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PART 5: From volcanic hazard to risk assessment

Chapter 3.3 – Quantifying damage and vulnerability for volcanic hazards

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Abstract

Reducing volcanic risk requires a comprehensive understanding of the potential impacts of volcanic hazards on various community elements, assets and critical infrastructure. This chapter considers systematic approaches to characterizing the interaction (impacts) between volcanic hazards and assets (broadly defined). Damage states provide a description of volcanic hazard impacts and can be used in pre- and post-eruption impact assessments. Fragility and vulnerability functions provide quantitative approaches for assessing impacts and can be used in conjunction with damage states to forecast likely impacts pre- and post-eruption. Fragility functions quantify the probability of reaching specific damage states, while vulnerability functions express mean damage or function loss. Despite challenges including limited data availability and discrepancies in hazard intensity measurements, these functions serve as critical links between hazard and risk assessments, informing disaster preparedness and response efforts and finding application in the insurance industry. Ongoing research is essential to refine these functions and improve impact, vulnerability and risk assessment accuracy.

Keywords

Fragility function, vulnerability function, damage state, function fitting.

1. Introduction

Reducing volcanic risk requires an understanding of the breadth and severity of impacts from different volcanic hazards considering their intensities and characteristics. Understanding the vulnerability of key community elements (e.g., critical infrastructure, buildings, agriculture) to volcanic hazards is fundamental in systematically documenting and assessing potential impacts and risk from future eruptions. For example, understanding the probability of a certain roof type collapsing under a given tephra thickness. This understanding enables the development of effective initiatives that improve community resilience, a key aspect of the United Nations' Sustainable Development Goal 11, to "make cities and human settlements inclusive, safe, resilient and sustainable".

Qualitative and quantitative approaches can be used to assess the vulnerability of exposed assets to volcanic hazards. Describing volcanic hazard impacts to different exposed assets forms an important foundation of volcanic impact data collection and empirical knowledge. Organizing these descriptors, or damage states, into a damage scale (an ordinal scale) provides a way to describe damage from volcanic eruptions. We discuss how damage states within a damage scale are developed and used to assess damage pre- and post-eruption in Section 2.

While descriptions and damage states are informative, a move towards quantification of impacts could facilitate robust quantitative risk assessments. A common approach is the use of fragility and vulnerability functions, which quantify the relationship between hazard intensity and damage. Fragility functions describe a range of possible damage outcomes and their associated probabilities, whereas vulnerability functions describe the mean damage response of an asset. We discuss how fragility and vulnerability functions are developed and used in volcanology and provide some examples in Section 3.

This chapter builds upon the vulnerability concepts introduced by Blong [1], and Aspinall and Blong [2] in the first two editions of the Encyclopedia of Volcanoes, by providing an updated overview of efforts to quantify volcanic fragility and vulnerability. In relation to the other chapters in Part 5 of this edition, this chapter is the key link between Chapters 2.1, 3.1, and 4. Hazard intensity outputs and exposure assessments (Chapters 2.1 and 3.1) are used with fragility and vulnerability functions (this chapter) to determine damage, within a risk assessment (Chapter 4.1).

1.1. Damage state and fragility function/vulnerability development framework

An approach to create damage states and fragility and vulnerability functions is outlined in Fig. 1. This approach is based on similar frameworks used for earthquake and tsunami vulnerability assessments. The ‘define hazard intensity metric’ and ‘function fitting’ steps apply specifically to fragility and vulnerability function development. All other steps apply to both damage state and fragility and vulnerability function development. The aspects in Fig. 1 are discussed throughout this chapter.

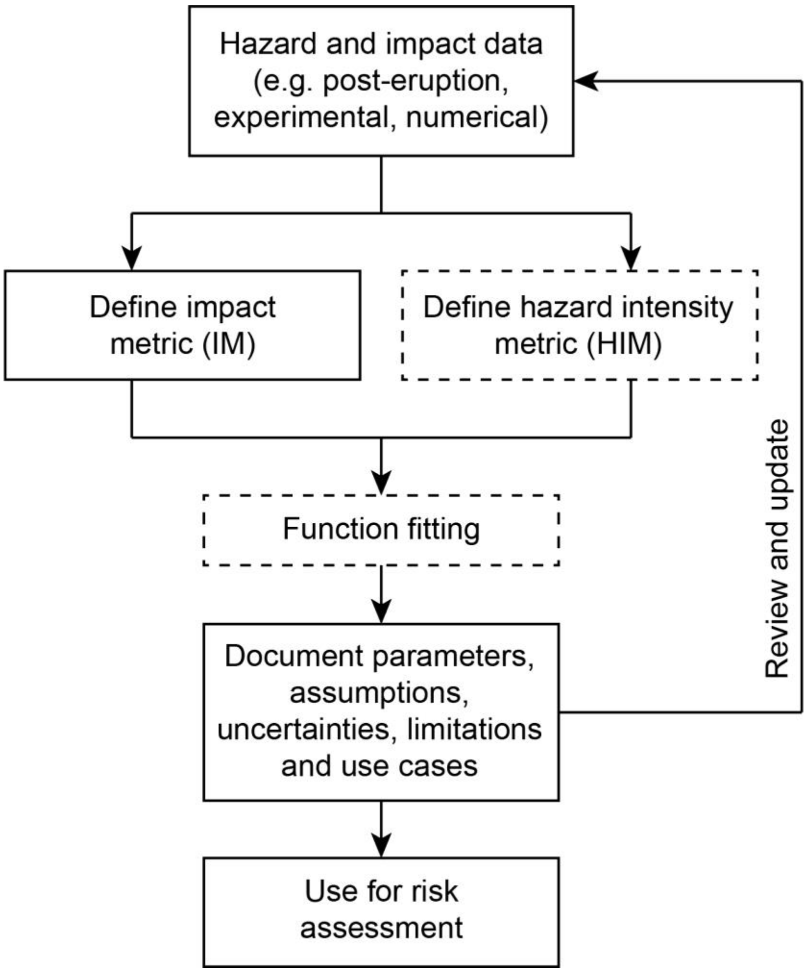

Fig. 1: Framework for developing volcanic damage states and fragility and vulnerability functions. The dashed boxes apply specifically to the development of fragility and vulnerability functions.

1.2. Impact data

Impact data used to develop damage states, and fragility and vulnerability functions, come from a range of sources. These data can be classified into post-eruption impact assessments, laboratory experiments, expert judgment, numerical modeling and hybrid data (Table 1).

Table 1: Classification, advantages and disadvantages of volcanic impact data used to develop damage states, and fragility and vulnerability functions, after [3] used under Creative Commons Attribution 4.0 International License http://creativecommons.org/licenses/by/4.0/.

