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Volcanic risk assessment: Quantifying physical vulnerability in the built environment

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ABSTRACT

This paper presents structured and cost-effective methods for assessing the physical vulnerability of at-risk communities to the range of volcanic hazards, developed as part of the MIA-VITA project (2009–2012). An initial assessment of building and infrastructure vulnerability has been carried out for a set of broadly defined building types and infrastructure categories, with the likelihood of damage considered separately for projectile impact, ash fall loading, pyroclastic density current dynamic pressure and earthquake ground shaking intensities. In refining these estimates for two case study areas: Kanlaon volcano in the Philippines and Fogo volcano in Cape Verde, we have developed guidelines and methodologies for carrying out physical vulnerability assessments in the field. These include identifying primary building characteristics, such as construction material and method, as well as subsidiary characteristics, for example the size and prevalence of openings, that may be important in assessing eruption impacts. At-risk buildings around Kanlaon were found to be dominated by timber frame buildings that exhibit a high vulnerability to pyroclastic density currents, but a low vulnerability to failure from seismic shaking. Around Fogo, the predominance of unreinforced masonry buildings with reinforced concrete slab roofs suggests a high vulnerability to volcanic earthquake but a low vulnerability to ash fall loading. Given the importance of agriculture for local livelihoods around Kanlaon and Fogo, we discuss the potential impact of infrastructure vulnerability for local agricultural economies, with implications for volcanic areas worldwide. These methodologies and tools go some way towards offering a standardised approach to carrying out future vulnerability assessments for populated volcanic areas.

1. Introduction

Damaging volcanic processes vary widely in their potential impact for the built environment over space and time. As a general rule, explosive volcanic eruptions are more damaging and result in more widespread impacts than their effusive counterparts. Immediate damage includes violent destruction through lateral forces and vertical loads, burial and exposure to high temperatures within pyroclastic density currents, lahars and debris flows. Buildings or key components of infrastructure that experience little or no physical damage can still be subject to a reduced or lost functionality, often at relatively low hazard intensities. Longer-term impacts include a reduction in the health and socio-economic wellbeing of affected communities through temporary or permanent relocation and a loss of housing or livelihood, particularly for agricultural economies that rely on the land. These impacts depend to a considerable extent upon the physical vulnerability of the different built components to the range of volcanic hazards. Physical vulnerability assessments are thus vital in helping to forecast the range of damage and disruption – and therefore casualties, losses and reconstruction costs – that may result from a future eruption. They can also be used to infer hazard dynamics, e.g. lateral dynamic pressures, from damage assessments.

Data that inform physical vulnerability estimates are generally sourced in three ways: 1) Collection of post-eruption empirical damage data (e.g. Baxter et al., 2005; Wilson et al., 2011); 2) Experimental testing of material and structural failure (e.g. Zuccaro, 2000); and 3) Theoretical calculations of material strengths (e.g. Petrazzuoli and Zuccaro, 2004; Jenkins et al., 2013). Quantitative observation data collected during or immediately after a damaging event are scarce due to the danger and inaccessibility of impacted zones and the comparatively low frequency of large eruptions impacting urban areas. Experimental data are also limited, and, where available, refer exclusively to materials, strengths, building codes and standards exhibited by the tested building stock. In the absence of observation data, theoretical calculations of

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building response to hazard parameters add greatly to the availability of quantitative information and, often in conjunction with engineering expert judgement, can support the creation of vulnerability functions. Vulnerability functions outline the probability of a certain level of damage occurring as a function of hazard intensity, with damage levels for buildings ranging from window failure to structural collapse and typically categorised by construction type. A large range of variables influence building response to volcanic hazards, including the age and condition of the structure, the workmanship and construction quality and the use of transient components such as shutters. The advantage of a vulnerability function, or curve, is that it accounts for some of the uncertainty inherent in forecasting building response without a detailed knowledge of each building and when faced with poorly understood and complex damaging phenomena. Vulnerability functions are common in seismic risk assessments but less so in volcanic risk assessments due to the infrequent and complicated nature of volcanic hazards and the difficulties in reproducing the physical processes in the laboratory.

To date, physical vulnerability estimates have typically focussed on one volcanic hazard (e.g. tephra fall: Spence et al., 2005) or, for the few studies that are multi-hazard, one volcano (e.g. Vesuvius: Zuccaro and De Gregorio, 2013). With this in mind, and drawing upon existing knowledge and practice, our study focussed on providing standardised survey methodologies and multi-hazard vulnerability estimates that could then be updated and expanded following local field studies at any volcano. This work comprised four main components, reflected in the layout of this paper: firstly, an initial assessment of building vulnerability has been carried out for a set of broadly defined building types, detailed in Section 2. Secondly, we considered that any loss or disruption to infrastructure (such as water, transport or electricity networks) is likely to fundamentally impact local economies and livelihoods and so infrastructure vulnerability should also be incorporated into any assessment of potential eruption impact. Thus, in Section 3 we identify critical infrastructure elements that support socio-economic activities in volcanic areas and qualitatively discuss their vulnerability to the key volcanic hazards. In the third part of the paper (Section 4) we discuss physical vulnerability survey methodologies and data requirements for more detailed study. In the final section (Section 5), we apply our methodology to two case studies by refining the preliminary vulnerability estimates of Section 2 through field surveys of the characteristics and distribution of exposed buildings, the local agricultural economy and infrastructure at Kanlaon volcano in the Philippines and Fogo volcano in Cape Verde. These volcanoes were chosen from the range of MIA-VITA (2009-2012)target volcanoes in developing regions because there had been no previous assessments of the physical vulnerability of the surrounding areas to volcanic hazards and because they represent differing volcanic settings and building stock profiles that may offer insights into a wider range of analogous volcanoes.

