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Potential Damages of Atmospheric Storage Tanks due to Volcanic Ash Aggregations in Presence of Water

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Recent studies of the effects of the volcanic ash fallout on storage tanks have shown the potential causes of failure for both fixed and floating roof tanks. The vulnerability of these facilities has been defined through the estimation of threshold values of the ash load on their roofs and exceedance probabilities of these limits. It has been observed that the amount of the overhead on the roof is much greater when the ash is saturated with rain because of the formation of aggregates. This paper aims to analyse the influence of this phenomenon on the potential damage of tanks located in the area surrounding Mt. Etna.

1. Introduction

Natural events can affect the integrity of urban systems, lifelines and industrial facilities (Krausmann, 2011). If industries at major risk are involved in such disasters, severe accidents as fires, explosions or toxic dispersions may also occur. In the literature these events are known as Natural-Technological scenarios (Na-Tech). A recent survey (Fabiano and Currò, 2012), showed that from 1930 to 2010, nearly 6.4% of the accidents occurred in the oil industry were due to natural causes, furthermore some scientists focused their researches on the integration of the risks associated with Na-Tech events in the standard Quantitative Risk Analysis (Campedel et al., 2008) and the development of specific approaches to the planning of related emergencies (Milazzo et al. 2013a) to be integrated in current available tools (Milazzo et al., 2009).

Contributions to the study of technological scenarios triggered by volcanic phenomena are more recent and mainly focused on the analysis of the effects due to volcanic ash fallouts; these need to be implemented as suggested by Milazzo and Aven (2012a), to estimate the uncertainty related to natural phenomena. Some authors proposed a simplified methodology estimating the fragility of atmospheric fixed roof tanks (Salzano and Basco, 2008), of floating roof tanks (Milazzo et al., 2013b) and filtration systems (Milazzo et al., 2013c) with respect to the volcanic ash fallout phenomenon. The method is based on the calculation of the threshold values of an intensity parameter, associated with the volcanic phenomenon and causing the facility's failure, and its exceedance probability. This paper aims to extend the previous studies related to the estimation of the potential loading damage of storage tanks as will be summarized later.

By means of the same approach used for snow , a complete analysis of the potential damages for fixed roof tanks has been made by Salzano and Basco (2008). Concerning external floating roof tanks, Milazzo et al. (2012b) have identified the sinking and the capsizing of the roof as the potential causes of failure due to deposition of ash. Although they concluded that extremely large explosive eruptions are required to bring about this kind of damage, the threshold limits of deposit causing these modes of failure have been estimated for the volcanic area surrounding Mt. Etna in Sicily (Italy).

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In this framework, as reported in the literature (USGS website), it must be pointed that the amount of load on a certain structure could be much greater when the ash is saturated with rain due to aggregation phenomena. In this work a physical characterization of the volcanic ash emitted from Mt. Etna has been carried out (experimental part), in order to verify the potential ash aggregation and provide a detailed quantification of the threshold limits for both dry and wet deposits leading to the damage of the tank. After a brief summary of the main characteristics of the volcanic ash, in the first part of the paper the characterization of the ash produced by Mt. Etna is described and related results are given. In the second part, the experimental data has been used to estimates the threshold values of dry and wet deposits leading to the damage of storage tanks.

2. Volcanic ash

The volcanic ash is produced by explosive volcanic eruptions. The diameter of the particles is smaller than 2 mm (<0.063 mm for fine ash and between 0.063 and 2 mm for coarse). Depending on the velocity of formation, the ash is made of various proportions of glassy (non-crystalline), crystalline and lithic particles. The density may vary within the following ranges: 700 ÷ 1,200 kg/m^3 for pumice, 2,350 ÷ 2,450 kg/m^3 for glass shards, 2,700 ÷ 3,300 kg/m^3 for crystals, and 2,600 ÷ 3,200 kg/m^3 for lithic particles (Wilson et al., 2012). Denser particles are deposited close to the crater, fine glassy material and pumice shards fall at distal locations. The abrasiveness of the volcanic ash is a function of the material's hardness and the shape of particles.

