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Natural Hazards and Earth System Sciences

Brief Communication
"Rain effect on the load of tephra deposits"

G. Macedonio[1] **and A. Costa**[1,2]

[1] Istituto Nazionale di Geofisica e Vulcanologia, Osservatorio Vesuviano, Napoli, Italy
[2] Environmental Systems Science Center, University of Reading, Reading, UK

Correspondence to: A. Costa (antonio.costa@ov.ingv.it)

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Abstract. Accumulation of tephra fallout produced during explosive eruptions can cause roof collapses in areas near the volcano, when the weight of the deposit exceeds some threshold value that depends on the quality of buildings. The additional loading of water that remains trapped in the tephra deposits due to rainfall can contribute to increasing the loading of the deposits on the roofs. Here we propose a simple approach to estimate an upper bound for the contribution of rain to the load of pyroclastic deposits that is useful for hazard assessment purposes. As case study we present an application of the method in the area of Naples, Italy, for a reference eruption from Vesuvius volcano.

1 Introduction

Explosive volcanic eruptions can eject large amounts of pyroclastic material mainly as pyroclastic density currents and tephra fallout (lapilli and ash). Due to their loading, tephra fallout deposit can cause roof collapses in limited areas near the volcano, when the weight of the deposit exceeds some threshold value (Blong, 1981; Spence et al., 2005; Macedonio et al., 2008). The additional loading of water that remains trapped in the deposit due to rainfall can contribute to increasing the loading of the deposit on the roofs.

Introducing some simplifications and considering the limit cases of dry and water saturated conditions, here we estimate some bounds for the contribution of rain to the load of pyroclastic deposits, useful for hazard assessment purposes.

2 Loading of wet vs. dry deposits

2.1 Porosity of the pyroclastic deposit

Deposits generated by fallout of pyroclastic material are typically incoherent and porous. Porosity is due to both *i*) void spaces between the grains (effective porosity), and *ii*) small interconnected bubbles in the juvenile material (capillary porosity). The total porosity, ϕ_{tot}, is the sum of the effective, ϕ_{eff}, and the capillary porosity, ϕ_{cap}:

$$\phi_{\mathrm{tot}} = \phi_{\mathrm{eff}} + \phi_{\mathrm{cap}} \tag{1}$$

2.2 Density of dry and wet deposit

The bulk density of the dry deposit (ρ_{d}) is related to the density of the dense rock (ρ_{DR}) and the total porosity (ϕ_{tot}) through the relationship:

$$\rho_{\mathrm{d}} = (1 - \phi_{\mathrm{tot}})\rho_{\mathrm{DR}} \tag{2}$$

The above relationship can be used to estimate typical values of ϕ_{tot}: $\phi_{\mathrm{tot}} = 1 - \rho_{\mathrm{d}}/\rho_{\mathrm{DR}}$.

Assuming, as the most cautious limit case, that all pores and interstices are filled with water (water saturation), the density of the deposit layers become

$$\rho_{\mathrm{sat}} = \phi_{\mathrm{tot}}\rho_{\mathrm{w}} + \rho_{\mathrm{d}} \tag{3}$$

where ρ_{sat} is the bulk density of the water saturated deposit and ρ_{w} is the density of the water ($\rho_{\mathrm{w}} = 1000\,\mathrm{kg\,m^{-3}}$).

2.3 Weight of wet pyroclastic deposits

For hazard assessment purposes we assumed that during rainfalls and rainstorms the water is adsorbed completely by the fall deposit and that the deposit is not mobilized until water saturation is reached. The condition of water saturation results in an upper limit for the water contained in the pores and is realistic for tephra layer on flat surfaces (e.g. flat roofs, terraces). However, debris flows and mudflows can be mobilized for a water content lower than saturation fraction; typical water fractions for debris flows and mudflows range from 20 to 50 % (Pierson, 1986), and in general it depends not only on water content but on rainfall intensity and duration (Fiorillo and Wilson, 2004). However, here we do not consider

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extreme rainfall events triggering debris flows. In that case, the debris flow itself represents a major hazard. For an analysis of rainfall induced debris flows of pyroclastic deposits, the reader is addressed to the study of Fiorillo and Wilson (2004).