Data type	**Advantages**	**Disadvantages**
Post-eruption impact assessments	Range of volcanic hazard and infrastructure characteristics taken into account. Previous impacts are likely to occur again in the future.	Data highly site-, region-, infrastructure-specific. Scarce data of variable quality. Does not always capture data from assets that are exposed to a hazard but not impacted. Damage from older eruptions may not be characteristic of recent eruptions (i.e., building construction methods and materials have improved over time).
Laboratory experiments	Repeatable experiments in controlled conditions. Can target gaps in current data with specific experiments.	Difficulties in replicating volcanic hazards and some asset types in the laboratory.
Expert judgment/elicitation	Consider a wide range of impacts, including those not previously observed. Not limited by impact data or models. Can be used to refine and update existing functions. Widely accepted elicitation methods available.	Quality depends on subjectivity and expertise, particularly if experience consists of atypical eruption impacts. Can be difficult to validate. Differing and contradictory opinions.
Numerical modeling	Increased reliability and repeatability and reduced bias. Models can be validated against post-eruption impact data. Can be extrapolated to new situations.	Substantial computation may be required for more complex modeling. Models based on simplifications and assumptions.
Hybrid - combination of different approaches	Can reduce limitations and uncertainties through the combination of different data types.	Limitations are the same as individual approaches. Differences in data scale and aggregation.

Due to the limited impact data sets available in volcanology, the hybrid data approach is most often used. When combining datasets, care is required to do this appropriately, as there will be different biases, sources, and magnitudes of uncertainty amongst datasets [4]; these discrepancies can influence the quality of the output(s).

For example, with post-eruption damage assessment data, there may be many different datasets available for numerous eruptions and locations, all of which could be of variable detail and quality. Wilson et al. [3] recommends that prior to combining datasets, impact data should be harmonized by assuring that: (1) data type are of the same form, e.g., if one dataset is at building-by-building scale and another contains grouped data (e.g., multiple buildings in one area), the more detailed data should be aggregated to the grouped scale; (2) building and infrastructure typologies are consistent among datasets; if not, the most general typologies should be used; and (3) impact scales are identical across datasets; if not, a conversion to the coarsest scale (i.e., the scale with the least levels) should occur. Ensuring consistency among the different datasets permits more meaningful derivation of vulnerability and fragility functions.

2. Damage states

2.1. Overview of damage states

Damage states are used to describe and categorize different levels of damage to particular items of interest (e.g., buildings, infrastructure, agriculture). They are widely used to categorize damage for other hazards such as earthquake, tsunami and flood. Damage states typically form an ordinal scale whereby an individual damage state is assigned to each level of damage. In this case, the order of the damage states matter but not the difference between the states. In practice, the most useful damage states are simple so that they can be applied across different asset types but granular enough to reveal insights on the observed damage and the damaging event (e.g., exposure to a volcanic hazard).

2.2. What are damage states commonly used for

Damage states are developed and applied in two settings in order to assess the impacts: 1) syn- or post-eruption to collect and catalog impacts that have occurred; and 2) pre-eruption (anticipated or in a hypothetical scenario) to forecast impacts that may occur.

2.2.1. Assessing impacts post-eruption

Damage states provide a simple way to document and quantify impacts syn- or post-eruption. The caveat here is that the damage states have to exist and be appropriate for the damaged assets being assessed. However, as mentioned in Section 2.3, one of the ways to create damage states is by conducting field damage assessments - therefore, this process can be iterative.

The main method for conducting post-eruption damage assessments is physically going into an area impacted by volcanic hazards to record the data. Simplistically this involves documenting the location of the damaged asset, the type of damaged asset (e.g., building type, farm type), the damage state, and the hazard intensity (e.g., tephra thickness) at that location. Some authors (e.g., [5, 6]) assign data quality metrics alongside damage states to indicate the reliability and uncertainty of the data. This can be a time-consuming process that requires thoughtful safety and ethical considerations. Increasingly, additional methods of data collection such as photos or satellite imagery (see Kelud Volcano Case Study) have become more widely used to supplement gaps that can occur from physical field data collection.

The added benefit of doing a post-eruption damage assessment is that it leads to the refinement of damage states, and fragility and vulnerability functions, as more data are available (see Box 1).

2.2.2. Forecasting impacts pre-eruption

Damage states can be used in hazard and risk assessments to provide indications of what the likely impacts are in an area not previously impacted by an eruption, based on a particular scenario(s) (e.g., [7]). For example, building damage can be estimated using damage states by using the output of a tephra fall model for a particular volcano and available information on the exposed building typologies. To do this, the damage states need to be associated with suitable tephra fall intensity metrics (e.g., thickness, load) for each of the damage states such that a damage state can be estimated from the tephra fall model output. Using damage states in this way provides an indication of which assets are most vulnerable and would benefit from mitigation actions to prevent or limit damage from further eruptions.

Box 1: Lava flow damage states

Many early lava flow damage states treated impacts as binary, i.e., damage either occurred or not based on the presence or absence of the flow. After reviewing the literature and revising imagery from the 2018 lower East Rift Zone lava flows of Kīlauea volcano, Island of Hawai`i, Meredith et al. [6] created a six-point damage state schema for lava flows (Fig. 1). This framework for assessing lava flow damage expanded upon and added significant detail to previous work, which classified lava flow damage from Fogo, Cabo Verde in 2014-2015 as unaffected, damaged, or destroyed. Both studies concluded that the assumption of binary damage from lava flows is an oversimplification that limits the ability to forecast damage from lava flows. Meredith et al. [6] found that structures impacted by thicker lava (>2 m) did show binary impact (complete destruction), whereas structures impacted by thinner lava (< 2 m) showed a range of damage states, with circular and metal structures being particularly resilient. Meredith et al. [6] noted that due to data availability they chose lava thickness and proximity to lava as the hazard characteristics but recognize that morphology, viscosity and velocity may also contribute to damage. See also the chapter on lava flow impacts (Part 4, Chapter 2.1) for more discussion around how these parameters can act as impact agents.

2.3. Creating damage states

Most damage states in volcanology are developed using damage information collected from field observations after volcanic eruptions (Section 2.2.1). Some have been developed by reviewing damage data from a range of different volcanic eruptions globally to create generic damage states that cover a range of damaged assets, while others are developed in the field specifically for the damaged assets present at a particular location. In some cases, generic damage states have been used and modified to fit the specific building types. For some assets, there might be opportunities to undertake laboratory experiments which can fill in data gaps and refine damage states for different assets.

The choice of the number of damage states will depend on the information available, the type of asset the states are being developed for, and the use-case context (i.e., the different data requirements for insurance assessment versus rapid information gathering for emergency management). A suitable level of differentiation between damage states is required so that the extent of damage can be adequately determined, but the states should not be so specific that they cannot capture all damage exhibited across the study area.

Most commonly, damage states are 4-6 levels where damage state DS0 is no damage and the highest damage state is complete damage or destruction. Different authors have used different scales for various asset types, so that, for example, a DS3 is not comparable across scales but the highest number in all scales represents total damage and the lowest no damage; for example: Bautista et al. [8] - lahar: DS0-5; Craig et al. [9] - tephra: DS0-4; Hayes et al. [5] - lahar/tephra DS0-5; Jenkins et al. [10] - lahar: DS0-4; Meredith et al. [6] - lava: DS0-5; and Wilson et al. [11] - tephra: DS0-3. See Figs. 2 and 3 for some examples of damage scales for tephra and flow hazards respectively.