Small voids are typically contained in glassy particles, these are known as vesicles and are formed by the expansion of magmatic gas before the magma solidification. Ash particles have a varying degree of voids, which gives them an extremely high surface area to volume ratios.

Volcanic particles naturally tend to bind giving aggregates. As reported by volcanologists (Textor et al., 2006), the information on the aggregation processes are still either lacking or very incomplete. It seems that for dry particles electrostatic or van der Waals forces lead to successful coalescence, although such dry clusters are weakly bound and quickly collapse landing on the ground. If water is available, much stronger particle bonds result from short-range surface tension forces. The presence of dissolved salts establishes more durable aggregations when evaporation leads to enhanced concentrations finally resulting in crystal bridges that greatly increase the strength of the inter-particle bonds.

3. Ash characterization

Some experimental tests were made in order to determine the possible aggregation of particles of ash in presence of rain and estimate both the dry and wet densities of the deposit. Two samples of ash produced by eruptions of Etna were taken at different locations: the first sample (ID=1) was collected close to the Cratere Silvestri (coordinates: lat. 37°41'55.73"N , long. 15°0'16.94"E; distance 5,5 km) and the second one (ID=2) was taken in urban area of Messina during the eruption of the 23rd February 2013 (coordinates: lat. 38°10'16.66"N, Long: 15°31'25.56"E; distance 65 km). Then the following tests have been performed in the laboratory:

1. Analysis of the size distribution for the dry and wet samples
2. Determination of the hygroscopy of the samples
3. Determination of the densities both of the dry and wet samples

3.1 Analysis of the size distribution

The sieving is the method used in this work to determine the size distribution of the volcanic particles. The analysis makes use of special sieves arranged in a column, each of them retains the fraction of granules having larger dimensions compared with those of the holes of the sieve. The sieves must be stacked in such a way that the top has the larger mesh and the others have a gradually smaller mesh going down to the bottom. At the base of the column, there is a plate which is used to collect the granules with smaller diameters than the holes of the sieve with the lower mesh. The column is placed on a mechanical shaker for 20 min and, after the shaking, the solid fractions retained by each sieve is weighted. The weight of each solid fraction is then compared to the weight of the total solid to obtain the percentage of solid retained by each sieve. In this study a wet sieving has also been used to determine the potential of the particles to coalesce due to the weak interaction with water.

To determine the size distribution of the dry samples, these have been weighted and dried in an oven, then each sample was placed in the top sieve and the column was shaken. The wet samples are the result of a mixing process of ash and water and a subsequent filtration. The mixing allowed to simulate the effect of the rain. The sieving operation gave the size distribution also of the wet samples. The results are presented in a logarithmic graph of the retained percentage of solid versus the parameter ϕ (Krumbein parameter), which is expressed by the following correlation:

$$\phi = -\log_2 \frac{D}{D_o} \tag{1}$$

where D is the diameter of the particle and D_o is a reference diameter, which is equal to 1 mm to make the equation dimensionally consistent.

Figure 1 and Figure 2 give the size distributions of both dry and wet samples.

