How rainfall influences tephra fall loading — an experimental approach

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Abstract

The load a tephra fall deposit applies to an underlying surface is a key factor controlling its potential to damage a wide range of assets including buildings, trees, crops and powerlines. Though it has long been recognised that loading can increase when deposits absorb rainfall, few efforts have been made to quantify likely load increases. This study builds on previous theoretical work, using an experimental approach to quantify change in load as a function of grainsize distribution, rainfall intensity and duration. A total of 20 laboratory experiments were carried out for ~ 10-cm thick, dry tephra deposits of varying grainsize and grading, taken to represent different eruptive scenarios (e.g. stable, waxing or waning plume). Tephra was deposited onto a 15° impermeable slope (representing a low pitch roof) and exposed to simulated heavy rainfalls of 35 and 70 mm h⁻¹ for durations of up to 2 h. Across all experiments, the maximum load increases ranged from 18 to 30%. Larger increases occurred in fine-grained to medium-grained deposits or in inversely graded deposits, as these retained water more efficiently. The lowest increases occurred in normally graded deposits as rain was unable to infiltrate to the deposit's base. In deposits composed entirely of coarse tephra, high drainage rates meant the amount of water absorbed was controlled by the deposit's capillary porosity, rather than its total porosity, resulting in load increases that were smaller than expected. These results suggest that, for low pitch roofs, the maximum deposit load increase due to rainfall is around 30%, significantly lower than the oft-referenced 100%. To complement our experimental results, field measurements of tephra thickness should be supplemented with tephra loading measurements, wherever possible, especially when measurements are made at or near the site of observed damage.

Keywords Ash fall · Hazard · Impacts · Building damage

Introduction

When tephra fall accumulates on buildings, it can result in a wide range of damage, with the most severe being complete building collapse. Tephra falls from large explosive eruptions can damage or destroy thousands of buildings at once (e.g. Pinatubo, 1991; Spence et al. 1996; Kelud, 2014; Blake et al. 2015), and thus, having the ability to robustly estimate the likely extent of building damage from future eruptions

is an important aspect of volcanic risk management. Tephra fall building damage forecasts are made by combining an estimate of tephra accumulation (from dispersal modelling or based on previous deposits) with information on a building population's susceptibility to damage (e.g. Zuccaro et al. 2008; Biass et al. 2016; Retnowati et al. 2018). The hazard posed by a tephra fall deposit to a building is most commonly quantified based on the loading of the deposit (Jenkins et al. 2014). The load that a tephra fall applies to a building (or any surface) is a function of the deposit's thickness and density. Both of these values can be readily influenced by rainfall (Blong 1981; Macedonio and Costa 2012). Unfortunately, our current understanding of how rainfalls can and have influenced tephra fall loading represents a substantial source of uncertainty in both pre-eruption damage estimates and post-eruption damage assessments (Spence et al. 1996; Jenkins et al. 2015; Biass et al. 2016; Williams et al. 2020). To improve understanding of this interaction,

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and thereby to provide more accurate estimates of tephra fall loads from a given eruption, this study presents a series of experiments that quantify how loading changes as a function of deposit grainsize, rainfall intensity and duration.

Background

It has long been recognised that rainfall can increase the load that tephra fall deposits apply to their underlying surface, be it a roof, powerline or tree branch, thereby increasing their probability of sustaining damage (Blong 1981; Spence et al. 1996). The first tephra fall building damage survey, conducted by Spence et al. (1996), following the 1991 eruption of Pinatubo in the Philippines, noted that typhoon rains would have increased the tephra loads sustained by buildings and that in situ deposit density measurements would have been useful to quantify the increase. Despite the potential value of these measurements having been recognised, in situ tephra deposit densities are rarely recorded during post-eruption building damage surveys. Reasons given for this include time constraints in the field (Mcsporrán 2019), use of remote damage assessment techniques (Williams et al. 2020; Biass et al. 2021) or that at the time a damage survey was conducted, it was not intended to compare damage with hazard intensity (Hayes et al. 2019). As a result, where deposit densities have been measured, it was typically at a much later date and/or in the laboratory. For example, Hayes et al. (2019) reported a tephra deposit density increase of 45% from 1115 to 1615 kg m⁻³, after saturating an oven-dried sample of tephra from the 2015 Calbuco eruption. Hampton et al. (2015) reported a 27% increase from 1572 to 2000 kg m⁻³ after saturating basaltic lava that had been milled and sieved to produce ‘pseudo-ash’. Samples of Pinatubo 1991 tephra had measured densities of 1200–1600 kg m⁻³ (Spence et al. 1996). When these samples were later saturated with water in the laboratory, density was found to increase by 25% to 1500–2000 kg m⁻³. This load increase suggests if heavy typhoon rains had not coincided with the eruption, that the total number of roof collapses, and the 189 deaths attributed to these collapses, would likely have both been reduced (Paladio-Melasantos et al. 1996; Lin et al. 2020). Similarly, following the 1990 eruption of Kelud volcano, Indonesia, all 34 recorded casualties were caused by roof collapse at a single evacuation centre, under the weight of tephra that had been made heavier — by an unmeasured amount — by rain (Bourdier et al. 1997; Hidayati et al. 2019). More recently at Kelud, Williams et al. (2020) conducted a remote building damage and vulnerability assessment, using tephra thicknesses and a published dry deposit density value of 1400 kg m⁻³ to estimate tephra loading on buildings from Kelud’s 2014 eruption. Five days after the eruption began, heavy rainfall