While the states are commonly referred to as ‘damage’ states, research has also focused on disruption, function loss and criticality (e.g., [9, 13, 14]). States that capture a broader range of impacts, such as disruption, may be referred to as impact states. Impact may occur in the form of disruption to a service, business or asset operation, with or without damage (i.e., physical effect on the asset). By examining observed impacts and hazard intensity relationships, Wilson et al. [11] found that most infrastructure sectors can be disrupted by the direct impact of tephra fall, pyroclastic density currents (PDC) and lahars in addition to being damaged. Disruption typically initiates at lower hazard intensities than damage. For example, during low intensity tephra falls, there is not enough accumulated tephra mass to cause any static loading damage on infrastructure components (e.g., roof collapse of a power station) and therefore the tephra will simply accumulate on exposed components causing disruption (e.g., blockages of air and water filters, covering of road markings). Likewise, for low intensity regions of PDCs and lahars (i.e., flow peripheries) the low dynamic pressures may not cause physical damage but may have similar disruption effects as tephra through deposition of material. In addition, the presence of tephra particles in the atmosphere can cause significant and prolonged disruption for some infrastructure. This is particularly the case for transportation where suspended tephra will reduce visibility or damage jet engines. For example, the 2010 eruption of Eyjafjallajökull, Iceland, and subsequent immediate closure of European and North American airspace for six days to prevent aircraft damage.

Figs. 2 and 3 provide non-exhaustive examples of damage states that have been used in volcanology and that could be used and/or adapted for other locations. Note that while the description of each damage state is broadly the same, the characteristics and consequences vary based on the asset and context (such as geographic location).

TEPHRA DAMAGE SCALES

DS[1]	Asset	Description	Characteristics[2]	Consequence[3]
0	Buildings	No damage	No damage caused	
	Small pastoral farms *(< 500 ha)*	No disruption	No damage	No production change
	Large pastoral farms *(> 500 ha)*			
1	Buildings	Minor damage to non-structural elements	• Damage to gutters • Few tiles dislodged • Damage to fittings, e.g., air-conditioning units and appliances • Damage to contents • Dents in the roof covering	Minor repairs and cleaning necessary
	Small pastoral farms *(< 500 ha)*	Some disruption	Pasture available not enough to sustain livestock.	Supplementary feed required to maintain production (up to 15% production loss)
	Large pastoral farms *(> 500 ha)*		Some grazing still available, possible abrasion to milking equipment and condensers for dairy farms	Most losses absorbed within normal boundaries of fluctuating production (<25% production loss), some short-term supplementary feed use
2	Buildings	Moderate damage but vertical structure and roof supports intact	• As above • Bending or excessive (e.g., perforation, cracking) damage (with or without collapse) to up to half of roof covering, e.g., tiles, metal sheet • Little to no damage to principal roof supports, i.e., rafters or trusses • Damage to roof overhangs or verandas	• As above • Interior may require cleaning, repainting, and/or overhaul of electrical systems for habitability and health (e.g., heating and cooking)
	Small pastoral farms *(< 500 ha)*	Moderate disruption	Most animals unable to graze, animal illness/deaths start to occur, open water sources contaminated	Large amount of supplementary feed required (15–50% production loss), possible issues with transportation of animals and products due to road transport disruption
	Large pastoral farms *(> 500 ha)*		Pasture available not enough to sustain livestock	Some supplementary feed required, adverse health effects in exposed animals (~25–50% production loss), possible issues with transportation of animals and products due to road transport disruption
3	Buildings	Severe damage to the roof and supports	• As above • Bending or excessive (e.g., perforation, cracking) damage (with or without collapse) to over half of roof covering • Damage to any single principal roof supports and some damage to walls • Severe damage or partial collapse of roof overhangs or verandas	• As above • Building likely unsafe for occupancy
	Small pastoral farms *(< 500 ha)*	High disruption	Animals unable to graze due to tephra cover, majority of animals dead, in poor condition, or sold, basic soil fertility indicators (nitrogen [N], phosphorous [P], potassium [K]) negatively affected	Discontinuation of normal farm activities (e.g., mating, shearing, etc.) (50–70% production loss)
	Large pastoral farms *(> 500 ha)*		Animals unable to graze due to tephra cover. Possible damage to farm buildings and fences	Total reliance on supplementary feed, widespread animal sales and evacuations (60–70% production loss)
4	Buildings	Partial or total collapse of the roof and supports	• Wall, frame, roof or foundation failure • Collapse of roof covering and any single principal roof support(s) • At least half of the external walls and/or internal walls deformed or collapsed	• Building unsafe for occupancy • Potentially irreversible damage and demolition required
	Small pastoral farms *(< 500 ha)*	Total loss of capabilities	Total abandonment of farm - often permanent, vegetation dead	No production possible for at least one year (>70% production loss)
	Large pastoral farms *(> 500 ha)*		Very low likelihood of soil recovery in the next 12 months, >50 % animal deaths. Difficulties ploughing tephra into soil. Damage to farm buildings likely	Widespread mitigation and rehabilitation needed in order for production to resume (>70% production loss)
5	Buildings	Building collapse	• As above • Collapse of roof, principal roof supports and/or supporting external walls over >50% of floor area of building	• Building unsafe for occupancy • Irreversible damage to most contents and fittings • Demolition required

Notes:
[1] "DS0" through "DS5" in Hayes et al. [5]; "0" through "4" in Craig et al. [9]
[2] "Damages" in Craig et al. [9]
[3] "Effects on Production" in Craig et al. [9]

Demonstration cases:
Hayes et al. [5]: 2015 eruption of Calbuco volcano, Chile
Craig et al. [9]: hazard footprint 1995/6 Ruapehu eruptions and ~1315 CE Kaharoa eruption, New Zealand, using asset data current at time of publication

Fig. 2: Select examples of tephra damage states (DS) used for building damage and agriculture impacts.

BUILDING DAMAGE (FLOW HAZARDS)

