ESTIMATING BUILDING AND INFRASTRUCTURE VULNERABILITY IN THE CITY OF AREQUIPA (PERU) FROM VOLCANIC MASS FLOWS: A CHALLENGE

Kim Martelli [1], Jean-Claude Thouret [1], Cees van Westen [2], Denis Fabre [3], Michael Sheridan [4], & Ruben Vargas [2]

1 Laboratoire Magmas et Volcans, Université Blaise Pascal, 5, rue Kessler, 63000 Clermont-Ferrand, France (k.martelli@opgc.univ-bpclermont.fr)
2 International Institute for Geoinformation Science and Earth Observation, P.O. Box 6, 7500AA Enschede, The Netherlands
3 Conservatoire National des Arts et Métiers (CNAM), 2 rue Conté, 75003 Paris, France
4 Department of Geology, Unviersity of Buffalo, SUNY, Buffalo, NY 14260, USA

INTRODUCTION

Rapid population growth and urban expansion has led to an increase in the vulnerability of communities living within close proximity to an active volcano. Arequipa, the second largest city in Peru with a population exceeding 860,000 is no exception, and is much like the city of Naples in Italy is exposed to Vesuvius. Arequipa has experienced rapid population growth since the 1940s, and from 1970 onwards the urban area grew substantially due to social unrest and related migration from rural areas, mainly in the form of poorly designed suburbs and illegal settlements. Settlements have now expanded onto the southwest flank of the volcano, the Río Chili River terraces and adjacent to tributaries within 9 km of El Misti summit. Studies of the type, extent, and volume of Holocene pyroclastic and lahar deposits have concluded that future eruptions of El Misti, even if moderate in magnitude, will pose a serious threat to Arequipa (Thouret et al., 1999; Delaite et al., 2005). Here we discuss computer simulation of mass flows, classification of buildings and infrastructure and the challenges we are faced with while assessing building and infrastructure vulnerability within Arequipa.

GEOLOGIC SETTING AND VOLCANIC MASS FLOW HAZARDS

El Misti is one of the seven active volcanoes within the Central Volcanic Andean Zone (CVZ) of southern Peru. Arequipa is located 17 km to the southwest and 3 km below the summit of the active El Misti volcano (see figure 1). The city is situated upon volcaniclastic fans of pyroclastic-flow and lahar deposits from El Misti that are less than 10,000 years old.

Three possible hazard scenarios have been proposed for El Misti volcano (Thouret et al. 1999; Delaite et al. 2005). Scenario 1 is described as the most probable type of future activity with a VEI2 and a recurrence interval of 300 to 1000 years; Scenario 2 is a moderate magnitude (VEI3) / frequency (1600 to 5000 years) eruption; and Scenario 3 is the maximum expected pyroclastic eruption with a VEI>3 and a recurrence interval of 10,000 to 20,000 years. All eruption scenarios result in the formation of volcanic mass flows. These could include; dam-break floods, pyroclastic flows, block-and-ash flows; lahars; and pumice flows, surges and high energy directed blasts. In addition, lahars

Figure 1. The locality of Arequipa City with respect to El Misti Volcano. The area studied for the purpose of a vulnerability assessment is illustrated in orange from the Puente Bolognesi to the Military in Chilina. Flows were simulated with Titan2D in the upper catchment of the Río Chili River, and in the upper reaches of the Quebradas San Lazaro and Huarangal.

and flash floods can occur in the Río Chili River and Quebradas without an eruption (occurring on average once every ten years from El Misti) from rainfall, snow meltwater, and a dam break flood.

THE CHALLENGE OF MODELLING

Previously the designation of volcanic mass flow inundation zones had been undertaken using geological studies of the past events at a volcano, now computer simulated numerical flow models such as FLO-2D, LaharZ and Titan2D are being used in tandem with geological studies to assist in the determination of inundation areas. Stinton et al. (2004), Delaite et al. (2005) and Vargas et al. (2007) have attempted the delineation of lahar prone areas on El Misti flanks, ring plain, and in the city of Arequipa using LaharZ and Titan2D (single and two-phase models). Our research extends on the work of previous authors by investigating the sensitivity and resolution of the DEM, and what affect this could have on the simulation outputs.

