selection of basal rheologies (e.g. Hungr, 1995; McDougall, 2006; Pirulli, 2005; Pastor et al., 2009; Pitman et al., 2003; Bouchut et al., 2003).

Most recently, bi-phase flow models have been introduced, which allow for the momentum of the solid and fluid phases to be followed simultaneously (Iverson and George, 2014; Iverson and Denlinger, 2001). These models require algorithms for mechanical linking the motion of the two phases and tend to be both complex and demanding of data and constitutive relationships.

All models reviewed herein are based on the principles of fluid mechanics, i.e. they do not consider elastic rigidity of the moving material. However, landslides develop in material which is initially solid and only transitions into a fluid state during movement, as described in the case histories presented later in this article. In some landslide types this transition occurs rapidly, e.g. in flowslides (Hungr et al., 2014). In others, it may be more gradual, as the landslide commences sliding movement as a rigid, or semi-rigid block, then gradually disintegrates into a fluid. This occurs commonly in rock avalanches. Fluid mechanics models, applied to such cases, commonly predict excessive lateral and longitudinal spreading of the sliding mass in the source area. The extent of the path as well as the runout can be substantially distorted by this. The model described in this paper provides an extension to an existing SH type model that allows for the simulation of this type of extremely rapid landslide.

The model utilized in this work is DAN3D, developed by McDougall (2006). Dan3D is a depth-averaged Lagrangian implementation of the equivalent fluid approach. The equations that govern Dan3D are similar to the shallow water equations, however the formulation allows for an anisotropic internal stress distribution using the Savage and Hutter (1989) algorithm. The solution method used by Dan3D is smooth particle hydrodynamics (SPH) (Monaghan, 1992). SPH is a mesh-free method, which allows for bifurcations and large strains to be simulated without mesh distortion problems. An overview of the application of SPH to model geohazards is provided by Huang and Dai (2014).

The parameters that govern a Dan3D simulation are not true material parameters. Instead, these parameters must be determined through trial and error inverse analysis. The parameters that are calibrated are the basal resistance parameters as well as the internal friction angle. Due to the use of inverse analysis to determine parameters, Dan3D is semi-empirical (McDougall and Hungr, 2004). DAN3D has been used to successfully model a number of cases (Hungr and McDougall, 2009). For a detailed description of the derivation and assumptions of DAN3D the reader is referred to McDougall and Hungr (2004). An overview of the entrainment algorithm is provided in McDougall and Hungr (2005).

2. Initially coherent rock avalanches

It is uncommon for rock avalanches to be in a state of fully developed internal deformation at the onset of their motion. Instead, many rock avalanches initiate as translational slides which only gradually fragment and turn flow-like. The physics that govern these two phases of motion are different. The initial coherent stage is best described by solid mechanics, whereas the flow-like portion is well described with a fluid mechanics solution in the context of an SH model as discussed earlier. An example of this behaviour can be seen in Fig. 1 which shows a photo taken during a flyover of the North Nahanni Slide (Wetmiller et al., 1987). The major part of the deposit features a large intact block covered by vegetation, while the distal part is fluid-like. The dynamics of the block would be poorly described by fluid mechanics.

Many researchers have noted excessive lateral spreading in the source zone when applying Dan3D to initially coherent rock avalanches (Fitze, 2010; Chalindar, 2005; McDougall, 2006). Two rock avalanche cases have been selected to demonstrate this problem: Goldau in Switzerland and Mystery Creek in Canada. It is not the intention of this work to provide a detailed description of these cases. They are presented in order to demonstrate the results produced by equivalent fluid runout models as a consequence of the implicit assumption of instant fluidization. References are provided to papers that discuss these cases in more detail.

2.1. Goldau Rock Avalanche

The Goldau Rock Avalanche occurred in Central Switzerland in 1806. This tragic event claimed 457 lives, destroyed 111 houses and triggered a 20 m high wave in nearby Lake Luarez. The failure involved the detachement of 35–40 $\times$ 10^6 m^3 of material along a planar rupture surface of a dip slope in marlstone and conglomerate (Fitze, 2010). A detailed investigation of the geology and future hazard potential is given by Berner (2004). A contemporary photo of the source area is shown in Fig. 2. Numerical modelling of the failure mechanism is described by Thuro et al. (2006). It was found that the rupture surface exploits highly weathered marlstones near the main scarp, and then cuts through conglomerate layers lower down. Friction angles of about 23° were found within the weathered marlstone and evidence of brittle fracture was found within the conglomerates. Based on this, it was suggested that the slope was near limit equilibrium conditions and progressive failure through the conglomerates initiated brittle failure of the whole sliding mass along a rupture surface parallel to the bedding planes. The simulations presented here build on a previous Dan3D analysis performed by Fitze (2010). The topography files and simulation constraints are the same as those used in that analysis.

The model parameters used in the fully fluid simulations are shown in Table 1, and the spatial distribution of the parameters is shown in Fig. 3a. The frictional rheology is used in the source zone, and the Voellmy rheology is used where the landslide overrode and entrained loose saturated sediments, consistent with previous analyses of similar rock avalanches (Hungr and Evans, 2004; McDougall, 2006). An overview of the basal rheologies is provided by Hungr and McDougall (2009). The results of the fully fluid simulation are shown in Fig. 3b and compared with the reported trimline of the actual landslide. The fully fluid simulations predict excessive spreading of the sliding material during the early stages of the event, mainly along the unconstrained right flank of the source area, as indicated by the velocity vectors on Fig. 3b. The fluidized sliding mass is acted upon by gravitational forces which move the slide downslope, but also by lateral forces due to fluid pressure. These forces cause the sliding mass to spread in the direction perpendicular to the downslope direction. Comparing the width of the source volume to the width of the trimline during the initial stages shows that the actual sliding mass did not spread laterally. Presumably, the source block began sliding along a weak bedding plane without much internal deformation. Internal breakdown only occurred once the block accelerated to high velocity and was shaken by the irregularity of the natural path downslope from the toe of the rupture surface.

It can be argued that the poor fit of the simulation to the landslide trimline could be caused by poorly chosen parameters. Fitze (2010)