measurements were made in an area nearby where building damage was assessed, likely before building residents were able to return and clean tephra from the roofs of all their homes (Dibyosaputro et al. 2015). If tephra deposits had absorbed rainfall, then the dry deposit density assumed by Williams et al. (2020) would have underestimated tephra loads on roofs, meaning these buildings may be more resistant to damage than the study’s vulnerability models suggest.

Studies seeking to estimate tephra load increases under rainfall without having a sample of tephra available for testing, such as when tephra dispersion is being modelled, typically use the saturation assumption method of Macedonio and Costa (2012). This method provides a repeatable, practical approach to estimate the maximum possible tephra load increase for a deposit that is saturated, i.e. when all void spaces in a dry deposit are filled with water. However, there are several situations in which the complete saturation assumption is flawed. Firstly, on sloped surfaces, rainfall can erode tephra deposits (Yamakoshi et al. 2005; Barclay et al. 2007; Baumann et al. 2019), which in the case of a sloped roof could wash parts of the deposit away, meaning rain has the potential to reduce loads as well as to increase them. Secondly, after rain falls on a freshly fallen deposit, it can cause compaction of up to 50%, especially in relatively low density, fine-grained deposits (Engwell et al. 2013; Blong et al. 2017). There are two components of compaction that affect the theoretical calculation of density increase by complete saturation: (i) compaction by rain increases deposit density by decreasing the void space available for water absorption; and (ii) compaction by rainfall has been observed to aid formation of structural surface crusts in tephra deposits both in the laboratory under simulated rainfalls and under natural conditions in the field (Armenise et al. 2018; Tarasenko et al. 2019). This zone of reduced permeability near a deposit’s surface can then promote surface runoff that, even under intense rainfall, can prevent water from infiltrating to the base of the deposit, meaning complete deposit saturation might not occur (e.g. Leavesley et al. 1989; Hampton et al. 2015; Jones et al. 2017). At the other end of the grainsize spectrum, coarse tephra deposits might also be unsusceptible to saturation given their high permeability rates, which can exceed natural rainfall rates by an order of magnitude such that rain absorbed into coarse deposits drains out faster than it can accumulate (Fiorillo and Wilson 2004). This collection of factors means that certain types of tephra fall deposits are unlikely to become fully saturated when exposed to rainfalls and so the risk posed by tephra hazard can be overestimated where complete saturation is assumed. Whilst a conservative approach to risk assessment is commended in the absence of robust data that might allow for a more detailed assessment, this study aims to provide a methodology and set of data to provide evidence-based estimates of rainfall adjusted tephra loads that do not require upper limit calculations reliant upon

the saturation assumption. To achieve this, we carried out a set of experiments measuring changes in tephra loading through time as deposits of different grainsize distributions are subjected to rainfalls of different intensities.

Many factors control how tephra loading on roofs might be altered by pre-depositional, syn-depositional or post-depositional rainfall. Factors related to the deposit itself include deposit thickness, porosity, permeability, chemical composition, moisture content at the time of deposition and whether any sublayers exist within the deposit (Leavesley et al. 1989; Fiorillo and Wilson 2004; Macedonio and Costa 2012; Tarasenko et al. 2019). Factors related to the rainfall include the timing of rainfall relative to the tephra fall as well as rainfall duration and intensity (Bielders and Grymonprez 2010; Hampton et al. 2015; Jones et al. 2017). Factors related to the roof include the pitch, material and condition of the roof covering — as this controls the friction between roof surface and deposit base — as well as the flow of the water through the deposit (Spence et al. 1996; Hampton et al. 2015). Experiments in this study aim to investigate only the effects of varying rainfall intensity and grainsize distribution (GSD) and replicate an impermeable, pitched roof. Further experimental studies could be undertaken using the methodology developed here to determine the additional influence of roof type, pitch and roof condition on tephra loading under rainfall.

Methods

In this section, we first outline our method for creating our tephra deposits and simulating rainfall within the laboratory. We then describe the experimental approach used to observe deposit-rainfall interactions and to measure changes in tephra load and thickness over time. Methods used to measure the porosity of tephra deposits are also described.