2. Preliminary estimates of building vulnerability

Quantifying the vulnerability of buildings may be undertaken for three primary reasons: firstly, to identify buildings that may benefit most from mitigation measures that could be undertaken to ensure the safety, as far as possible, of inhabitants (or livestock) who may be trapped in buildings during a volcanic eruption; secondly, in cases where the area has been successfully evacuated prior to an eruption, to quantify the potential damage for loss estimation and rehabilitation planning; and thirdly, to support the development of criteria or guidelines for construction of new buildings and modification of existing buildings. The term vulnerability is used here in the engineering sense as the likelihood of achieving a certain damage state given certain hazard intensity, for example the likelihood of roof failure as a function of ash fall load. Damage from volcanic hazards such as lava flows, lateral blasts, sector collapse or debris avalanche damage can be considered binary, with total damage in the areas impacted and zero damage in areas not impacted, regardless of building type (Table 1). This may be simplistic in some cases because, for example, lava flows can cause fires outside of the zone of impact (Blong, 1984) and damage may be gradational towards the peripheries of lateral blasts (Jenkins et al., 2013).

Major volcanic hazards that do inflict gradational damage affect different components of a building (Table 1) and so require separate estimates of vulnerability. Over the following subsections, we discuss the damage and categorise major building types for each of the key volcanic hazard parameters: impact energy (projectiles), horizontal load (ash fall), lateral dynamic pressure (pyroclastic density current) and ground shaking (volcanic earthquake). In many cases, building types borrow from extensive seismic building stock data inventories (e.g. Zuccaro and Papa, 2002; Spence et al., 2008; Jaiswal et al., 2011). In the absence of local building data, we provide preliminary estimates of vulnerability for each of the major building types and each of the hazards. To do this, we considered the existing knowledge and literature, including empirical data collected post-eruption, experimental data collected through the testing of certain materials, theoretical calculations of building strength and engineering expert judgement. This draws in particular on several previous collaborative studies and surveys of building vulnerability to volcanic eruptions developed through the EU-funded European Laboratory Volcanoes project (1994–1996: Casale et al., 1998), the EXPLORIS Project (2004–2007: Marti et al., 2008; Spence et al., 2005; Spence et al., 2007; Zuccaro et al., 2008), the SPeeD Project (2009–2011: Jenkins and Spence, 2009a) and field observations following the eruptions of Pinatubo in 1991 (Spence et al., 1996), Montserrat in 1997 (Baxter et al., 2005) and Merapi in 2010 (Jenkins et al., 2013). These vulnerability values act as a starting point for more refined estimates and should be re-evaluated when new data become available, i.e. following post-eruption impact assessment or engineering studies. Vulnerability estimates based on the generic building types outlined in this section should not be used within a risk assessment without a sufficient knowledge and understanding of the local building stock characteristics and distribution, typically identified through comprehensive field surveys, to ensure the suitability of the classification.

2.1. Projectiles

Explosive eruptions produce hot projectiles that vary in size from 6.4 cm to 100 cm and can potentially impact more than 10 km from the vent, but more typically land within 5 km (Blong, 1984). The impact energy of projectiles is enough to puncture holes in roofs (Fig. 1), kill people or livestock through blunt trauma, damage critical infrastructure components and cause serious damage to crops. Projectiles not large or dense enough to penetrate roofs can contribute to roof collapse through overloading or through repeated impacts that may seriously weaken a structure and leave it more vulnerable to future impacts or hazards. A projectile's impact energy (E_i, in Joules) and thus potential to cause damage, is a function of its mass (m, in kg) and terminal velocity (v, in m/s), as shown in Eq. (1). v in turn depends primarily on the height to which projectiles have been ejected

$$E_i = \frac{1}{2} m v^2. \tag{1}$$

Blong (1981) and Pomonis et al. (1999) consolidate and summarise empirical and experimental examples of blocks and bombs penetrating roofs and identify relationships between roof materials and the impact energy required to puncture such roofs for projectiles of varying size, shape and density; we present salient results for six key roof classes in Table 2, which can be considered preliminary vulnerability estimates. Projectile impact to sheet or slab roofs is resisted by a single structure over the whole roof area, while for tiled roofs each tile is a separate structure with a relatively small area that may be damaged at lower impact energies. The brittle nature of tiles also means that once they have been damaged they will probably require replacement. Tiled roofs are