DS[1]	Hazard	Description	Characteristics[2]	Consequence[3]
0	Lava flow	No visible damage	No evidence of structural or non-structural damage	
	Lahar	None	-	-
	Pyroclastic flow	No damage	0.5 to 1 kPa	Windows and roof intact. *No or minimal ash penetration. Minimal external burn damage to buildings, including even flimsy wooden houses. No evidence of pushed-over fences or posts, but light charring of wooden posts and vegetation, including trees in places. Infiltration of ash due to window catch or frame in bad condition.*
1	Lava flow	Negligible	Negligible structural damage, minor surface damage, such as melting of plastic exterior façade	
	Lahar	Minor	Infiltration into building under door and through gaps, e.g., cracks or ventilation grills, not produced by lahar	Damage to contents of building
	Pyroclastic flow	Light damage	1 to 3 kPa	One or two windows on side facing crater with windowpane broken, PVC[4] louvers melted, aluminum frame catch in bad condition breaks, allowing ingress of ash. No, limited, or even extensive fire damage to roof. Effects mainly due to intense heat, not dynamic pressure. *Thin layer of ash inside. Heat damage localized to impacted room or rooms, and even to within a corner of a room. Fencing and posts intact and unbent. PVC guttering melted.*
2	Lava flow	Minor	Minor structural or non-structural damage, such as cracking and holes in wall, or <30% inundated	
	Lahar	Moderate	Window and door glass failure. Possible weak door and window frame failure	Deposition of sediment inside building, significant damage to contents
	Pyroclastic flow	Moderate damage	3 to 5 kPa	Several aluminum and old wood window and door frames imploded on side facing crater, exit windows or panes blown outward but window frames intact, part of roof burnt out from internal fire, or roof partially burned through in places from external heat of flow. In surrounding area visible effects of dynamic pressure and heat. Patchy sandblasting of walls facing volcano, scattered flow debris. *All ordinary wooden houses consumed. Deep layer of ash in rooms where penetration has occurred, but fine layer only in remainder of building. Fire caused by combustion of furnishings by hot ash deposit. If no furnishings, roof stays intact but externally damaged by heat of flow. Complete combustion in rooms where fire occurs.*
3	Lava flow	Moderate	Partial structural damage or roof destruction, partial destruction of non-structural wall, or 30-60% inundated	
	Lahar	Major	• Loss of parts of external and/or internal walls and infill panels • Burial by sediment	• Significant internal deposits; building likely to be unsafe for occupancy • Potentially irreversible damage or costly clean-up
	Pyroclastic flow	Heavy damage	5 to 9 kPa	All windows on side of volcano imploded, frames missing, and windows on opposite sides blown out or outward, including frames, roofs lifted off (especially light ones as galyanized *[sic]* sheets). Some serious damage to masonry structures. Terra-cotta infill panels of RC[4] structures implode in numerous buildings. 1–2 stories weak nonaseismic RC structures collapse; multistory (3–7) strong, nonaseismic and weak aseismic RC structures collapse. Evidence of flow missile damage. *Widespread internal fire with ash deposit throughout, roof burnt away by internal fires, radiant heat from deposit, or heat transfer from flow. Missiles such as galvanized sheets and wood more abundant and gathered against walls facing crater. Tops of sturdy trees cut off, most trees and utility poles downed or pushed over. Fences and posts pushed over.*
4	Lava flow	Major	Major structural and non-structural damage; wall, column, beam or roof collapse, or >60% inundated	
	Lahar	Complete	• Wall, frame, roof or foundation failure • Burial by sediment	• Building unsafe for occupancy; may have to be demolished • Potentially irreversible damage or costly clean-up
	Pyroclastic flow	Partial devastation	9 to 25 kPa	As for Level 3, but loss of parts of external and/or internal walls. Large single or multiple small missile impacts to wall facing volcano, most or all of roof missing from fire or lifting off of non-RC roofs. Lightweight masonry infill panels collapse. No flimsy buildings left standing. Diffuse serious damage to masonry buildings, most types RC structures collapse except for strong aseismic RC structures. Abundant missile debris.
5	Lava flow	Complete destruction	Complete structural destruction or burial	
	Pyroclastic flow	Total devastation	>25 kPa	Walls removed, only parts or none of the structure still standing except for strong aseismic 1–2-story RC structure. All masonry and nonaseismic RC structures collapse. Multiple large missile impacts. *Complete devastation from heat, dynamic pressure, and missiles; ground scoured with little deposit or remaining debris.*

Notes:
[1] *"Level" in Spence et al. [12]; "0" through "4" in Jenkins et al. [10]*
[2] *"Pressure range (kPa)" in Spence et al. [12]*
[3] *"Effects" in Spence et al. [12]* [4] *PVC = polyvinyl chloride; RC = reinforced concrete*

Demonstration cases:
Meredith et al. [6]: 2018 eruption of Kīlauea volcano (lower East Rift Zone), Hawai'i, USA; includes schematic depiction in paper
Jenkins et al. [10]: 9 January 2011 lahar at Merapi volcano, Indonesia
Spence et al. [12]: hypothetical eruption of Vesuvius volcano, Italy

Fig. 3: Select examples of damage states (DS) used for building damage from flow hazards.

Case study: Remote damage assessment for Kelud Volcano, Indonesia

Located in East Java, Kelud Volcano is one of the most active and deadly in Indonesia. On the evening of 13 February 2014, a volcanic explosivity index (VEI) 4 eruption began; the main explosive phase lasted about four hours. Over 160,000 people were evacuated from a 10 km radius around the volcano before the eruption, and seven fatalities occurred.

The eruption produced pyroclastic density currents running out to 6 km and rain-triggered lahars that damaged buildings up to 35 km away from the vent. Tephra was mostly dispersed to the west, causing 20 mm thick ash deposits in Yogyakarta (a city with over 400,000 residents at the time, more than 200 km west of the vent). Wind shear at ~5 km altitude caused a secondary ash cloud that produced <1 mm of ash around 80 km northeast of Kelud.

Carrying out a comprehensive field-based building damage assessment after the eruption was complicated by the large numbers of buildings damaged across a widespread area, and by rapid building repairs that began less than a week after eruption onset. Subsequent to the eruption and not part of the response effort, Williams et al. [15] completed a building damage assessment in the most impacted areas using remote satellite imagery. They used freely available high resolution (30-70 cm pixels) pre- and post-eruption images from Google Earth to assess 1154 structures.

In the study, they used color changes of roofs to infer the extent of repairs that were carried out after the eruption, as a proxy for damage. To facilitate rapid roof repair, new light colored clay tiles and blue tarpaulins were widely issued after the eruption. When old dark tiles were replaced with new ones, this was visible on satellite images. To categorize damage, Williams et al. [15] created a four-level damage state schema based on the observed changes in roof appearance. The damage states classify the type of damage and the observed changes in building appearance. Each building assessed was given one damage state and associated hazard intensity, in this case tephra load (kPa) which was derived from thickness measurements and tephra fall modeling.

The results showed that 2.3% of the assessed buildings experienced severe roof damage or building collapse (damage state 4/5). They found that asbestos fiber roof sheets made up a disproportionately high number of the damage state 4/5 observations, implying that buildings with such roofs fail at lower loads than those with tile roofs. With tiled roofs, they found that a large proportion (56%) had their entire roof replaced and a number of other buildings repaired only the verandas. Williams et al. [15] then used this building damage data from Kelud to create fragility functions (see Fig. 6A).

Williams et al. [15] highlight a few limitations in the study, including the inequitable access to financial and humanitarian aid some building owners had around Kelud. Some areas did not receive free building materials initially, which could have resulted in satellite images showing different levels of damage as there would have been no visible roof repair. In addition, field investigations can provide other contextual information about the eruption and damage through interviews with people in the area. However, using remote sensing can be helpful in gathering damage data when other methods are impractical. Further work by others built upon this remote sensing approach by developing deep learning tools that automate the assessment of tephra fall damage to buildings into six damage states, using the 2021 eruption of La Soufrière volcano, St Vincent and the Grenadines as a case study.