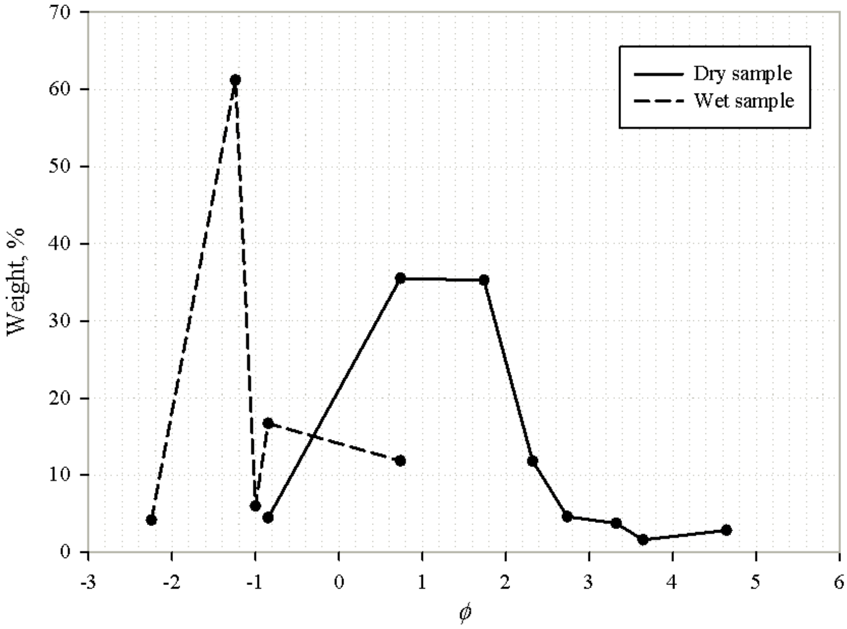

Figure 1: Size distribution for the sample 1. The bold line refers to the dry volcanic ash and the dashed line to the wet volcanic ash

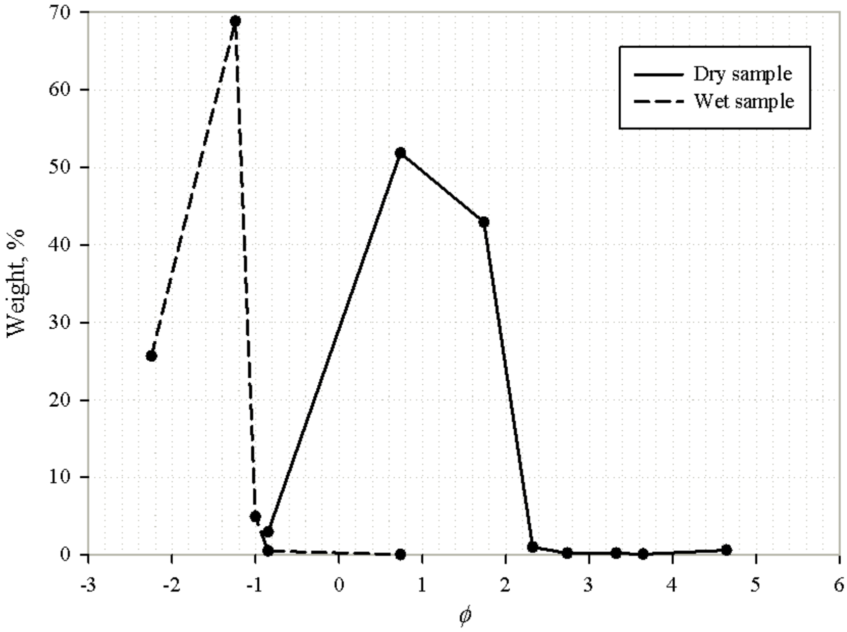

Figure 2: Size distribution for the sample 2. The bold line refers to the dry volcanic ash and the dashed line to the wet volcanic ash

Figure 1 and 2 show that the prevailing diameters for the dry particles are: 0.1 ÷ 2 mm (ϕ = 3.3 ÷ -1) for the sample 1 and 0.15 ÷ 2 mm (ϕ = 2.7 ÷ -1) for the sample 2. After the mixing of the ash with distilled water a certain degree of aggregation is observed, as indicated by Textor et al. (2006); the prevailing diameters for the aggregates are 0.6 ÷ 4.75 mm (ϕ = 0.7 ÷ -2.2) for sample 1 and 2 ÷ 4.75 mm (ϕ = -1 ÷ -2.2) for the sample 2.