Tephra deposit

To examine how rainfall interacts with different types of tephra deposits, large quantities of pseudo-tephra were created, with three distinct grainsize distributions. Pseudo-tephra is often used in laboratory experiments in place of natural tephra when large unweathered, homogeneous deposits are desired (e.g. Wilson et al. 2012; Wardman et al. 2014; Williams et al. 2019). Pseudo-tephra was also used in field experiments by Blong et al. (2017), who investigated the preservation and compaction of 6–10-cm thick tephra deposits exposed to tropical rainfalls. All pseudo-tephras used in these experiments were milled from the same basaltic scoria source rock, purchased in Singapore and quarried in Java, Indonesia, unfortunately from a location the supplier could not specify. To produce deposits with varying

but realistic grainsize distributions, the milled material was sieved into different grainsize fractions, and then proportions of each grainsize were combined according to the plots in Fig. 1. Median grainsizes of 2, 0 and -2 phi (0.25, 1 and 4 mm, respectively) were chosen with the aim of observing a range of tephra deposit-rain interactions that might occur at varying locations within a tephra fall footprint. We used symmetrical, normal distributions because these approximate distributions often observed in tephra fall deposits (e.g. Mannen 2006; Yang et al. 2019; Maeno et al. 2019). We also aimed to avoid using overly specific, skewed or bimodal distributions as these might make it difficult for our results to be applied to future studies. In addition to varying the median grainsize, the standard deviations of the distributions were also varied, decreasing for finer tephtras (Fig. 1). This was done to reflect that finer deposits typically travel farther from the volcano, giving them time to become more highly sorted (Walker 1971; Paladio-Melasantos et al. 1996).

From these pseudo-tephras, deposits were developed to represent those formed by eruptions where the eruption intensity was either waxing, waning or stable (Fig. 2). Waxing and waning eruption intensities were represented using inversely graded and normally graded deposits, respectively. Ungraded deposits were used to represent those formed by a stable eruption column. Using the same sieving method as Wilson et al. (2012) and Hampton et al. (2015), deposits were built up within a container that would later be placed on top of a mass balance during rainfall simulations. In all experiments, deposit thicknesses of 10 cm were used. Deposits > 10 -cm thick could have been tested, but because we were interested in observing runoff and erosion of deposits, we built deposits up within a three-walled container, that allowed tephra to wash away downslope (see Figs. 2 and 3). This meant that for deposits > 10 -cm thick, a large proportion of the deposit's upper surface would have a relatively unstable slope, controlled by its angle of repose, rather than by the 15° slope of the bottom of the container. Given the length of our container, limiting deposit thickness to 10 cm meant that at least half of the deposit's surface would have a slope roughly parallel to the 15° slope of the base of the container. This slope is the minimum advised slope for rain to drain efficiently off a roof and is the minimum requirement for shingle or tile roofs in certain countries (e.g. New Zealand: Department of Building and Housing 2011). The ungraded deposits were built up using only one of the three tephtras, where each tephra comprised one of the three grainsize distributions shown in Fig. 1. Prior to sieving, the entire batch of each tephra was thoroughly mixed so that the different phi grainsize fractions could be distributed as evenly throughout the deposit as possible. The inversely graded deposits (representing those from waxing eruptions) consisted of a 3-cm thick layer of fine tephra with a 7-cm layer of coarse tephra on top. The opposite ordering but

Fig. 1 Grainsize distributions, standard deviations of distributions (σ) and photos of the three tephras used in experiments. The same scale applies to all photos

Fig. 2 The three main types of deposits used in experiments. Photos **a**, **b** and **c** are normally graded, inversely graded and ungraded (medium), respectively. Photo **d** shows the surface of an ungraded, medium deposit post-rainfall

the same proportions were used to produce the normally graded deposits representative of those formed by waning

eruptions. The 7:3 ratio for the thicknesses of coarse and fine tephra was chosen somewhat arbitrarily, but also reflects an

Fig. 3 An illustration (a) and photos (b) and (c) of the experimental setup used in this study. The photos are of an inversely graded deposit exposed to 70 mm h^{-1} rainfall. Photo **b** was prior to the experiment and photo **c** was taken 70 s after the experiment began. Note that the weight of the lamp and camera (230 g) placed on the stage are accounted for

often-observed pattern that for tephra deposits containing multiple layers with distinct grain sizes, the finer-grained layers are thinner. Some eruptions that have produced deposits exhibiting this pattern include those from the 1977 Ukinrek Maars (Self et al. 1980), both the 1990 and 2014 eruptions of Kelud (Bourdier et al. 1997; Goode et al. 2018) and the 1991 eruption of Pinatubo (Paladio-Melasantos et al. 1996). Sieves were agitated at $> 2 \text{ m}$ above the depositional surface of the tephra container, allowing particles from the fine and medium grain size tephra to reach their terminal settling velocities prior to deposition (Wilson and Huang 1979; Dioguardi et al. 2017). The coarsest particles from the coarse tephra, with diameters of up to 16 mm, could not reach their terminal fall velocities as these would require a drop height of $> 5 \text{ m}$ that could not be attained within the available laboratory space. As these particles make up only 10% of the coarse deposit, the fact that they could not be deposited at their full terminal fall velocity is expected to have little measurable effect on the deposit-rainfall interaction, especially considering naturally formed coarse deposits are not highly prone to compaction by rainfall (Engwell et al. 2013; Blong et al. 2017).

