The LaharFlow Model for Sediment Flows and its Application to Huaycos in Chosica

Jeremy Phillips[1], Mark Woodhouse[1] Andrew Hogg[2], Jake Langham[2]

[1] *School of Earth Sciences, University of Bristol, UK.*
[2] *School of Mathematics, University of Bristol, UK.*

Palabras clave: sediment flows, mathematical model, webtool, huayco.

Introduction

When volcanic sediments are mixed with water the slurry of material can be highly mobile, flowing for long distances (up to 100 km) from steep volcanic flanks. These flows are commonly referred to as *lahars* and are one of the most dangerous hazards related to volcanic activity [Tilling, 1989; Auker et al., 2013; Gudmundsson, 2015; Vallance and Iverson, 2015]. They can inundate large areas up to depths of a few metres, destroying buildings and infrastructure and damaging agricultural land, and can occur during eruptions and for many years afterwards. Lahars can be initiated by a numerous mechanisms [Manville et al., 2013; Gudmundsson, 2015; Vallance and Iverson, 2015], including eruptions of pyroclastic material onto glaciers or snow caps [e.g. Pierson, 1985; Pierson et al., 1990], disturbance of volcanic lakes [e.g. Manville and Cronin, 2007; Manville, 2015], mixing of volcaniclastic material from flank collapses with water [e.g. Scott et al., 2005], or rainfall onto tephra [e.g. Lavigne et al., 2000; Barclay et al., 2007]. The solid material carried by a lahar typically increases rapidly after initiation due to erosion of larger soils, rocks and boulders from the underlying surface, and can span a wide range of concentrations, from hyperconcentrated flows with solids mass fraction of 10–50% to debris flows where the solids mass fraction exceeds 50% [Pierson & Major, 2014].

The diverse mechanisms leading to lahar initiation makes forecasting difficult. Physical models that describe lahar dynamics are useful tools in managing lahar hazards, allowing quantitative hazard assessments to be performed. In addition to predicting flow routing and inundation, which are core components of hazard mapping, physical models can provide quantitative predictions of flow variables that are valuable for assessing impacts on infrastructure (such as depth, velocity, dynamic pressures), as well as arrival times of lahars, which are critical for emergency response planning and the development of early-warning systems.

Lahars (particularly when triggered by rainfall) are closely related to other typically lower solids concentration energetic flows such as flash floods, or huaicos, which show similar dynamical behaviour. Huaicos result from typically short duration (10s minutes) of intense rainfall onto arid catchments. The resulting flows are rapid, strongly erosional and usually confined by topography, both natural and urban. In Perú, huaicos in spring 2017 caused more than 100 deaths, economic losses of more than US$ 3 Bn and 3000 km of roads unusable. These impacts represent a significant obstacle to economic development, critically impact social welfare and human health, and disproportionally affect the most vulnerable.

The LaharFlow model

Here we present an overview of our new model of lahar dynamics, which we call LaharFlow, that we have developed as a tool for hazard assessment. As such, our model includes only the dominant physical processes and adopts simplifying parameterizations. We adopt a shallow-water framework because the thickness of lahars and huaicos is typically much smaller than their length ($< 10^{-3}$), so the pressure gradient is nearly hydrostatic (depends only on the depth in the flow). The horizontal velocity and other variables can thus be approximated by *depth-averaged* values throughout the flowing layer. In the model we treat the suspension of particles as a two-phase mixture, in which the fine particles remain suspended in the water column (the fluid phase), and coarse particles (the solid phase) can sediment through the fluid according to settling laws including the hindering effects of higher particle concentrations [Soulsby, 1997; Spearman and Manning, 2017].