2.4. Limitations of damage states

There are a number of limitations of damage state development and application, including:

- **Loss of information:** Assigning a damage state to an individual asset (building, farm, infrastructure asset) removes nuanced information about the damaging event the asset experienced such as how and when the asset was impacted.
- **Scope of damage states:** When developing and applying damage states, the developer must decide if the states will focus on one typology (e.g., one type of building) or be more generic (e.g., cover a range of different building types). Application beyond the stated purpose (e.g., applying a timber-framed building damage state to a masonry building) will lead to incorrect and/or inappropriate damage assessments.
- **Limited temporal information:** Damage states on their own do not indicate whether the assessment represents one-time acute damage or accounts for longer exposure; for example, some economic effects can take many years to manifest. This is the same with long-term abrasion of infrastructure components or the degradation of agricultural land over many years. This may also apply to the collection of hazard data, where recorded intensities could be influenced by reworking, compaction of deposits over time or from clean-up operations.
- **Treatment of multi-hazard exposure:** Many of the damage states in volcanology and those presented here are designed for one volcanic hazard rather than multiple concurrent or sequential hazards. As assets may be subjected to multiple different volcanic hazards, care needs to be taken when applying damage states in the field as to whether the observed damage was caused by a specific hazard or is the result of exposure to cumulative hazards.
- **Subjectivity and reproducibility:** Descriptive words mean different things to different people, even among native speakers of the language. For example, expressions such as “few”, “many”, “most”, “negligible”, “partial”, “total” are common in sources of information about damage. Individual interpretations of the meaning of “frequency” or “severity” words contribute to the subjectivity of damage states.

3. Fragility and vulnerability functions

3.1. Overview

Fragility and vulnerability functions quantify damage from volcanic hazards to elements/assets by relating hazard intensity to the degree of damage or impact. These functions are defined as:

- Fragility functions: the probability that a particular damage state will be equaled or exceeded as a function of hazard intensity.
- Vulnerability functions: a component's mean damage or function loss as a value relative to total impact or as an economic cost, as a function of hazard intensity.

Fig. 4 shows the general shape of fragility and vulnerability functions.

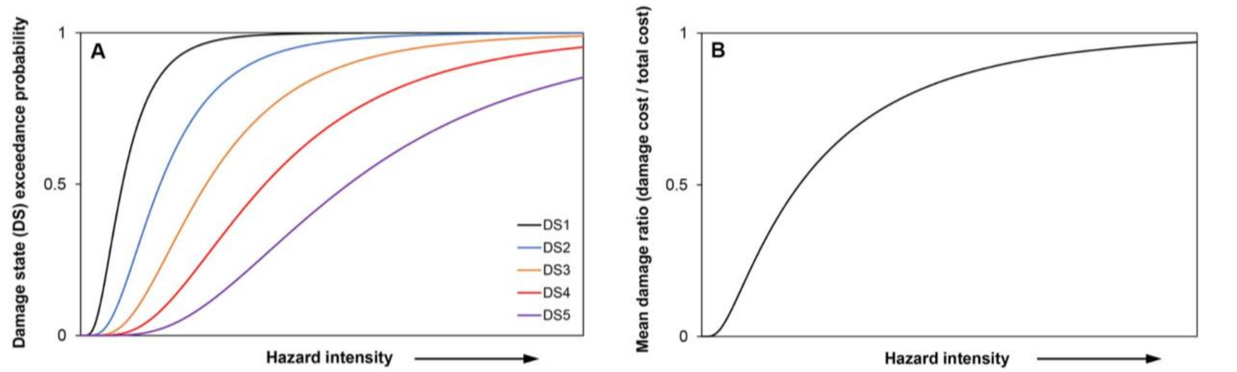

Fig. 4: Typical representation of (A) fragility and (B) vulnerability functions.

3.2. What are fragility and vulnerability functions used for

Fragility and vulnerability functions are primarily used in volcanic risk assessments. These functions are the key link between hazard and risk models, as they quantify the susceptibility of the exposed asset to a specific hazard intensity. Hazard intensity outputs from hazard models are input into fragility and vulnerability functions to determine damage of modeled assets. Risk can be determined by combining this damage output with the probability of occurrence of volcanic hazards. Volcanic fragility and vulnerability functions have been used in risk assessment for individual volcanoes or multi-hazard risk assessment software (e.g., RiskScape, CAPRA - Probabilistic Risk Assessment Platform, Oasis Loss Modelling Framework, FEMA's Hazus Program). Volcanic risk assessments are vital for effective, targeted risk reduction strategies to be put in place to increase a populations' resilience. See Chapters 2.1 and 3.1 for hazard and exposure assessments and Chapter 4.1 for how these aspects are combined into risk assessments. It is important to note that quantitative impact and risk assessments are only suitable in certain circumstances, such as those mentioned here for assessing impacts to physical assets (infrastructure, buildings, agriculture). These approaches are not suitable for assessing societal vulnerability which require qualitative assessment (see Part 7).

Fragility and vulnerability functions are also commonly used in the insurance industry. Models used there typically contain a number of simulated hazard events with probabilities that, when combined with vulnerability functions and insurance portfolio exposure, determine the insurance company's potential loss.

3.3. Deriving functions

To derive fragility and vulnerability functions, first the hazard intensity metrics (x-axis of the function, or independent variable) and the impact metrics (y-axis of the function, or dependent variable) need to be defined. These two steps, along with function fitting methods, are explained in the following section.

3.3.1. Hazard intensity metrics

Volcanic hazards have a number of different measurable characteristics, such as thickness, load, dynamic pressure, temperature, or density. A hazard intensity metric (HIM) describes the intensity (or severity or strength) of a volcanic hazard at a particular site. It is the x-axis (independent variable) of fragility and vulnerability functions.

As different hazards can have different damaging mechanisms, a single HIM might not adequately capture all of the impactful attributes of a specific volcanic hazard [11]. Therefore, the selection of an appropriate HIM is important. The selection of a HIM must consider: (1) the HIM's appropriateness to describe a range of asset damage intensities; (2) the ease of HIM measurement in the field or laboratory; (3) the applicability of the HIM to hazard model outputs; and (4) which HIM has been measured in existing damage datasets.

The most common HIMs are: thickness or mass loading (tephra fall, PDC deposits, lahar deposits); dynamic pressure (PDC, lahar); flow height (lava flow, lahar); density per unit area (ballistics); impact energy (ballistics); and concentration (gas emissions, tephra fall).

3.3.2. Impact metrics

An impact metric (IM) is used to assess the level of damage sustained by an asset subjected to a volcano hazard. The IM is commonly bounded between 0 and 1 or 0–100 and is the y-axis (dependent variable) of fragility and vulnerability functions.

The IM for fragility functions is the probability of an asset equaling or exceeding a specified level of damage.

For vulnerability functions, the IM can be a value or index which describes impact or economic loss. Any IM can be used for a vulnerability function depending on applicability and justification. Common IMs for vulnerability functions are:

- Damage percentage – percentage of damage sustained by an asset compared to pre-impact condition (e.g., a building is 90% damaged after a lahar impact).
- Loss of function – loss of function of an asset as a percentage compared to pre-impact condition (e.g., a water treatment plant lost 20% of its functionality after a tephra fall).
- Damage index – damage percentage normalized between 0 and 1.
- Function loss index – loss of function percentage normalized between 0 and 1.

- Damage ratio – a ratio between the cost of repair relative to the cost of replacement.
- Economic cost – absolute cost of impact(s) in monetary value.
- Damage state – states of damage and disruption defined by damage scales (see Section 2).

The choice of IM is determined by the output required (e.g., an output for a particular model) or the type of impact data available.