In accord to Fiorillo and Wilson (2004), once that deposit reached its field capacity (i.e. the maximum amount of water that a particular soil can hold), each storm producing an amount of retained water larger than a characteristic water threshold Z_t induces a debris flow (for pyroclastic deposits at Vesuvius, rainfalls that reach the field capacity have a Z_t of $\sim 60-80$ mm Fiorillo and Wilson, 2004).

Using the water saturation assumption, the upper limit of the amount of water adsorbed by a wet deposit is related to the total porosity, whereas for thick deposits, this upper limit is related to the maximum rainfall h_{max}. As we mentioned above, this represents a practical upper limit for hazard assessment that is quite realistic in the limit of low drainage rate (Fiorillo and Wilson, 2004). As a better approximation, we could use directly the maximum amount of retained rainwater as the function of the rainfall intensity and the deposit drainage coefficient.

In this way we can estimate the increase of the load (kg m^{-2}) of tephra deposit from dry to wet condition. Let w_{d} be the load of a dry tephra deposit having a thickness h_{dep}, then we have:

$$w_{\mathrm{d}} = \rho_{\mathrm{d}} h_{\mathrm{dep}} \tag{4}$$

Let h_{w} be the height of the rainfall (in meters). Then, before saturation is reached, the load of the wet deposit w_{w} is:

$$w_{\mathrm{w}} = w_{\mathrm{d}} + \rho_{\mathrm{w}} h_{\mathrm{w}} \tag{5}$$

Finally, considering the simplifying assumption of water saturation condition, we can calculate the weight of the wet deposit as:

$$w_{\mathrm{w}} = w_{\mathrm{d}} + \rho_{\mathrm{w}} \min\left(\phi_{\mathrm{tot}} h_{\mathrm{dep}}, h_{\mathrm{max}}\right) \tag{6}$$

that is equivalent to:

$$w_{\mathrm{w}} = w_{\mathrm{d}} + \rho_{\mathrm{w}} \min\left(\frac{\phi_{\mathrm{tot}}}{(1-\phi_{\mathrm{tot}})} \frac{w_{\mathrm{d}}}{\rho_{\mathrm{DR}}}, h_{\mathrm{max}}\right) \tag{7}$$

where h_{max} is the maximum rainfall.

3 Application to Vesuvius pyroclastic deposits

In order to show the effect of Eq. (7) on pyroclastic deposit weight, here, as a case study, we apply it to tephra deposits in the Vesuvius area, although such an effect is general and was observed elsewhere. For example, ashfall from the 15 June 1991 eruption of Mount Pinatubo, Indonesia, resulted in the accumulation of 5–10 cm of wet ash in the area of former US Clark Air Base, located 20 km northeast of the volcano. Densities of ash samples collected there ranged from 1200 to 1600 kg m^{-3} (dry) and 1500 to 2000 kg m^{-3} (wet) (G. Heiken and Riker, D., written communication, 1994, reported in Spence et al., 1996), showing an increase in density of 25 % from dry to wet.

Table 1. Typical characteristics of pyroclastic soils in the Vesuvius area. After Fiorillo and Wilson (2004).

Material	γ_{d} (kN m^{-3})	ϕ_{eff} –	ϕ_{tot} –	K (m s^{-1})
Pumice	7.8	0.33–0.037	0.68	$> 10^{-4}$
Ash	8.7	0.05–0.06	0.67	10^{-7}–10^{-6}

For typical tephra deposits from past eruptions of Vesuvius, a specific weight of $\gamma_{\mathrm{d}} = 7.8$ (dry pumice) and 8.7 kN m^{-3} (dry ash) was measured (Fiorillo and Wilson, 2004), corresponding to bulk densities of $\rho_{\mathrm{d}} \approx 800$ kg m^{-3} for dry pumice layers and 890 kg m^{-3} for dry ash layers (see Table 1).