Multiple simulations were undertaken on a 30 m and a 10 m DEM of El Misti volcano using both the Titan2D single- and two-phase models. The 30 m DEM was created by digitising 1:25,000-scale topographic maps and radar interferometry, and the 10 m DEM was computed using DGPS data, aerial photographs and stereophotogrammetry. Detailed topographical data for the 10 m DEM was acquired from a DGPS survey undertaken on the four main terraces of the Río Chili River, an area of approximately 5km^2, from the Military Camp (approximately 15 km from the summit) downstream to the Bolognesi Bridge (city centre) during 2007. Lahars ranging from 0.01x106 m^3 to 11x106 m^3 in volume were simulated down the Río Chili valley, and the Quebradas San Lazaro and Huarangal. Solid fractions of 0.3 to 0.5 were incorporated into the simulated flows. The sensitivity of the DEM was analysed by changing the simulation input parameters and observing what affect this would have on the modelled flow features (see figure 2). Changes in the simulation parameters included starting point, internal and bed friction angles, and the solid fraction ratio. Runout length, super-elevation, ponding, flow divergence and convergence were the observed flow features.

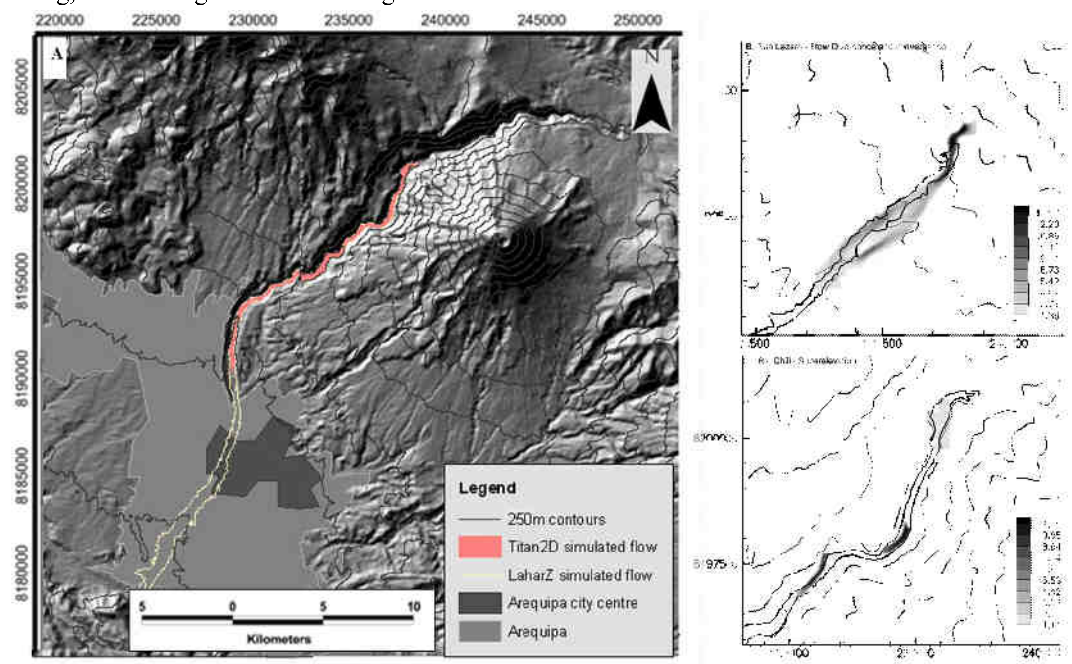


Figure 2. A– Map showing the difference between Titan2D runout and LaharZ runouts. B – Examples of characteristics of flow behaviour observed from Titan2D simulations. The top simulation indicates flow divergence and convergence on Qda. San Lazaro; this closely resembles reality as the flow moves around an obstacle in the channel. The lower simulation shows the superelevation of a flow in the Río Chili River. Note: the dark black outline is the LaharZ simulated flow outline (Stinton et al., 2004).