3.3.3. Function fitting

Fragility functions

In general, developing fragility functions for volcanic hazards has been done using limited and/or incomplete datasets, particularly when compared to equivalent functions for earthquake hazards that can draw on large damage assessment and laboratory datasets. The limited volcanic impacts data have meant existing volcanic research has adopted a range of pragmatic approaches to fragility curve development, including:

- Manual fitting: selecting distribution parameters to fit curves within upper and lower threshold bounds.
- Linear interpolation: fitting straight line segments between discrete data points.
- Equal spacing: defining classifications to evenly space a suite of curves across a range of damaging hazard intensities (e.g. [16]).

The following is summarized from Williams et al. [17] discussing fitting functions to binned data, using generalized link models (GLMs) and cumulative link models (CLMs). Table 2 shows the advantages and disadvantages for each approach.

Table 2: Advantages and disadvantages of various statistical models for fitting fragility functions to empirical damage data, from [17] used under Creative Commons BY-NC-ND License https://creativecommons.org/licenses/by-nc-nd/4.0/.

Model	**Advantage**	**Disadvantages**
Data binning	Established fragility functions for various volcanic hazards and assets have been developed using this method. Intuitive handling of data as ratios. Data can be supplemented by expert elicitation data.	The number of bins and their ranges are subjective which introduces variation. Data aggregation reduces available data points. Manual adjustment of functions is needed.
Generalized linear models (GLM)	Minimal manual data processing. Effective with small datasets; no data lost through aggregation. Confidence intervals can be calculated.	Functions for consecutive damage states may cross.

Cumulative link models (CLM)	Proper treatment of cumulative probabilities (i.e., fragility functions for different damage states will not cross or have negative slopes). Uses data from all damage states, useful for sparse data. Confidence intervals can be calculated.	Only applicable to ordinal damage states. Can only produce curves for immediately sequential damage states (e.g., DS1 & DS2, not DS1 & DS3). Functions are characterized by a common slope coefficient (β) which is shared across all damage states and may not always be representative.

In the binned data approach, the process begins by dividing the range of hazard intensities into bins of specified intervals. Each damage observation (which consists of a hazard intensity and damage state) is then assigned to one of these bins. Next, the fraction of observations that meet or exceed a particular damage state is computed for each bin (see Fig. 2 in [3] for an example). These fractions represent the damage state exceedance probabilities, which are plotted on the y-axis of the fragility function graph. The median hazard intensity value for all observations in the bin is then plotted on the x-axis.

Fragility functions can then be derived using these probabilities and median hazard intensities. One common method involves fitting straight lines between plotted points using methods described by Wilson et al. [3]. Alternatively, a more sophisticated approach such as maximum likelihood estimation (MLE) can be used. MLE is a statistical technique used to estimate parameters of a probability distribution based on observed data. For fragility functions, MLE can fit a lognormal cumulative distribution (as detailed in Eq. 7 of [18]), producing a probabilistic model that characterizes the relationship between hazard intensity and the probability of exceeding a damage state. Confidence intervals can then be derived for the fitted fragility functions.

These fragility functions can be used to calculate the probability of reaching or exceeding a given damage state (DS or ds) at any hazard intensity using the optimized fragility function with the following form:

$$P(DS \geq ds|HIM) = \phi\left(\frac{ln(HIM_{\square}/\mu)}{\sigma}\right) \quad \text{Eq. 1}$$

where P is the probability of equaling or exceeding a given damage state (DS) conditioned on the hazard intensity metric (HIM), Φ is the standard cumulative normal distribution function (see Box 2 for why this distribution is used), μ is the estimated median and σ is the estimated standard deviation.

Function fitting using a generalized linear model does not require the manual grouping of data into bins. The GLMs take the following form:

$$P(DS \geq ds|HIM) = \phi(\beta_1 + \beta_2\, ln(HIM)) \quad \text{Eq. 2}$$

where β_1 and β_2 are the intercept and slope parameters of the linear predictor, which is transformed by the inverse of a chosen link function. An inverse link function takes the full range of possible values (from negative to positive infinity) and transforms the values to a finite range. For example, a commonly used inverse link function is a standard cumulative normal distribution

(Φ), also referred to as a probit link; here negative infinity corresponds to a probability of 0% (or 0), 0 corresponds to a probability of 50% (the mean, or 0.50), and positive infinity corresponds to a probability of 100% (or 1). In the process of fitting fragility functions with GLMs, it is essential to transform the data into a binary format. In other words, each observation is assigned a binary outcome: 0 signifies that the observation did not reach the specific damage state being modeled by the GLM, while 1 indicates that the observation did reach this damage state (see Fig. 3 in [17] for an illustrative example).

Using GLMs and data binning can cause fragility functions to cross, especially with limited datasets (often the case with volcanic damage assessments). Cumulative link models (CLMs) are an extension of GLMs that ensure that fragility curves for different damage states can converge but will not cross each other, satisfying the assumption that higher hazard intensities should be required to cause greater damage.

CLMs make use of the ordinality of damage states, where increasing damage states correspond to increasing damage severity (e.g., no damage, light damage, heavy damage). Damage state ordering allows for cumulative probabilities to be calculated for each damage state (j) simultaneously.

$$P(DS \geq ds_j | HIM) = \phi\left(\beta_j + \beta_2\, ln(HIM_i)\right), j = 1, \ldots j = -1 \quad \text{Eq. 3}$$

where each cumulative probability has its own intercept (β_j) but shares a common slope coefficient (β_2).

CLMs are better for smaller datasets as they use all damage data for all damage states to fit each fragility function. For example, CLMs make use of the fact that DS2<DS3 to fit the DS3 curve.

Box 2: Why the lognormal cumulative distribution function is widely used for fragility

Most fragility functions use the typical lognormal cumulative distribution function (CDF) [19]. There are a number of reasons why CDFs are used:

- It has numerous convenient characteristics for modeling fragility. On the x-axis, log-normal CDFs have a lower bound of zero, which satisfies the expectation that hazard intensities cannot be negative. On the y-axis, log-normal CDFs are bounded between 0 and 1, which satisfies the constraint that the probability of a damage state being reached is also bounded between 0 and 1.
- It has been used in previous studies in volcanology and other geohazards (e.g., earthquakes).
- It often reasonably fits observed distributions of data of interest such as how damage increases with increasing hazard intensity.

Vulnerability functions

Vulnerability functions can be derived directly from fragility functions using cost coefficients or through expert elicitation. After deriving a suite of fragility functions for different damage states, the first step in developing a vulnerability function is calculating the probability of being in each damage state for a particular hazard intensity, $P(DS=ds_i \mid HIM)$. Each of these probabilities is multiplied by the corresponding cost coefficients (c_i) for each damage state. The damage ratio (i.e., proportion of replacement cost or asset value), D_{HIM}, for each hazard intensity (HIM) can be represented as:

$$D_{HIM} = \sum_{i=1}^{n-1} \left(c_i \times P(DS = ds_i \mid HIM)\right) \quad \text{Eq. 4}$$

where n is the number of damage states. Note that when applying Eq. 4, DS0 (no damage) is not used as it does not have an associated cost coefficient. An additional assumption is that if the hazard intensity is 0, then DS0 = 1. Fig. 5 shows this calculation diagrammatically.