3.2 Determination of the hygroscopy

The samples have been weighted and dried in an oven, then these have been kept for two days in two controlled humidity chambers with a relative humidity equal to 58 % and 100 %. The humidity was controlled by using solutions of sulphuric acid (Lide, 1990-1991). After to the humidification process the samples have been weighed. Both those placed in the chamber with humidity equal to 58 % did not undergo to any change in weight, the samples kept in the chamber having the 100 % of humidity increased their weight of about 5 %.

3.3 Determination of the density

The determination of the densities of the dry and wet samples have been executed according to the EN 1097-3 (1998) standard. The dry density is the “loose bulk density” which is defined as the mass of the dried particles (not compressed), contained in a container, divided by the total volume they occupy (volume of the container). The total volume includes particle volume, inter-particles void volume and internal pore volume (Brisi, 1981).

According to this definition, the determination has executed by using a container, whose volume and weight are known. It has been filled with dry and wet volcanic ash and, subsequently, weighed. The weight and the volume of the ash allowed to determinate the density. The ash densities for both the samples are given in Table 1. Results show that rainwater can increase the density by a significant percent, that can be more than 50 % if the ash becomes saturated by water. According to the experimental work, the increase in density is due to aggregation phenomena which are caused to interaction with the water.

Table 1: Ash densities

Sample ID	Condition	Density (kg/m^3)
1	Dry	1,594
1	Wet	1,935
2	Dry	832
2	Wet	1,409

4. Threshold values of the ash deposit

In this Section the results of the quantification of the threshold values of dry and wet ash deposits on the roof of storage tanks are given. These estimations have be made by using the densities determinate during the experimental work.

4.1 Fixed roof tanks

The heights of the ash deposit on fixed roof tanks causing (i) light damage, (ii) structural damage and (iii) collapse have been calculated as suggested by Salzano and Basco (2008). Results are given in Table 2.

Table 2: Height of deposit

Sample ID	Condition	Height for light damage (cm)	Height for structural damage (cm)	Height collapse (cm)
1	Dry	7.7	22.4	44.8
1	Wet	6.3	18.4	36.9
2	Dry	14.7	42.9	85.7
2	Wet	8.7	25.3	50.7

4.2 Floating roof tanks

Two potential failures have been analysed for floating roof tanks: (i) the sinking and (ii) the capsizing of the roof (see Milazzo et al., 2012).

In order to sink a floating roof, Archimedes principle requires that the combined weight (M) of the floating roof (M_{roof}) and the ash deposit (M_{ash}) displaces a volume of liquid greater than that of the roof. The height of the ash deposit can be calculated with respect to the estimated ash densities. Results are shown in Figure 3, where the height of ash deposit (h) vs. the level of roof immersion (δ_{imm}).