Analysis of the multi-simulations revealed Titan2D is very sensitive to changes in the input parameters, especially the location of the starting point and the basal friction value, with changes in the basal friction angle even as small as 1° having a noticeable effect on the flow distribution, runout and even the flow path direction. Simulations revealed several flow characteristics were modelled satisfactorily with Titan2D such as superelevation, flow divergence and convergence, ponding and uphill flow, and overbanking. At abrupt changes in channel direction, particularly where the Río Chili canyon opens out from a steep sided gorge to a wide river valley (near the Chacani hydro-electric dam) the flow forms temporary ponds, or even ceases to move altogether; the basal topography has great influence on the simulated flow. Obstacles in the path of a mass flow also affected the simulation, with flows diverted around a hummock or similar obstacle. An example of this can be seen in Titan2D simulations by Stinton et al. (2004) where a modelled flow diverges around an obstacle in the channel and converges again. The simulated flow (in Quebrada San Lazaro) clearly diverges upstream ahead of the obstacle, flowing around in two pulses that converge downstream of the obstacle. This is due to the fact that Titan2D simulated flows react well to underlying topography.
Along with previous authors (Stinton et al. 2004; Delaite et al. 2005; and Vargas et al. 2007) we recognised that the largest flow volume simulated by Titan2D (11.0 x 106 m3) did not reach further than the smallest volume of a flow (1.5 x 106 m3) modelled for LaharZ (Delaite et al., 2005) and discrepancies may be explained by the differing models. LaharZ is a statistically based method for delineating lahar-prone zones (Schilling, 1998), while Titan2D is a depth-averaged, thin-layer Computational Fluid Dynamics program (Pitman et al., 2003).
Small differences in flow characteristics were observed (convergence, ponding, uphill flow, and overbanking) when making comparisons between the 10 m and the 30 m DEM. However, this was mostly confined to simulations of larger flow volumes where the flow occurred within the DGPS study area. More detailed geographical data is required upstream of the Arequipa city centre to refine the better resolution DEM.

ASSESSING THE PHYSICAL VULNERABILITY OF BUILDINGS AND INFRASTRUCTURE: CLASSIFICATION OF CONSTRUCTION AND LANDUSE

Modelling of the runout and extent of volcanic mass flows is important to identify areas that could be affected during a future mass flow event; similarly it is just as important to identify the elements that could be at risk during such an inundation. Damage caused by volcanic mass flows has been observed during historic eruptions such as Vesuvius in AD 79 and 1631, Nevado del Ruiz in 1985, and Soufrière Hills Volcano in 1997 (Spence et al., 2004). Damage resulting from lahars and floods can include burial, foundation failure, debris impact with forces as high as 10^4-10^6 kgm^{-2}, transportation, excessive wall or roof loads, collapse, undermining and corrosion. A survey was carried out on the characteristics of buildings and infrastructure within the study area. Different classes of building were identified with the aim to define the probability of a building being in a particular damage state, given the intensity level of the particular hazard concerned.
The descriptive survey using a method adapted from Chevillot (2000) and Spence et al. (2004) was conducted at street and city block level and where permitted, within the boundaries of the land-owners property. Building types were defined according to the dominant building material; number of floors; building reinforcement; roof type and style; opening type and quantity; and overall building structural integrity. Nineteen land-use patterns and ten construction types were identified (refer to table 1 and figure 3).