The model consists of equations for conservation of mass and momentum in the shallow layer. We solve equations for conservation of mass of the fluid and solids independently, to allow the solid concentration to evolve as a consequence of erosion of the underlying bed (adding mass to the flow) and deposition onto the bed (removing mass from the flow). The flow of the mixture is resisted by a basal stress whose form evolves with the solids concentration of the flow. We employ widely-used parameterisations for the end-member flow regimes: in the dilute limit basal stresses are predominately due to fluid drag and we therefore use a Chezy Drag parameterization; and for high solids concentration we use a Coulomb friction model with a coefficient that depends on the local flow rate, which has been shown to be an accurate model of dense granular flows [Forterre and Pouliquen, 2008]. Between the end-member flow regimes, the basal stress is modelled using a novel drag parameterization which is weighted on the contribution of the fluid and granular drag in proportion to the concentration of the coarse solid fraction.

Erosion of the bed and deposition of the solid material alter the local topography which feeds back into the mobility of the flow. We model the erosion rate as dependent on the balance of the flow basal stress with the weight of submerged particles that make up the underlying surface, a commonly used approach in hydraulics and flooding, and compute this balance using parameterisations presented by Soulsby [1997] and Mayer-Peter & Muller [1948]. The erosional and depositional fluxes are linked to morphodynamic changes in the topography, with important effects on the flow dynamics, through couplings shown in Figure 1.

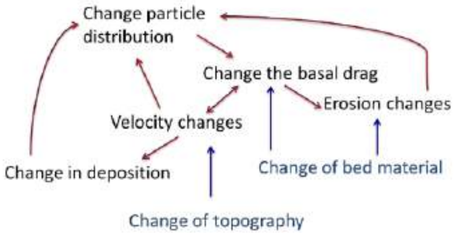

Fig. 1 – Physical process couplings within the LaharFlow model

Model inputs include the location of the flow source, its initial volume or volumetric flux as a function of time (a 'source hydrograph'), and the initial sediment concentration. The system of equations is solved on topography using an Earth-centred coordinate system, to compute flow properties such as depth, speed and sediment concentration as functions of time and position, and changes in topography resulting from erosion and deposition.

The LaharFlow Web Interface and User Training

A web-based interface to LaharFlow has been developed to allow access to the model without needing special computational infrastructure. The web interface (www.laharflow.bristol.ac.uk; Figure 2) is a convenient way to set up and start simulations and to view results during the calculation, which is run on servers at the University of Bristol. The web-based interface allows the specification of lahar sources as discrete volumes or as a source hydrograph, and selection of multiple active sources in a single simulation.

Data produced by the LaharFlow model can be download for further processing, visualization and analysis. LaharFlow provides data as a .kml file that can be opened in Google Earth, allowing easy three-dimensional visualization of the flow path. Numerical data can also be exported from the model in a format that is easily imported into GIS software such as ArcGIS and QGIS.

The webtool includes near-global 30 m Shuttle Radar Tomography Mission (SRTM) digital topographic maps which are used as a default representation of the topography. For some studies, high resolution digital topographic maps are available (e.g. from Lidar or UAV surveys). The webtool features a topography upload facility (available to 'advanced users' who have received training in the use of LaharFlow) that allows topographic data in the form of georeferenced tiff files (geotiffs) to be used in the model.

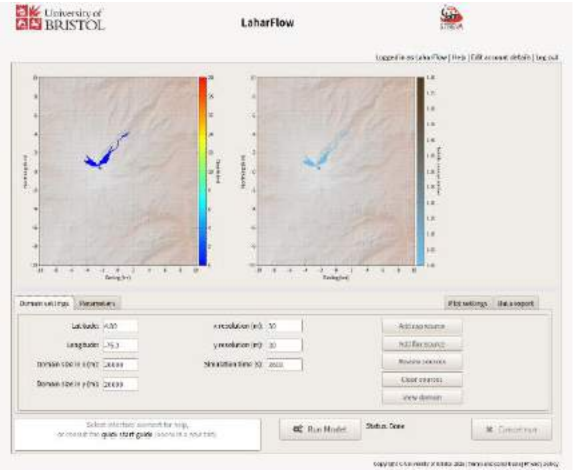

Fig. 2 – The main user interface of the LaharFlow web-tool. Users can specify the location of a simulation, adjust parameter values and define source conditions to initialize a simulation. Calculation results are displayed graphically during a simulation and can be downloaded for further analysis.