To allow for observation of rain infiltration into deposits, the tephra container was built using Perspex sheets for its three walls (Fig. 2). A fourth Perspex sheet was used for the floor of the container and was painted so that friction between tephra particles and the sheet surface might better

represent that on a painted roof. This floor sheet measured 0.41 m by 0.2 m , which was sloped at 15° presenting a depositional area of 0.08 m^2 .

Simulating rainfall

Rainfall simulators are used to conduct research across a number of scientific disciplines and, accordingly, a variety of different simulator types have been developed (e.g. Tosell et al. 1987; Pérez-Rodríguez et al. 2009; Yakubu and Yusop 2017). We use a pressurised nozzle rainfall simulator fitted with a full cone Shiwaki 1/8-SS20 nozzle operating at a flow rate of 28 ml s^{-1} . Pressurised nozzle simulators are a practical option for most laboratory spaces because sprayed water drops can reach their terminal fall velocities with relatively little ground clearance (i.e. $< 1.5 \text{ m}$), compared to other main type of simulators (drop forming simulators) that typically require $> 8\text{-m}$ fall heights (Armenise et al. 2018). Compared to drop forming simulators, pressurised nozzle simulators also produce drop size distributions that better represent natural rainfalls. One limitation of pressurised nozzle simulators, however, is that they do not effectively produce raindrops with large diameters ($> 3.1 \text{ mm}$), meaning sprayed rain drops typically have lower impact energies (measured in $\text{J m}^{-2} \text{ mm}^{-1}$) than natural rainfalls of the same intensity (Yakubu and Yusop 2017).

Rainfall intensity and uniformity were measured simultaneously by placing the tephra container at various locations beneath the spray nozzle and measuring the amount of water collected inside an array of test tubes placed inside the container. A 3 by 5 array of test tubes with 2.7-cm diameter openings were arranged with their centres 7-cm apart inside the container. Rainfall intensity was calculated as the average intensity across all 15 test tubes, and rainfall uniformity was calculated using Christiansen's uniformity coefficient (Christiansen 1942). Calculating the uniformity coefficient (C_u) required the mean rainfall value from all test tubes ($\bar{x}$), the number of test tubes (n) and the sum of the deviations from the mean: $\sum_1^n (|x - \bar{x}|)$. The coefficient is expressed as a percentage, with higher percentages indicating higher rainfall uniformity. Values over 80% are required for acceptable simulations of rainfall (Loch et al. 2001).

$$C_u = 100 \left(1 - \frac{\sum_1^n (|x - \bar{x}|)}{n\bar{x}} \right) \quad (1)$$

Different rainfall intensities were simulated by positioning the tephra container at specific positions offset from the point directly beneath the nozzle. The lowest rainfall intensity used for testing was 35 mm h⁻¹ as intensities lower than this could only be achieved by moving the container farther from the nozzle at the cost of reduced uniformity. The highest intensity used was 70 mm h⁻¹ as this represents very intense rainfall towards the upper end of observations from a selection of tropical rainfall datasets (e.g. van Westen and Daag 2005; Thouret et al. 2014; Lee 2015). The 35 and 70 mm h⁻¹ intensities had average C_u values of 83 and 85% respectively.

Experimental procedures

We tested five types of deposits — ungraded fine, medium and coarse, normally graded (coarse to fine), and inversely graded (fine to coarse tephra) — under two rainfall intensities (35 and 70 mm h⁻¹). The 10 unique combinations were repeated to give a total of 20 rainfall experiments carried out in this study. Each experiment was performed for a maximum of 2 h, or for a minimum of 15 min after the onset of major deposit erosion off the roof if it occurred. Heavy rainfall events ≥ 35 mm h⁻¹ lasting longer than 2 h have rarely been observed in the rainfall datasets referenced in the previous section. The experimental setup, including the tephra deposit, the various components of the rainfall simulator and measurement equipment are depicted in Fig. 3.

Two balances were used to simultaneously record changes in the mass of the deposit and of the runoff from the deposit. Each balance continuously output its mass reading to an external computer, recording a timeseries of change in mass for the duration of each experiment. Two cameras were used

to record visual observations, such as deposit compaction and wetting. One camera filmed the side of the deposit, whilst the other filmed the underside of the deposit, through an unpainted section of the base Perspex sheet, to record when or if the base of the deposit became wet.