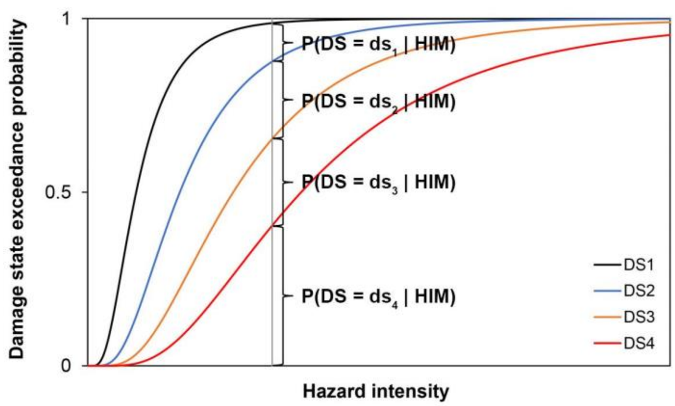

Fig. 5: Shows how to calculate the probability of being in each damage state (DS) to derive a vulnerability function.

The cost coefficients can be considered as proportions of total replacement costs or as proportionate losses of asset value. These coefficients can be determined through damage assessments, expert judgment or from analogous vulnerability models for other hazards. The coefficients will also likely change between asset types and geographic location. The resulting vulnerability function(s) are sensitive to the cost coefficients and care should be taken determining these values. Monte carlo methods could be used to determine the coefficients during modelling to account for the variability. As an example, the coefficients used in conjunction with Fig. 5 are: $c_1 = 0.25$ for DS1, $c_2 = 0.50$ for DS2, $c_3 = 0.75$ for DS3, and $c_4 = 1.00$ for DS4.

Plotting Eq. 4 for all hazard intensities of interest produces a single vulnerability function. This can be thought of as a function showing the mean or expected value of total damage across a range of hazard intensities. Vulnerability functions generally take the characteristic shape of negative exponential curves as opposed to the S-shaped fragility functions.

Uncertainty

Uncertainties associated with fragility and vulnerability functions must be characterized and communicated for damage and loss estimates to be robust, reliable, and trusted. Fragility functions already have an element of uncertainty built into them as they are assessing the probability of exceeding a given damage state. Recently, there have been efforts to further characterize this uncertainty by resampling damage data to create numerous simulated datasets which are then used to assess sampling uncertainty (“bootstrapping”; e.g., [17]). For vulnerability functions, the curve typically represents the central damage value; proper uncertainty characterization will include a standard deviation surrounding the curve.

Another approach is to explore the aleatory uncertainty in the damage process explicitly through stochastic simulation of the key factors influencing the hazard loading and building response. This type of desktop computer study would complement field and laboratory studies.

To date, there have been relatively limited published studies investigating the performance accuracy or benchmarking of fragility and vulnerability functions. This is partially due to limited opportunities to undertake such studies, which require a well characterized impact dataset to compare models with reality. However, it is important to undertake these assessments to identify knowledge gaps and refinement opportunities. Levels of uncertainty and model limitations will differ between asset and hazard types, with use-cases determining the level of uncertainty acceptable.

3.4. Examples of fragility and vulnerability functions

Fig. 6 shows a few fragility functions used in volcanology. These functions represent different hazards, assets and geographical locations. With the exception of Figs 6. B and F which were based on experimental data, the functions were derived from post eruption damage assessments.

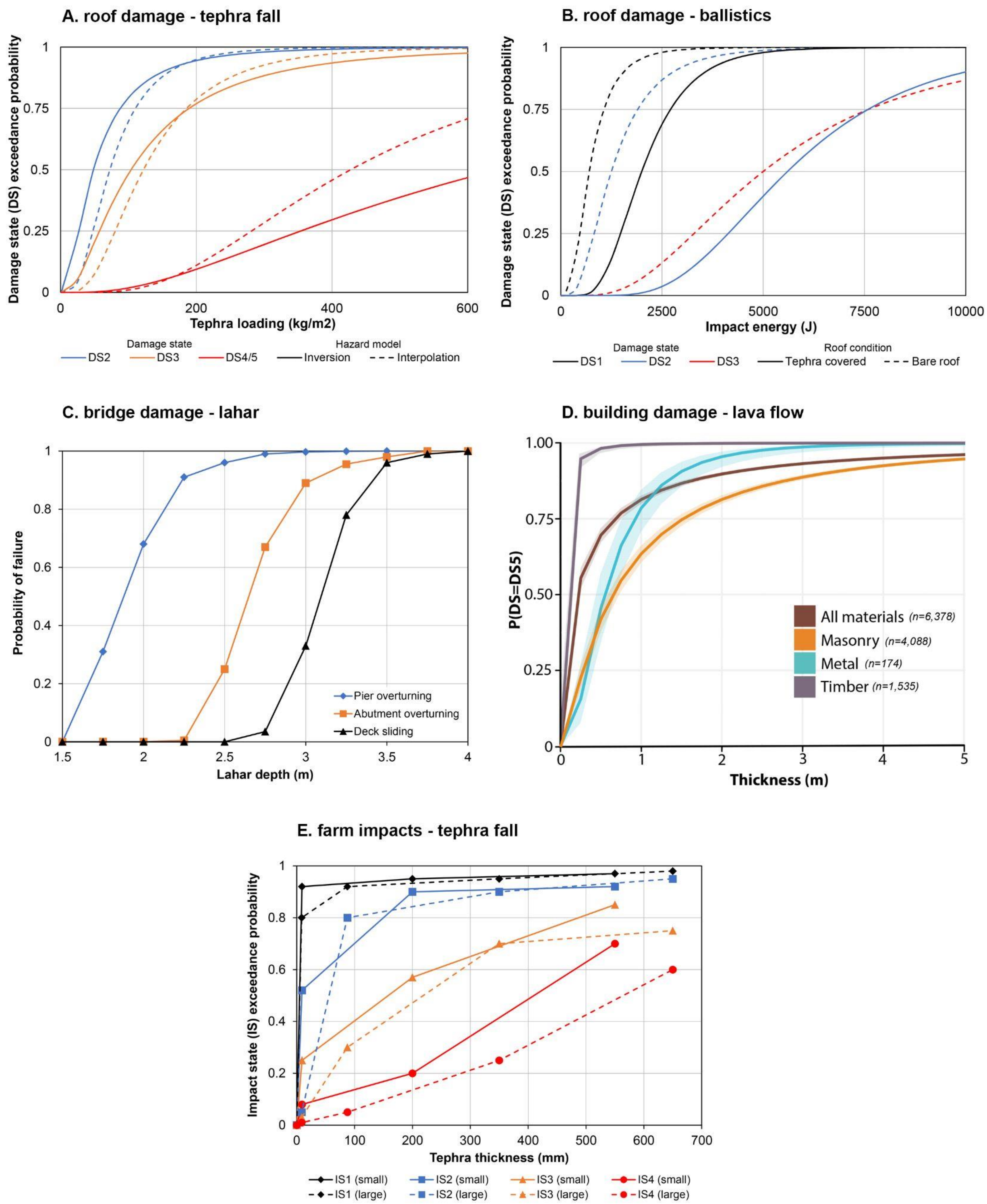

Fig. 6: Examples of fragility functions for different assets and volcanic hazards: A) Fragility curves for damage to tiled roofs in Indonesia from tephra fall; B) Fragility curves comparing ballistic impact resistance of bare and tephra covered (50mm thick) reinforced concrete slabs; C) Fragility curves for bridge substructure overturning and deck sliding due to lahars; D) Fragility

functions for building damage exceeding damage state 1 (negligible damage) from lava flows thickness; and E) Suite of fragility functions for high intensity, non-dairy pastoral farming fragility for vulnerable small and large farms.