Hence, considering as reference a total porosity for ash and pumice layers of $\phi_{\mathrm{tot}} \simeq 0.68$ (see Table 1) and a typical magma density of $\rho_{\mathrm{DR}} = 2500$ kg m^{-3} (Arrighi et al., 2001), from Eq. (2), we obtain $\rho_{\mathrm{d}} = 800$ kg m^{-3}, in agreement with the bulk density of other pumice deposits of past eruptions in the Neapolitan area (Cioni et al., 2003; Pfeiffer and Costa, 2004; Macedonio et al., 2008; Costa et al., 2009). In order to estimate a typical range of values for ϕ_{tot}, we can consider that bulk densities of proximal and medial deposits of pyroclastic material range from 600 to 1500 kg m^{-3} (Durant et al., 2009; Pfeiffer and Costa, 2004). For example, tephra deposit densities are of about 900 kg m^{-3} for the 472 AD (Pollena) Vesuvius eruption (Cioni et al., 2003; Macedonio et al., 2008), and of about 700 kg m^{-3} for the Agnano-Monte Spina (AMS) eruption in the Campi Flegrei (Pfeiffer and Costa, 2004; Costa et al., 2009). Considering $\rho_{\mathrm{DR}} = 2500$ kg m^{-3}, from Eq. (2), we obtain that ϕ_{tot} ranges typically from about 0.40 to 0.75 ($\sim$0.64 and 0.72 for the cases of Pollena and AMS deposits, respectively).

To proceed with calculations, we need to estimate the maximum rainfall height h_{max} for the Vesuvius region. For instance, for the deposits of past eruptions of Vesuvius ($\phi_{\mathrm{tot}} \simeq 0.68$), 680 kg of water per cubic meter of dry deposit is needed to reach pore saturation. This corresponds to 340 mm of rainfall needed to saturate 0.5 m of dry deposit. This amount of water has to be compared with the typical daily rainfalls in the Vesuvius region, shown in Fig. 1 (from Ricciardi et al., 2007). Fiorillo and Wilson (2004) reported that on average, a maximum rainfall of about 210 mm of two day cumulative rainfall can occur in Castellammare (near Vesuvius) and Cervinara. As reference, in this study we use 100 and 200 mm rainfall. The latter represents already a high rainfall value that was able to trigger more than 50 debris flows (Fiorillo and Wilson, 2004). However, in the last

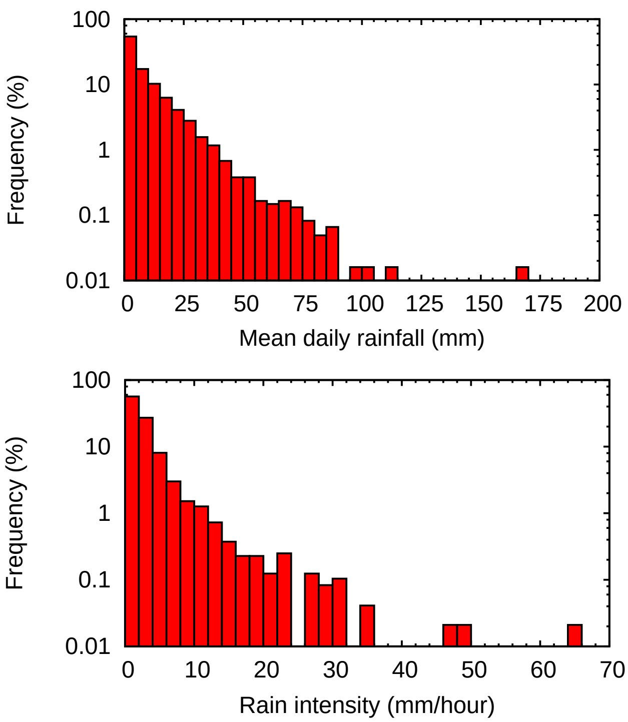

Fig. 1. Top: Frequency of the mean daily rainfall at Vesuvius in the period 1943–2001. Bottom: Frequency of the rain intensity at Vesuvius (same period). Data from Ricciardi et al. (2007).