Porosity measurements were made to compare the maximum amount of water that could be absorbed by deposits at saturation with the amounts of water actually absorbed by deposits under heavy rainfall. Measurements of total porosity and its two components, effective and capillary porosity, were calculated using a method similar to that of Fiorillo and Wilson (2004). In Fiorillo and Wilson (2004) and in the current study, 'total porosity' refers to the proportion of a deposit that is fillable by water. The pore space occupied by completely isolated vesicles that cannot be filled by water is therefore not being accounted for. Following this definition, effective porosity is the proportion of fillable void space within a medium from which a liquid will freely drain out under gravity. Capillary porosity, or field capacity as it is often referred to, is the opposite as it represents the void space in which water will remain after liquid has stopped draining out under gravity (Fiorillo and Wilson 2004). Each total porosity measurement was made by first sieving > 500 g of dry tephra into a large Buchner funnel so that a precise volume of tephra could be measured inside the funnel. The funnel was then placed on a balance and water was continuously dripped onto the tephra until a pool of water formed above its surface. A permeable glass disk at the base of the Buchner funnel then allowed the water to drain from the deposit, at a rate much slower than the input of water so that deposit saturation could be reached. At the moment when the pool of water above the tephra's surface disappeared, the weight of water absorbed was recorded and used to calculate total porosity. After 8 or more hours, once water had completely ceased to drain from the deposit, the weight of the drained water was used to calculate the tephra's effective porosity, which could then be subtracted from the total porosity to calculate capillary porosity.

Results

Amongst all the experiments conducted, an inversely graded deposit exposed to 70 mm h⁻¹ of rainfall experienced the highest maximum increase in weight of 30%. Considering the deposits are confined within the same depositional area (0.08 m²), measured increases in deposit weight can be directly converted into load increases, typically measured either in kg m⁻² or kPa. The lowest maximum load increase was experienced by a normally graded deposit exposed to 35 mm h⁻¹ rainfall at just 18%. Of the three ungraded deposits, on average, the medium grainsize tephra displayed the highest load increase of 29%, and the coarse tephra deposits

displayed the lowest maximum increase at 24%. This low increase was recorded despite the coarse tephra having the highest porosity and therefore the highest potential for water absorption. For each deposit type, the maximum load increases tended to be slightly higher under the more intense rainfall (Fig. 4). This is with the exception of the fine tephra, which experienced a slightly lower maximum increase under the 70 mm h⁻¹ rainfall (Fig. 4) perhaps due to deposit erosion beginning before the entire deposit had absorbed as much water as it had under the 35 mm h⁻¹ tests. The deposit experiencing the highest load increase in absolute terms was an ungraded, medium tephra, which increased from 96 to 124 kg m⁻². This 28 kg m⁻² or 0.27 kPa increase in load corresponds to mass increase of 2.2 kg (from 7.7 to 9.9 kg).

Compared to their total fillable porosity, the coarse deposits absorbed less than half of their potential maximum during rainfall experiments (Fig. 5), around 400 kg m⁻³ at saturation compared to around 200 kg m⁻³ under rainfall. The difference between maximum and observed absorption became much smaller for the medium tephra and was < 2% for the fine tephra (only 24 kg m⁻³ less water in the rained-upon deposit compared to the saturated one). Similarly, comparing the bulk densities reached under simulated heavy rainfall with those calculated using the porosity estimation and saturation assumption methods of Macedonio and Costa (2012), the difference is the largest for the coarse tephra but relatively small for both the fine and the medium tephtras (Table 1). For all three of the ungraded deposits, the maximum bulk density increase reached under rainfall was more closely matched by the bulk density calculated when only

Fig. 5 Bulk densities of different tephtras when dry, saturated and whilst at their maximum during simulated rainfall experiments (see values in Table 1). Labelled percentage values for heavy rain and saturated densities represent the mean maximum density increase relative to the mean dry deposit density (orange circle marker). Three measurements were taken for each tephtra in each condition with the highest opacity markers indicating the mean value

the deposit's capillary porosity was saturated (Table 1). Note that the maximum bulk density values under rainfall have not been directly measured, but rather estimated based on the maximum increases in weight recorded during experiments. Density increases associated with rainfall-driven compaction of the fine tephtra deposits (2–4% compaction) have been accounted for.

At the start of each experiment, all deposits experienced a linear increase in mass as they absorbed almost all of the incoming rainfall. After ~5–10 min, however, different rainfall interactions were observed with each of the deposit

Fig. 4 Tephtra load increase through time for five different 10-cm thick tephtra deposits (see the "Tephtra" section) subjected to two different simulated rainfall intensities, with each experiment carried out twice to give a total of 20 experiments

Table 1 Mean bulk density of deposits after being heavily rained upon compared with bulk densities that would be calculated if the deposit's capillary porosity or total porosity was saturated. The ranges from all experiments are provided in square brackets. Also provided are the saturated bulk densities estimated using the method described

