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Estimating building and infrastructure vulnerability in the city of Arequipa, Peru, from volcanic mass flows: A challenge

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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 SW of and 3 km below the summit of El Misti. 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 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

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). The "single" phase model is used to model dry flows, and the "two phase" model allows the definition of a solid and a liquid fraction for the simulated flow. Lahars ranging from 0.01×10^6 m^3 to 11×10^6 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 in Titan2D was analysed using changes in the simulation parameters and the impact of flow features such as starting point, internal and bed friction angles, solid fraction, runout, super-elevation, ponding,, flow divergence and convergence were examined. Previous simulations performed on a 30 m DEM, based upon digitising 1:25,000-scale topographic maps and on radar interferometry, compared Titan2D with LaharZ and highlighted discrepancies between the two models. The largest flow volume simulated by Titan2D (11.0×10^6 m^3) did not reach further than the smallest volume of a flow (1.5×10^6 m^3) modelled for LaharZ (Delaite *et al.*, 2005), refer to figure 1. 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).

To investigate the effect of the DEM on simulated results a 10 m DEM was computed using DGPS data, aerial photographs and stereophotogrammetry. Detailed topographical data 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). Characteristics such as overbanking, uphill flow, lateral spreading and flow divergence and convergence were identified in Titan2D simulation outputs, and the results are more realistic than flow features identifies from LaharZ simulations. 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 flows form temporary ponds or even cease moving altogether. The DEM will be further refined with additional DGPS data to be collected this year, and compared with previous DEMs. Lahar-prone areas and eruption scenarios will be now used to establish the impact of mass flows on buildings and infrastructure within the city of Arequipa.

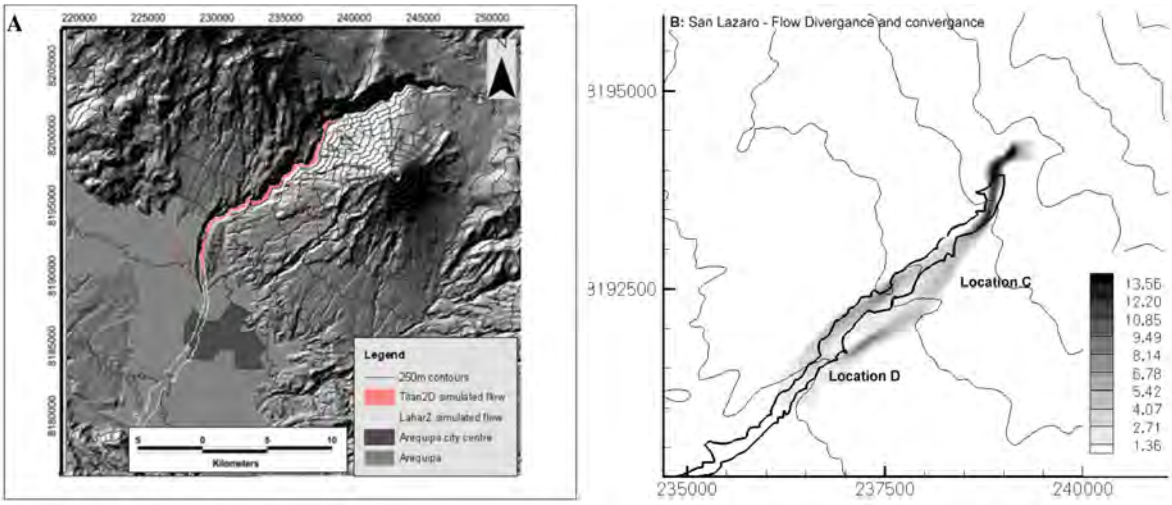
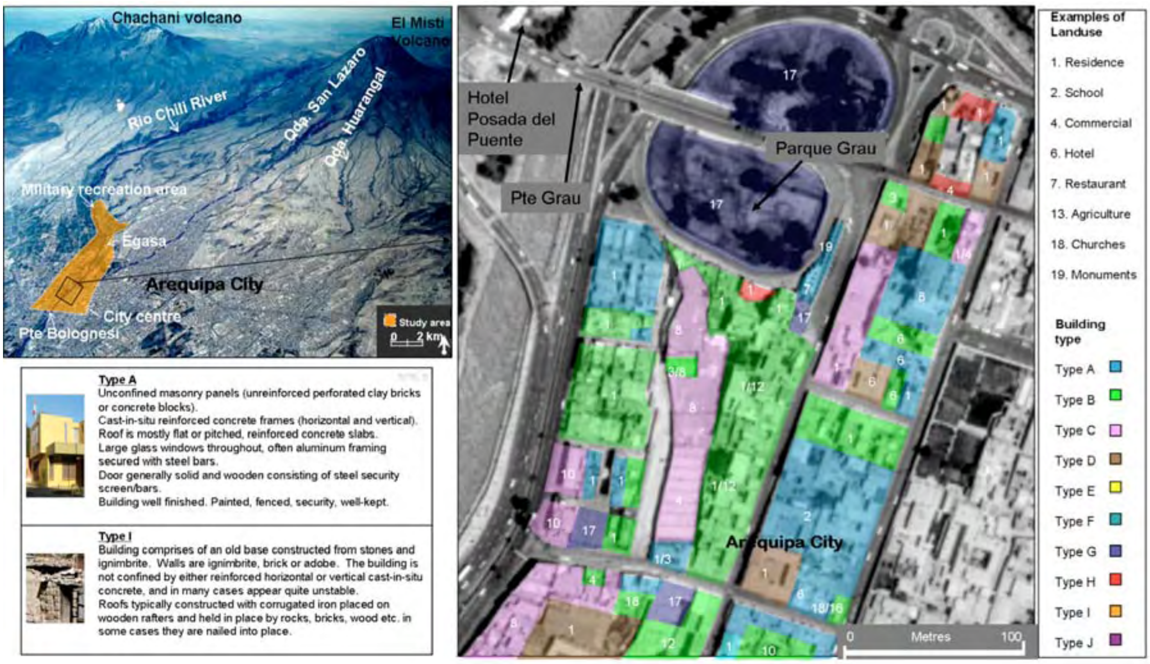