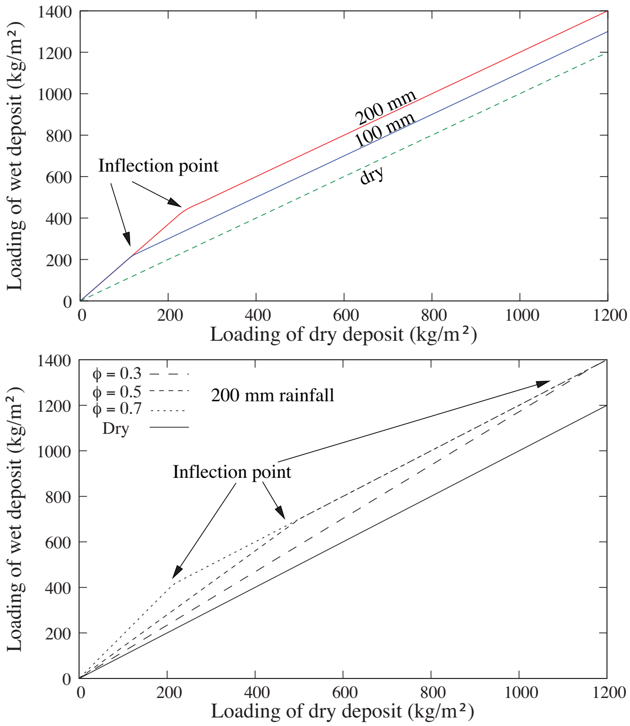

Fig. 2. Top: Maximum loading of a wet vs. dry tephra deposit for rainfall of 100 mm and 200 mm, assuming a deposit porosity $\phi_{\rm tot} = 0.68$. The inflection points in the curves occur for $\phi_{\rm tot} h_{\rm dep} = h_{\rm max}$. Bottom: Effect of porosity on the load of wet deposits, for a rainfall of 200 mm: a change in the deposit porosity produces in a shift of the inflection point.

century, the cumulative rainfall in two days reached a maximum of 504 mm at Salerno (26 October 1954), with the generation of more that 100 debris flows causing 318 deaths (Fiorillo and Wilson, 2004).

Samples collected at Cervinara, at about 30 km NE from Vesuvius, show that effective porosity of pumices is smaller than effective porosity of ash (Fiorillo and Wilson, 2004). Table 1 reports typical values of the effective porosity ($\phi_{\rm eff}$), the total porosity ($\phi_{\rm tot}$) and the hydraulic conductivity K ($\mathrm{m\,s^{-1}}$) of different pyroclastic material collected around Vesuvius. The hydraulic conductivity K ($\mathrm{m\,s^{-1}}$) describes the ease with which water can move through pore spaces or fractures. A typical time scale for this process is $h_{\rm dep}/K$. For $K \sim 10^{-4} - 10^{-6}\,\mathrm{m\,s^{-1}}$ (Fiorillo and Wilson, 2004) and $h_{\rm dep} \sim 0.5$ m we have time scales that range from ~ 1 h to ~ 100 h, which implies that, depending on the kind of material, water drainage can be a relatively fast (for instance in the case of a pumice layer) or slow process. Obviously, in the case of fast drainage, the assumption of water saturation condition is not realistic.

Summarizing, from Eq. (3) results that for $\phi_{\rm tot} = 0.68$ under saturated pore conditions, the deposit density increases by 680 $\mathrm{kg\,m^{-3}}$ passing from dry to water satured conditions, that is 85 % of its dry weight for pumice layers and 76 % for ash layers. We assume that beyond the saturation fraction the deposit is mobilized. The last process is not considered in the present study, focused only on static deposit conditions.

The main result of this work is represented by Eq. (7), that gives the wet deposit load as a function of the load of the dry deposit. For the range of parameter values estimated for Vesuvius, we reported a plot of this relation in Fig. 2 (top) for two extreme rain events of 200 mm and 100 mm (*i.e.* $h_{\rm max} = 0.5$ m and $h_{\rm max} = 0.2$ m) for the values of $\phi_{\rm tot} = 0.68$, typical of pyroclastic deposits near Vesuvius (Fiorillo and Wilson, 2004; Costa et al., 2009), and $\rho_{\rm RD} = 2500\,\mathrm{kg\,m^{-3}}$ (Arrighi et al., 2001). In Fig. 2 (bottom) we explore a larger range of porosity values, showing the effect of changing deposit porosity $\phi_{\rm tot}$ on the load of the wet deposit. This results in a shift in the position of the inflection point. In particular, for thinner deposits (left of the inflection point), a decrease in porosity corresponds to a decrease of the load of the wet deposit.