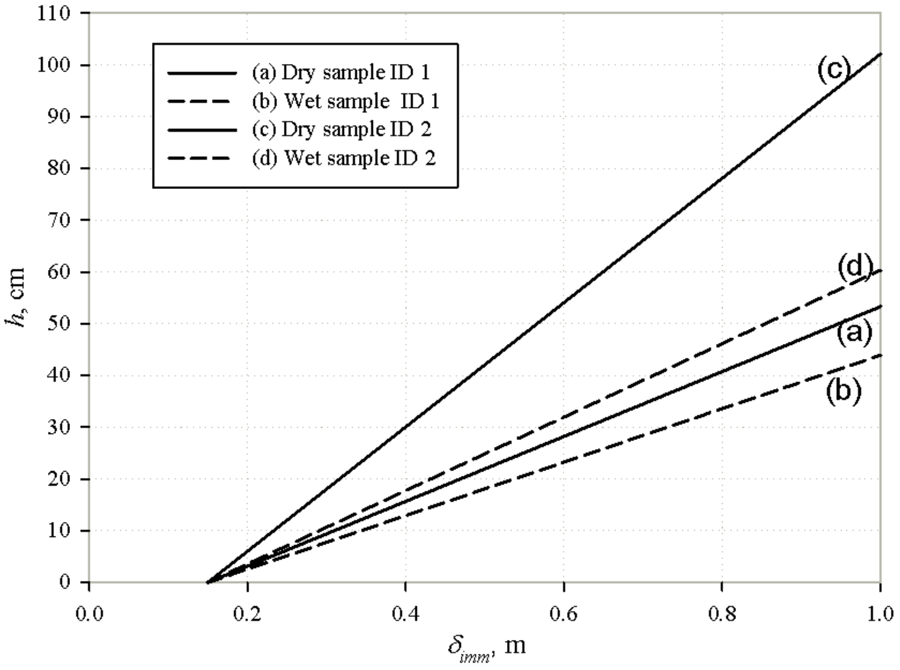

Figure 3: Thickness of the ash deposit required to sink the floating roof for $\rho_{liq}=1{,}000\ kg\cdot m^{-3}$ *(a)* $\rho_{ash}=1{,}594\ kg\cdot m^{-3}$ *(b)* $\rho_{ash}=1935\ kg\cdot m^{-3}$ *(c)* $\rho_{ash}=832\ kg\cdot m^{-3}$ *(d)* $\rho_{ash}=1{,}409\ kg\cdot m^{-3}$.

To define a threshold value of deposit for the capsizing is complex. The stability of floating bodies against small displacements from equilibrium was treated by Bouguer who introduced the concept of the metacentre. Euler gave a general criterion for stability based on the couple produced by the weight acting vertically down through the centre of gravity and the buoyancy force acting vertically upwards through the centre of buoyancy (Mégel and Kliava, 2010): the body remains stable if this couple produces a restoring moment. According to these concepts, it is possible to define the conditions when the roof capsizes. As suggested by Milazzo et al. (2012), it is necessary know the weight which must be applied to a point on the edge of the roof (minimum weight) and, then, given a certain distribution of the ash on it, it is possible to calculate the weight causing the capsizing. The calculation procedure is described elsewhere, in this paper it has only been applied. Results given in Table 3 are related to a distribution of ash as shown in Figure 4, these have been expressed as the maximum value of height (h_{max}).

Table 3: Maximum height for the roof capsizing

Sample ID	Condition	Height (cm)
1	Dry	4.87
1	Wet	4.01
2	Dry	9.32
2	Wet	5.51

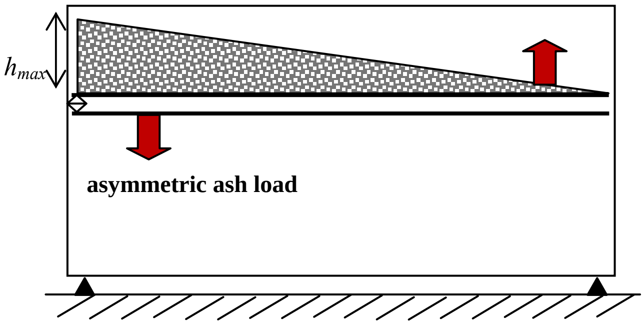

Figure 4: Asymmetric distribution of volcanic ash deposit on floating roof tanks.

5. Conclusions

In this paper an extension of the previous studies related to the estimation of the potential loading damage of storage tanks has been made. The main aim was to study the effects of the rainwater when a deposition of volcanic ash occurs over a tank. The literature shows that the amount of the overhead on a structure is much greater when of ash is saturated with water because of aggregation phenomena.

The experimental work has proved the formation of aggregates of particles, which contribute to an increase in density. Furthermore the determination of the dry and wet densities of the ash, emitted from the Mt. Etna, allowed to estimate the threshold values of deposits leading to the damage of storage tanks. Results show a significant reduction of the height of the deposits, causing the various modes of failure, when these are wet. According to these findings, the fragilities of atmospheric storage tanks must be estimated assuming both dry and wet depositions.

Finally, this study is a part of a more extended project for the analysis of the volcanic Na-Tech risks related to the eruptions of Etna aiming at the definition of vulnerability maps for infrastructure and industrial installations located in the area affected by the volcanic ash fallout.

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