Application to Huaycos in Chosica, Perú

We are using the LaharFlow model for assessment of huayco routing and inundation in Peru, in collaboration with Instituto Geológico, Mineralo y Metalúrgico (NGEMMET), and the NGO Soluciones Practicas. We are focusing on an event which occurred in La Libertad quebrada in Chosica, near Lima, on 23rd March 2015, as a calibration study. La Libertad is at the base of a small natural basin, and 12 mm of rainfall in about 30 minutes resulted in a huaico that flowed through the urban topography downhill into the Rio Rimac, causing significant damage to housing and about 1 m of erosion depth to the pedestrian routes at the upper end of the settlement.

The flow routing is controlled by buildings and narrow alleys, so the model needs to be run using a high-resolution topographic map to correctly predict flow routing; we are using 0.5 m horizontal resolution topographic mapping derived from photogrammetry of drone images that were obtained in a field visit in

February 2018 (Fig. 3). Figure 4 shows a single frame of LaharFlow model output from a simulation of the 23 March 2015 huaico event. This initial result shows that the model can correctly reproduce the observed flow routing around the urban topography, and flow depths and speeds are in good agreement with observations made by residents during the huaico event. Ongoing work is refining model calibration with erosion parameters appropriate to urban surfaces.

Fig. 3– A projection of the drone-derived topographic mapping of La Libertad, showing buildings and routes.

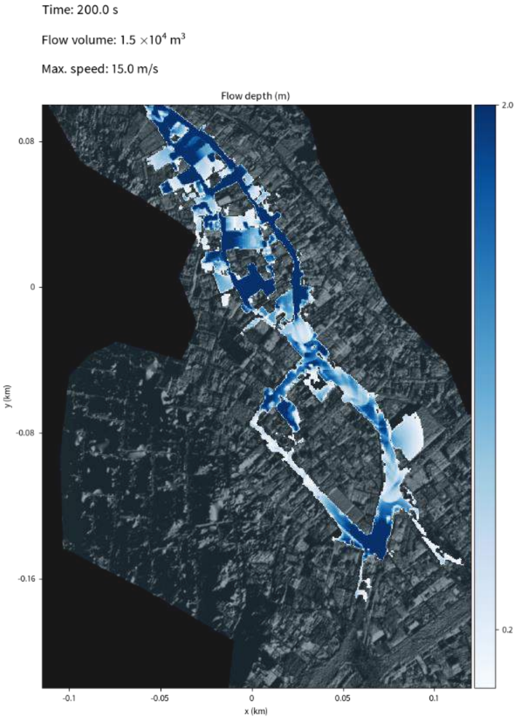

Fig. 4 – A LaharFlow simulation of the 23rd March 2015 huaico at Chosica on a high-resolution (50cm) topographic map. The flow in the urban area is strongly affected by the artificial channels created by buildings and streets. The simulation captures the effects of buildings and open spaces in the town. Streets become flow channels with steep and high 'banks' from the buildings. Colours denote the flow depth.

Acknowledgements

The LaharFlow model was developed as part of the 'Strengthening Resilience in Volcanic Areas' project, funded by the Natural Environment and Economic and Social Sciences Research Councils, UK. We are collaborating with Manuel Vilchez Mata and Sandra Villacorta Chambi of INGEMMET on the Chosica case study, in the project 'Supporting Recovery from 2017 Coastal El Nino Sediment-laden Floods in Peru' funded by the Engineering and Physical Sciences Research Council UK.

Background and Interests

Jeremy Phillips is a physical volcanologist with broad interest in environmental hazard, risk and resilience. His physical science background is in fluid dynamics and volcanic processes, including fundamental processes of explosive volcanic eruptions, and multiphase environmental flows including volcanic ash transport, and dynamics of suspensions and granular flows. His main career focus has been the prediction of volcanic hazards and their impacts, including volcanic ash transport, lahars and landslides, volcanic gases and crater lakes. He now works across disciplines to integrate hazard assessment with social and physical vulnerability, risk management structures and community engagement, with social scientists, engineers, mathematicians and statisticians.

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