As an implication for tephra fallout hazard assessment, areas enclosed by either critical isomass or isoprobability curves can increase significantly due to the effect of rain on the load of pyroclastic deposits. In Fig. 3 we show the effect of tephra loading increase due to two rainfall events of 100 mm and 200 mm. For instance, if we consider the ground

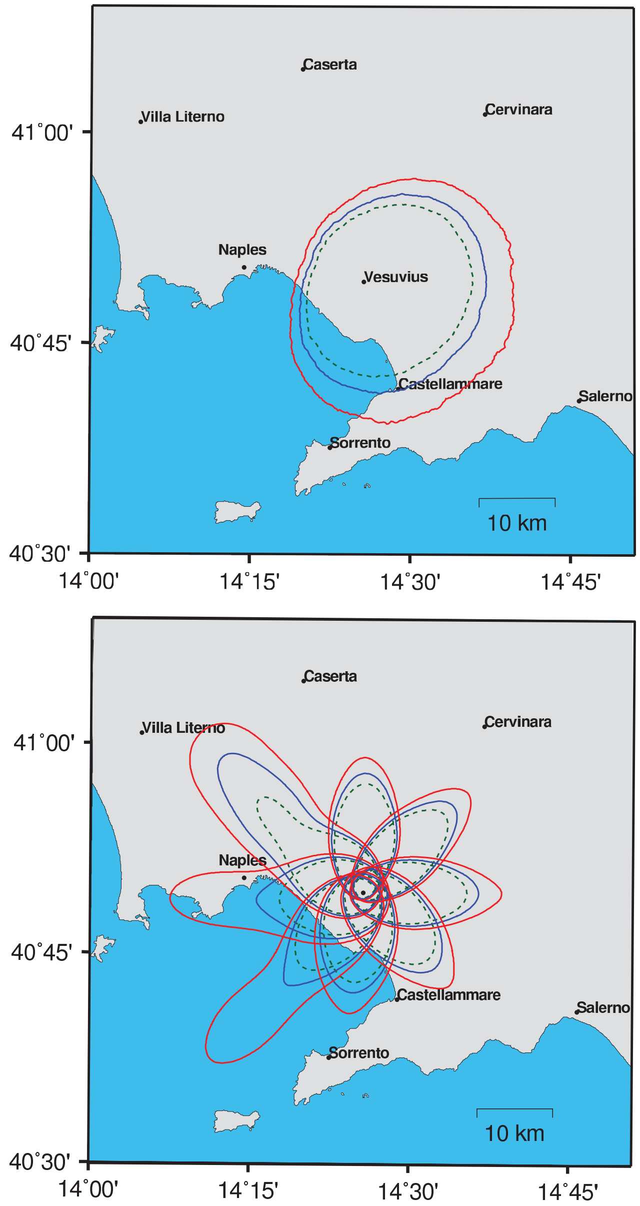

Fig. 3. Top: 5 % tephra loading probability curve to exceed 500 kg m^{-2} for Sub-Plinian I scenario under dry (green dashed line) and wet (full lines) conditions for 100 mm (blue line) and 200 mm (red line) of rainfall. Bottom: Simulations of tephra loading using 8 different wind profiles representative of 8 radial sectors for a loading 500 kg m^{-2} for Sub-Plinian I scenario under dry (green dashed line) and wet (full line) conditions for 100 mm (blue line) and 200 mm (red line) of rainfall.

load probability map for a loading threshold of 500 kg m^{-2} (a value considered critical for roof collapse of high quality buildings in the Neapolitan area; Zuccaro et al., 2008), for the Sub-Plinian I scenario (Macedonio et al., 2008) and 200 mm of rainfall, the area enclosed by the curve of 5 % probability of exceeding the threshold, in case of fully water saturated conditions, is 1.92 times larger than the curve obtained for dry conditions (see Fig. 3). Considering the same scenario, a similar effect is clearly evident on the extension of the 500 kg m^{-2} isomass curves of the most representative deposits on the eight main sectors around Vesuvius (Macedonio et al., 2008). These results suggest to consider seasonal effects on the hazard assessment in order to account for the possibility of rainfall effect on pyroclastic deposit loading.

4 Conclusions

We analyzed the effect of rainfall on tephra deposit loading and estimated an upper (water saturated) and a lower (dry) bound. The proposed formulation is useful for hazard assessment purposes. As an application we estimated rainfall loading contribution to pyroclastic deposits in the Vesuvius region, presenting also its effect on tephra fallout hazard map for a reference scenario (Subplinian); showing that the areas enclosed by critical curves can cover much larger areas than those obtained assuming dry deposits, commonly used for the hazard assessment of the Vesuvius region.

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