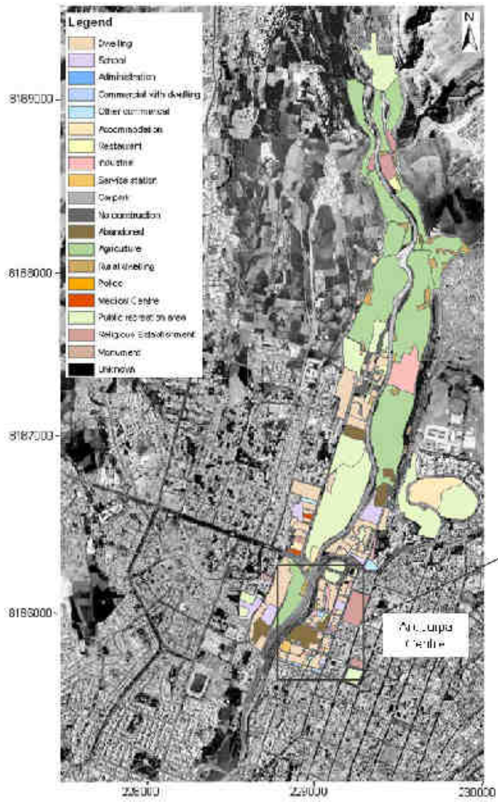
Type A	30%	**Type F**	10%
•Unconfined masonry panels, typically 1-2m in each direction. Wall material generally consists of perforated clay bricks or concrete blocks that are un-reinforced. •Cast-in-situ reinforced concrete frames (horizontal and vertical). Generally reinforced with four No.3 (9mm) bars and traverse ties of heavy-gauge wire. •Commonly in-situ filler block floors. •Roof is mostly flat or pitched built of reinforced concrete slabs. •Some covered with stucco which may increase the strength and stiffness. •Large glass windows throughout the building, often with aluminium framing and lower windows secured with steel bars. •Doors are generally solid and wooden, with steel security screen/bars. •Overall building is well finished with paint, fencing and security. The building and surrounds are well-kept. •Upper-class houses, clubs, hotels, churches, schools, medical centres		•The same structural components as Type A buildings, however the structure is degraded and unstable. •The building is often unfinished or constructed poorly, or has been damaged (e.g. earthquake) and not remedied. •Ground floor and 1st storey consructed from brick with no stucco or paint. •Windows are often small and few with aluminium or wood framing. It is not uncommon for the windows to have no glass or to be boarded up. Security bars not as common as buildings of Types A-C. •Doors are constructed of mainly tin/aluminium, and are somewhat flimsy and with or without security. •Roofing is the same as Type A or constructed of corrugated iron. The overall quality is poorer than that of Types A-C. The corrugated iron roofing is often held in place by objects such as rocks and pieces of wood if not nailed in place. •Overall long-term evolution of the structure will be negative. •Overall, the environment and building are not well kept.	
Type B	24%	**Type G**	5%
•The same structural components as Type A buildings, however the structure has not been completed (even though occupied). •Often the ground floor is completed and the second floor unfinished with exposed brick and no paint. •Often the ground storey is lived in but not completed to the same standard as Type A buildings. •In some cases there is evidence of a 3rd storey in construction. With incremental building the vulnerability of the structure increases due to inadequate connections with the existing structure, as well as unsymmetrical configuration. •Windows, doors and roofing are the same as Type A buildings. •The overall evolution of the structure is positive and the house is well finished with paint, fencing, and security. The building and the surrounds are well-kept.		•The building generally comprise of an old base constructed from stones and ignimbrite. •The walls are constructed from ignimbrite, brick or adobe and are not confined by either reinforced horizontal or vertical cast-in-situ concrete, and in many cases appear quite unstable. •Roofs typically constructed with corrugated iron placed on wooden rafters and held in place by rocks, bricks, wood etc. In some cases they are nailed into place.	
Type C	11%	**Type H**	1%
•Same structural components as Type A buildings, however the structure has not been completed (even though occupied). •Ground floor and 1st storey are in bricks (no stucco or paint). •Vertical extension unfinished and some material that has been used are unstable. •Windows, doors and roofs often the same as Type A buildings. Roofs may be constructed with corrugated iron. •Overal long-term evolution will be positive. •Environment and building not well kept. •Body of building fenced •Often used for professional use e.g. factory		•Building construction a composition of heterogeneous objects, such as bricks (red, ignimbrite, and adobe), rocks, plastic, wood, straw, iron etc. •Little to no structural integrity. No constructed floor (ground, plastic etc.). No windows or doors. Roof is constructed out of any material available. •Slum environment with construction mainy by illegal squatters. •Overall long-term evolution will be negative. •Environment and building not well kept.	