3.5. Challenges and limitations of developing functions

There are a number of challenges and limitations associated with fragility and vulnerability functions. Some of these are similar to those for damage states outlined in Section 2.4, such as loss of information, limited temporal information, and treatment of multi-hazard exposure in addition to the following:

- **Limited damage data availability:** Compared to other hazards, there are less empirical damage data available for volcanic hazards. This is because damaging volcanic eruptions are often infrequent events on human timeframes. Limited data means researchers need to develop functions with few data points, often filling in gaps in data with expert judgment or small laboratory experiments.
- **Discrepancies in hazard intensity measurements:** There can be discrepancies in the literature of a hazard measurement for the same location. This can be due to local variability but can also be caused by different methods being used to collect or determine the measurement. For example, a town could have conflicting published tephra thickness data, because different research groups created different isopach maps. These discrepancies can lead to large differences in damage and therefore completely different fragility or vulnerability functions for the same exposed asset. Some researchers suggest taking hazard intensity measurements at each damage observation site. However, methodological approaches to measuring hazard intensities may still be inconsistent between impacted populations, researchers in the field, and other interested parties such as emergency management personnel and insurance assessors.
- **Discrepancies in impact assessment:** Volcanic impact assessment is a growing field, and there is less standardization in impact assessment than for some other hazards. It is rare that a trained engineer is part of a volcanic impact assessment effort. Across large research teams there is generally a concerted effort, including training, to ensure consistency within the team. However, different groups may have different standards.
- **Differences in construction materials, condition, and design:** The variability in the type of construction material and its condition (e.g., corroded vs. new metal sheet) will change the structure's responses to the hazards impacts and consequently their fragility and vulnerability functions. Similarly different designs can make a structure more or less vulnerable to volcanic hazards, e.g., steep versus shallow roof inclination will change the response to tephra accumulation. Some fragility function suites attempt to account for these differences by developing functions for different structural categories; however, these still do not account for all the variability seen in structures. Calculating and showing the uncertainty associated with each fragility function is a way of accounting for and communicating this variability (e.g., shaded areas on Fig. 6D).
- **Complexity of impacted assets:** Some assets that are exposed and damaged by volcanic hazard are complex and are unable to be simplified into a few fragility or

vulnerability functions. For example, critical infrastructure assets or agriculture environments are inherently complex systems with many interdependencies. Often these systems need to be treated as a whole or a collection of smaller sub systems for which fragility and vulnerability functions can be developed.

- **Inadequate representation of uncertainty:** Fragility and vulnerability functions may not adequately account for or document uncertainties in their development. This could lead to potential underestimation or overestimation of vulnerability and risk. Recently, some researchers are more directly addressing uncertainties (e.g., [17]).

4. Future research opportunities

Research will continue to expand observational datasets and deepen our understanding of volcanic impacts and refining the quantitative relationships between hazard intensity and impact. Some key opportunities for researchers to focus on to improve fragility and vulnerability functions are to:

- **Make better use of existing data:** Data about past volcanic eruptions are spread across the literature, case study reports, media, and unpublished field notes, which if compiled into a single source could be used to develop fragility and vulnerability functions. While these data might be incomplete, as in some measurements might be missing and the dataset may not be fully representative, it can still provide a useful contribution to understanding impacts and vulnerability. In addition, the creation of standardized impact databases with guidelines that allow new data to be added would allow the research community to make better use of the data. Databases allow for impacts to be classified by a standardized taxonomy that would facilitate greater sharing of data and comparison between events. Having complete catalogs of past disasters is also fundamental to meeting the priorities of the Sendai Framework for Disaster Risk Reduction 2015–2030 and the United Nations Sustainable Development Goals.
- **Extract more information from sparse historical data:** Any historical event is just one of numerous possible realizations. The event dataset can be expanded by considering an ensemble of possible alternative outcomes. Of special importance for risk mitigation is a downward counterfactual perspective, where alternatives are considered where things turned for the worse.
- **Take advantage of new data sources:** Remote sensing and imagery are used extensively in humanitarian mapping for disasters such as volcanic eruptions and are starting to be used for volcanic impact and damage assessments (e.g., [15]). UAV (uncrewed aerial vehicle) technologies could also be used at a smaller and more cost-effective scale than satellite imagery. Ground-based images have also been effective for assessing exposure, impact, and hazard intensity (e.g., [5, 6]). Crowdsourced data and media observations have been used for other hazards and are starting to be used in volcanology. All of these new data sources aid in obtaining more impact data over broad spatial extents, which is crucial for understanding impacts. Integrating remotely obtained data with traditional approaches involving local experts or communities is key for the development of improved fragility and vulnerability functions.

- **Develop open access data repositories:** Making fragility and vulnerability functions (and associated metadata) freely available to researchers would promote their use and refinement. This means these functions can be reused by others and avoids duplication of effort. However, it must be kept in mind that the selection of functions appropriate for their context (e.g., geographical, building typology) is an important consideration when deciding to reuse or develop new functions. As a starting point, Hayes et al. [22] have compiled a list of volcanic vulnerability models (https://github.com/NZVHRM/Global_vulnerability_models).
- **Ensure reliability and accuracy in vulnerability models:** This is crucial for providing decision-makers with useful risk information. However, there is inconsistent addressing of uncertainty within existing models, although efforts are growing to effectively incorporate and communicate uncertainty. Recent efforts, such as using statistical techniques to quantify uncertainty around fragility function curves, align this field with comparable risk assessment fields (e.g., [17]). Additionally, improving treatment of model uncertainty through enhanced data and statistical techniques is essential [22]. Assessing the performance accuracy of functions is not often undertaken due to limited available validation and benchmarking data. Empirical data for such evaluations are scarce, hindering comprehensive assessment. Challenges also arise from comparing modeled and experimental outputs with real events due to data quality issues within impact datasets. However, increased use of model benchmarking and cross-validation processes can enhance user confidence in function accuracy.
- **Embrace new tools and technology:** The use of artificial intelligence and machine learning to process, analyze and manipulate data can more quickly identify trends in datasets. These tools can also be used to automate processes, for example image recognition and processing to assist with remote damage assessments.

5. Summary

Reducing volcanic risk necessitates a comprehensive understanding of the potential impacts of volcanic hazards on various community elements, assets and critical infrastructure. A key component of this is the assessment of the vulnerability of these assets to volcanic hazards.

The assessment of vulnerability typically involves descriptions of volcanic hazard impacts, through the use of damage scales, which can then be further quantified through fragility and vulnerability functions. These functions provide a means to quantify the relationship between hazard intensity and damage, facilitating robust numerical risk assessments. While qualitative descriptions and damage scales lay the foundation for understanding impacts, moving towards quantification through fragility and vulnerability functions enables more precise risk assessment, aiding in disaster preparedness, response and recovery efforts.

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