Deposit type	Dry density (kg m ⁻³)	Heavily rained-upon density(kg m ⁻³)	Capillary porosity filled density (kg m ⁻³)	Saturated density — measured (kg m ⁻³)	Saturated density — based on assumed total porosity (kg m ⁻³)
Fine	1538 [1497, 1588]	1941 [1890, 2005]	1937 [1895, 1986]	2024 [1994, 2062]	1923 [1898, 1953]
Medium	1346 [1274, 1384]	1742 [1649, 1791]	1728 [1656, 1766]	1791 [1700, 1837]	1807 [1764, 1830]
Coarse	859 [822, 890]	1065 [1019, 1102]	1087 [1050, 1118]	1499 [1466, 1526]	1516 [1493, 1534]

types (Fig. 4). For deposits composed of the coarse tephra, substantial amounts of rain drained out of the deposit, even whilst lower portions of the deposit remained dry. Even after 2 h of continuous heavy rainfall, the mass of the deposits continued to slowly increase in all four of the coarse experiments. For the medium tephra, mass increased at a steady rate, absorbing a consistent amount of rainfall, until the deposit was close to reaching its maximum mass increase. At this point all additional rain drained away at the same rate it was absorbed into the deposit, without large amounts of deposit erosion. Deposits composed of the fine tephra were the only ones that were eroded to the extent that the rained-on deposit eventually weighed less than the original, dry deposit. In these fine tephra experiments, erosion via surface runoff was minimal, with most erosion occurring via successive slope failures (starting from the toe of the deposit) that began only after rain had infiltrated to the base of the entire deposit. An additional video file shows this in more detail (see Supplementary data file 1).

In both the normal-graded and reverse-graded deposit experiments, the mass increase over time exhibited a similar pattern, with the load increasing approximately linearly until near the maximum load was reached (typically within the first 10 to 30 min of the experiment), before very slowly rising and/or plateauing until the end of the experiment (Fig. 4b). The fine tephra component remained largely uneroded by the rain, with only 1–2 cm of tephra being removed from the toe of the 40-cm long deposit. This minor erosion meant that a relatively small decrease in mass of ~50 g (contributing to a 3–4% reduction in the total mass gained) can be seen in five of the eight waxing and waning experiments after the fine tephra became completely wet.

In all four of the normally graded deposit experiments, the upper layers of fine tephra absorbed water but water did not infiltrate to the lower tephra, with large portions of the lower, coarsest tephra remaining dry, even after 2 h of heavy rainfall. This meant that the normally graded deposits exhibited the lowest maximum mass increases (18–23%) of all

by Macedonio and Costa (2012). This method assumes the maximum absorbed water volume is equal to the total porosity, which is calculated as the dry bulk density divided by a standard dense rock equivalent value of 2500 kg m⁻³

the deposits tested in this study. Similar infiltration patterns have been observed in cross-stratified sand dunes where preferential flow paths tend to develop in the higher bulk density, finer-grained layers (Ritsema and Dekker 1994). This is because when dry sand is initially exposed to water, finer layers of sand have higher hydraulic conductivities than coarser layers (Miles et al. 1988).

Deposits composed of the fine tephra were the only ones to be compacted in our experiments, with compaction decreasing deposit height by ~2–4% or 2–4 mm. These relatively low levels of compaction, compared to the 30% values reported by the natural field experiments of Blong et al. (2017), may be attributed to a number of factors. Firstly, the Blong et al. (2017) experimental tephra would likely have been exposed to relatively large raindrops from tropical rainfalls, and the higher impact energies associated with these may have been more efficient at compacting and eluviating deposits compared to our relatively smaller sprayed rainfall droplets (Yakubu and Yusop 2017; Tarasenko et al. 2019). Other factors that may have contributed to the high deposit compaction values from this study may have been the compaction or wilting of the 30–40-mm tall grasses some of the tephra were deposited onto or the possible elluviation of tephra into the soil below.

Discussion

Implications for damage assessment

For deposits composed, or containing layers of, tephra of a similar grainsize to the coarse tephra used in these experiments (median grainsize diameter 4 mm or – 2 phi), the use of the saturation assumption from Macedonio and Costa (2012) would likely result in large overestimates of tephra load increase under rainfall. Due to their ability to drain well, we suggest that for relatively coarse tephra deposits (median phi < 0, or diameter > 1 mm), the realistic volume

of water that can be absorbed under rainfall should be estimated using the capillary porosity (the void space in which water will remain after liquid has drained out under gravity) rather than the total porosity (the proportion of a deposit that is fillable by water). If laboratory measurements are not possible or feasible, capillary porosities for coarse tephra deposits could be assumed to be between 20 and 40%, based on measurements from Fiorillo and Wilson (2004) and those from this study (Fig. 6). Note that this range is derived from the average measurements taken on just three different samples. The relationship between grainsize and total porosity in tephra deposits is very different from that in typical alluvial sediments (Stephens et al. 1998), and for this reason, we do not recommend using the total porosity of these specific unconsolidated sedimentary deposits as analogues for the estimation of the total porosity of tephra deposits (Fig. 6). The total porosities of these alluvial sediments do however closely match the capillary porosities of tephra deposits in Fig. 6, though we are unsure what underlying processes may have caused this or if it could simply be a coincidence. From our porosity measurements, completely filling the capillary porosity of the coarse tephra would produce a load increase of 27.9%, which very closely matches the 28.4% highest load increase observed in the coarse tephra. This suggests that if rain is free to drain from such a coarse tephra, very little of the deposit's effective porosity (the proportion of fillable void space from which a liquid freely drains out under gravity) can be filled, even under high rainfall rates. Conversely, we find that the saturation assumption is appropriate for fine-grained tephtras with one caveat. That is, caution should be used when applying the saturation assumption

to deposits that are prone to compaction by rainfall as this decreases the void space available for saturation. The fine tephra used in these experiments had a relatively high bulk density of $\sim 1500 \text{ kg m}^{-3}$ when dry and displayed only minor compaction under rainfall.