Table 1. This table shows an example of our classification of buildings in Arequipa according to the main structural components and overall appearance (adapted from Chevillot, B, 2000). The surveys were undertaken from street level, and within the properties where permitted.

Most new construction comprised un-reinforced masonry panels (perforated red brick, or ignimbrite brick and mortar) with cast-in-situ reinforced concrete frames (horizontal and vertical), and flat or pitched reinforced concrete slab roofs. Large glass windows are present throughout with aluminium or wood framing and often secured with steel bars. Doors are solid and wooden with steel security screen/bars. Type A buildings represented 30% of those surveyed. Conversely, Type G construction comprised old stone/ignimbrite base with unreinforced masonry panels (ignimbrite, brick or adobe, with poor quality mortar). The walls are not confined by either reinforced horizontal or vertical cast-in-situ concrete, and in most cases appear unstable. Wooden rafters support corrugated iron roofs which are secured by rocks and wood. These buildings represented 5% of those surveyed, and were more commonly situated on the lower terraces of the Río Chili River and associated with agricultural lifestyle blocks. Less than 50% of the population surveyed reside in dwellings less than a Type C, however, the majority of those are situated in areas that are more hazardous (e.g. Río Chili lower terraces) areas.. Housing of poorer quality was often situated in the most vulnerable areas upstream of the city and within the river channels (apart from type A housing located on the confluence of the Río Chili and Qda. San Lázaro).

Land-use varied from agriculture to dense urban environments. Agricultural land is more common towards Chilina; where extensive crops occupy lower terraces of the Río Chili River, however, new housing developments are being built in these areas as pressure for land increases. La Posada del Puente Hotel, Sports Club (Club Internacional), tourist restaurants (La Choceta and Sillustani), a University (Universidad Catolina San Pablo) and a power station (Egasa) are some of the businesses located on the lower terrace adjacent to the Río Chili River.

Infrastructure within Arequipa is also susceptible. Bridges located within the Río Chili River are prone to debris accumulation due to their low deck height. During the floods of February 1992 and 1997 debris accumulated behind the bridges, subsequently overtopping and flooding nearby homes and businesses. If bridges are destroyed, access from one side of the city to the other will be severely limited. Water pipes and power lines are often located at bridges, and are thus equally susceptible to damage. Services such as the Egasa power station and the hydro-electric dams are vulnerable to inundation from even small volume lahars, possibly resulting in the severe disruption of power supply to the city, and having a flow-on effect for lifeline services such as hospitals and other emergency services.



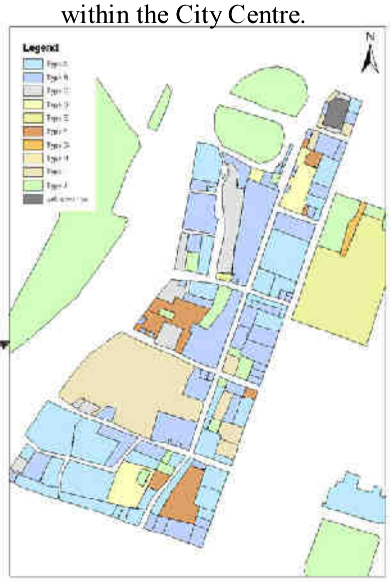


Figure 3. Orthophoto indicating the dominant landuse from the Bolognosi Bridge to the Military School in Chilina. The inset map below shows the classification of building stock (refer to Table 1) within the City Centre.