Figure 1. ***A***– Map showing the difference between Titan2D runout and LaharZ runouts. ***B*** – example of flow divergence and convergence with Titan2D modelling on Qda. San Lazaro. This closely resembles reality as the flow moves around an obstacle in the channel. The dark black outline is the LaharZ simulated flow outline (Stinton *et al.*, 2004).

Assessing the physical vulnerability of buildings and infrastructure: Classification of construction and landuse

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 that may be vulnerable to flow impact, 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.



Type A
Unconfined masonry panels (unreinforced perforated clay bricks or concrete blocks).
Cast-in-situ reinforced concrete frames (horizontal and vertical).
Roof is mostly flat or pitched, reinforced concrete slabs.
Large glass windows throughout, often aluminum framing secured with steel bars.
Door generally solid and wooden consisting of steel security screen/bars.
Building well finished. Painted, fenced, security, well-kept.

Type I
Building comprises of an old base constructed from stones and ignimbrite. Walls are ignimbrite, brick or adobe. The building is 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.

Figure 2. *Top left* – location map of the study area in Arequipa city centre in relation to El Misit. *Bottom left* – examples of two Types of buildings surveyed. *Right* – Classification map of the landuse and building construction classification in a section of the city centre.

Nineteen land-use patterns and ten construction types were identified (Figure 2). Most new construction comprised un-reinforced masonry panels (perforated red 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 I construction comprised old stone/ignimbrite base with unreinforced masonry panels (ignimbrite, brick or adobe, with poor quality mortar). The walls were 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 Rio Chili and associated with agricultural lifestyle blocks. Less than 50% of the population surveyed reside in dwellings less than Type C. 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).

Bridges located within the Río Chili River are susceptible to debris accumulation due to their low 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.

Discussion

At El Misti challenges have arisen due to the considerably different results of 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. Even on our enhanced DEM, these discrepancies arise; thus the need for additional DEM refinement and research into the input parameters for geophysical flow modelling. Our results highlight that simulations must only be used as a tool alongside geological mapping to aid the delineation of inundation zones. The results of the building and infrastructure survey identified a range of construction types, and 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. Further modelling would aid the characterisation of building and infrastructure vulnerabilities by redefining likely lahar prone zones, and therefore expected deposit thicknesses and flow velocities; all of which are of importance when defining the likely damage states of buildings inundated by volcanic mass flows.

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