The greatest tephra load increase observed in these experiments was $< 0.3 \text{ kPa}$, and this required 10-cm thick deposits being exposed to heavy rainfall, $35\text{--}70 \text{ mm h}^{-1}$ intensity, uninterrupted for at least 40–20 min, respectively. Load increases greater than this obviously require thicker tephra fall deposits (assuming the same porosity) and larger quantities of rain. For example, if a given tephra deposit has a bulk density of 1000 kg m^{-3} and we assume 30% is a credible maximum value for load increases (as our experiments suggest), an initial deposit thickness of 160 mm and the complete absorption of nearly 50 mm of rain are required to achieve the maximum load increase, from 1.53 to 2 kPa. This 30% increase in load corresponds to a 40% increase in roof collapse probability (from 10 to 50%) for buildings in the 'weak' roof class from Spence et al. (2005).

In many places around the world, rainfalls of 50 mm or more occur relatively infrequently, and large accumulations of tephra ($> 15\text{-cm}$ thick in this example) are typically constrained to areas relatively close to the vent. Despite this, theoretical calculations of building damage given tephra loads increased by rainfall show that even 20 mm of rainfall can still appreciably increase probabilities of roof collapse. Biass et al. (2016), for example, modelled that a 20-kg m^{-2} load increase (from 20 mm of rainfall — an amount that admittedly falls only around twice per year on average in the study area) to tephra deposits from long-lasting Vulcanian

Fig. 6 Relationship between median grainsize, total porosity and capillary porosity for several tephra deposits and the pseudo-tephra deposits from this study. The dashed line marks average values for the total porosity of typical alluvium deposits from Stephens et al. (1998), showing that the total porosities of granular sedimentary deposits follow the opposite trend of total porosities in tephra deposits. All studies in the figure have been referenced within the text with the exception of Diaz et al. (2005) and Hernández (2013)

eruptions could increase roof collapse probabilities by an average of 10% at Vulcano Island (i.e. half of all buildings exposed to tephra had a 20% chance of collapse under dry conditions, and this increased to a 30% chance with the addition of 20 mm of rainfall). At volcanoes with high building exposure, modest increases in damage probabilities can result in thousands of additional buildings receiving damage.

Considerations for roof design and cleaning

If the pitch of a roof exceeds the angle of repose for a given tephra deposit, it is expected that such tephra will be unable to accumulate on that portion of the roof (Blong 1981). The dry angles of repose for the fine, medium and coarse tephra were 35°, 39° and 42° respectively. This matches well with results from Hampton et al. (2015), who found that > 90% of tephra deposited onto new sheet metal roofs with a pitch $\geq 35^\circ$ was unable to remain there and accumulate. However, as also pointed out by Hampton et al. (2015) and Spence et al. (1996), if rain has fallen prior to or during deposition, the potential for tephra to shed from roofs is greatly reduced even at roof pitches of 45°. Other than having a high roof pitch, buildings could also be made more resilient to tephra falls by being designed with roofs that can be accessed safely for removal of tephra, ideally without causing damage to the roof covering or gutters. As it is widely recognised that rainfall absorption can trigger roof collapse, forecasts of rainfall can encourage residents to ignore evacuation orders or re-enter evacuation zones so they may pre-emptively remove tephra from their roofs. This behaviour was observed following the 2014 eruption of Kelud in Indonesia, and the 2020 eruption of Taal in the Philippines (Blake et al. 2015; Gutierrez 2020) and is perhaps a behaviour that should be anticipated during future eruptions when evacuation guidelines or orders are being communicated or put in place.

Limitations and future work

The key limitations of this study arise from the use of simulated rainfall on simulated tephra deposits. As stated in the "Methods" section, naturally formed raindrops are larger and have higher kinetic energies than those from pressurised nozzle rain simulators. Natural, fresh tephra deposits also have the potential to develop chemical surface crusts that could reduce the permeability of the deposit. Changing both of these inputs could contribute towards unexpected interactions, not observed during these experiments. However, given the difficulties associated with measuring or even observing such interactions in the field, the experimental approach adopted here provides useful information for quantification of tephra deposit-rainfall interactions. Future laboratory experiments could use natural rainfalls and investigate

lower rainfall intensities, or use unweathered, naturally fragmented tephra from a wider range of chemical compositions and containing a wider range of components (e.g. lithics and free crystals in addition to juveniles). Additional variables beyond grain size distribution and rainfall rate, such as roof pitch, roof material, and roof condition, and the effect of antecedent rainfall could all be investigated. Finally, it would be useful for future studies to provide a more comprehensive analysis of the relationship between tephra deposit grain size distribution and tephra deposit porosity, for the range of different deposit types that exist. This would allow for rainfall increased loading to be more easily or systematically included in tephra fall hazard assessments.