DISCUSSION

Numerical flow modelling assists in the identification of areas that could be prone to inundation during a volcanic mass flow event. Expected deposit thicknesses and flow velocities are additional outputs in the modelling process. All of which are important elements when defining the likely damage states of buildings inundated by volcanic mass flows.

The simulation of numerical flow models at El Misti has been challenging as a result of considerably different results obtained from two codes, Titan2D and LaharZ. While Titan2D models the behaviour of debris flows adequately, the runout of LaharZ simulations is more comparable to mapped deposits. Titan2D is very receptive to the underlying topography and thus has the ability to produce deposits that exhibit typical flow behaviour. The creation and analysis of a better resolution DEM has improved Titan2D simulations, however, only a small portion of the entire of the overall DEM area was surveyed. Surveying upstream of Arequipa could make a difference to future simulations; and additional research into the input parameters for geophysical flow modelling would be beneficial.

The survey undertaken of the buildings and infrastructure highlights the heterogeneous nature of the construction and landuse in Arequipa. There are a range of construction types, often within the same city block. The poorest quality houses (and not structurally sound) are often located closest to the river channels and in many cases could provide additional debris for the flow. Bridges, which link two sides of the city, are vulnerable due to their low height and narrow spans, acting as a dam for flow debris.

The combination of inundation zones and the characteristics of building and infrastructure highlights areas within the same inundation area that could behave differently due to the dissimilar structural components of the buildings and infrastructure, therefore the risk would be different to what had been previously determined.

REFERENCES

Chevillot B. 2000. Rapport de mission a Arequipa (sud Pérou) 26 julliet – 15 août 2000. Objet: mise en œuvre d'un S.I.G. appliqué aux risques hydrologiques et volcaniques. Rapport., Lab. De traitement de données géographiques ENITA de Clermont-Ferrand, p. 44.

Delaite, G., Thouret, J.-C., Sheridan, M. F., Stinton, A., Labazuy, P., Souriot, T., and van Westen, C. 2005. Assessment of volcanic hazards of El Misti and in the city of Arequipa, Peru, based on GIS and simulations, with emphasis on lahars: Zeitschrift für Geomorphology N.F., suppl.- vol. 140, p. 209-231.

Pitman, E.B., Patra, A., Bauer, A., Nichita, C., Sheridan, M. and Bursik, M. 2003. Computing debris flows. Physics of Fluids, vol. 15, p. 3638-3646

Schilling, S.P. 1998. LAHARZ: GIS program for automated mapping of lahar inundation hazard zones: U.S. Geological Survey Open-File Report 98, p. 638.

Spence R.S.J., Baxter P.J., Zuccaro, G. 2004. The resistance of buildings to pyroclastic flows: analytical and experimental studies and their application to Vesuvius. Journal of Volcanology and Geothermal Research, vol. 133, p. 321-343.

Stinton, A., Delaite, G., Burkett, B., Sheridan, M., Thouret, J.-C., and Patra, A.. 2004. Titan2D simulated debris flow hazards: Arequipa, Peru: Abstracts, International Symposium on Environmental Software Systems (ISESS), U.S.A.

Thouret, J.-C., Finizola, A., Fornari, M., Legueley-Padovani, A., Suni, J., Frechen, M. 2001. Geology of El Misti volcano near the city of Arequipa, Peru, Bulletin of the Geological Society of America, vol. 113, p. 1593-1610.

Vargas F.R, Thouret J.-C., Delaite G., Van Westen C., Sheridan M.F., Siebe C., Mariño J., Souriot T., and Stinton A. 2007. Mapping and assessing volcanic and flood hazards and risks, with emphasis on lahars, in the city of Arequipa, Peru. Geological Society of America Special Publication. (accepted).