This study has looked to quantify how building damage could be increased by the interaction of rainfall and tephra fall in the context of increased tephra fall loading on roofs. However, if rainfalls as intense as those applied in this study were to occur after a tephra fall, it is highly likely that this would trigger lahars that, for buildings in lahar-prone areas, could cause damage exceeding that caused by loading on roofs alone. This was the case in the town of Rabaul in 1994, where a small number well-built structures sustained little damage from heavy tephra falls (300–400-mm thick), but were eventually made uninhabitable when deposits from the surrounding hills were mobilised into mudflows during the wet-season (Blong 2003). It is important that tephra fall building damage assessments consider the full range of volcanic hazards as the damage from other volcanic hazards might make that caused by tephra falls largely irrelevant (Zuccaro et al. 2008).

The deposits tested in these experiments displayed wide ranges of bulk densities (Fig. 5). Even when dry, the bulk density of coarse tephra (860 kg m^{-3}) was close to half that of the fine tephra (1540 kg m^{-3}). Considering this, and that an ideal tephra fall building damage survey should include buildings exposed to a wide range of hazard intensities (i.e. in different areas along and across the tephra dispersal axis), it is highly unlikely that all buildings will receive tephra of the same bulk density. This suggests that the typical practice of measuring deposit thicknesses and converting these linearly to loads based on an average bulk density value introduces substantial error to hazard intensity quantification during damage surveys. To remedy this in the future, wherever possible, thickness measurements should be supplemented with tephra loading measurements, made at or near the site of each damage observation.

The results of tephra fall hazard assessments, both deterministic and probabilistic, are often communicated by identifying areas expected to receive tephra loads exceeding roof collapse thresholds (Bonadonna et al. 2005; Biass et al. 2013; Jenkins et al. 2015). Numerical modelling of tephra dispersion necessitates the use of wind data; for probabilistic modelling, this is often sourced from reanalysis databases

that also include rainfall data (Dee et al. 2011); thus, future assessments could combine wind and rainfall information to account for the increased loading associated with rainfall absorption across different areas during different seasons. However, long-term rainfall patterns in such databases would not account for the increased probability of heavy rainfall associated with eruption-induced storms (Todesco and Todini 2004), or for the fact that rainfall itself can trigger primary eruptive activity (Matthews et al. 2009).

Conclusions

This study presents the results of 20 rainfall simulation experiments examining how grainsize distribution and rainfall intensity influence the loads exhibited by tephra fall deposits. Exposing 10-cm thick deposits to 2 h of heavy rain (intensities of 35 and 70 mm h⁻¹), produced increases in load of less than 0.3 kPa. The loads increased by between 18% (for normally graded deposits) and 30% (medium ungraded or reversely graded deposits), far below the 100% increase which is often assumed and referenced in tephra fall hazard and risk assessments. Rainfall intensity had little effect on results with only the coarse and reverse-graded deposits showing a ~5% higher maximum load increase under the 70-mm h⁻¹ rainfall. The total amount of rainfall and how this relates to the capillary porosity of deposits were identified as the key parameters controlling load increases meaning these are the parameters — in addition to the standard parameters of thickness and dry bulk density — that should be used in studies assessing likely building damage from future eruptions. Unexpectedly low load increases occurred in normally graded tephra deposits, which can be formed by eruptions that are decreasing in intensity. This was due to the fact that when dry tephra were first exposed to water, the upper finer layers had higher hydraulic conductivities that prevented rain from infiltrating into the coarser layers beneath that have lower hydraulic conductivities. Our results highlight that failing to account for rainfall's effect on tephra deposit loading can lead to both underestimations and overestimations of risk posed to buildings. Underestimations of risk result from failure to consider the potential for rainfall to increase the loads of modelled tephra accumulations assumed to be dry. Overestimations of risk occur if post-eruption damage surveys underestimate the tephra loads that buildings have been exposed to. This can happen when loads are calculated based on bulk densities corresponding to deposits that have been oven-dried, when they may have in fact been wet whilst on the buildings. To reduce these errors, we suggest that tephra loading be measured during post-eruption building damage assessments (as opposed to just deposit thickness) and that

local rainfall patterns be considered during both probabilistic and deterministic tephra fall hazard assessments.

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Data availability Data from experiments will be uploaded as supplementary material.

Code availability Not applicable.

Declarations

Conflict of interest The authors declare no competing interests.

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