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Analysis of the Effects due to Ash Fallout from Mt. Etna on Industrial Installations

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The fallout of ash from Mt Etna has caused significant problems to the resident population, road/rail and air traffic and production activities. This work is focused on the study of the potential damage to industrial structures caused by the fallout of volcanic ash and describes the main objectives of a research project aimed at defining the potentially critical scenarios for industrial installations and infrastructures due to eruptions of Mt. Etna. In the first part of this paper, a description of the method used for the analysis of the potential damage to storage tanks due to ash fallout will be given. The second part will provide the results of the application of the method.

1. Introduction

Natural disasters are able to affect the integrity of industrial facilities and, if large amounts of hazardous materials are stored, incidental scenarios such as fires, explosions or toxic dispersions may occur. Numerous works (Antonioni et al., 2007; Campdel et al., 2008) analyse the effects of natural risk on chemical plants, but there are fewer works related to the estimation of the damage caused by volcanic eruptions. Among the possible effects of eruption, Baxter et al. (1982) have analysed the effect on water treatment and accidents related to the transport of hazardous materials due to slippery road conditions. Recent studies in the volcanic Natural-Technological (Na-Tech) risk for both process industries and infrastructures are those of Salzano and Basco (2008) related to Mt. Vesuvius. These authors uses the Volcanic Event Tree (ET) methodology of Newhall et al. (2002).
This paper has been focused on the study of the potential damage to industrial storage tanks caused by the fallout of volcanic ash in the territory surrounding Mt. Etna. Recently this volcano has several explosive eruptions with ash emission. With particular reference to Mt. Etna, the work of Rasà et al. (2007) is concerned mainly with the effects of the ash load deposited on the roofs of buildings, the problem associated with the clogging of gutters and pipes and the possible damage to the moving parts of machines and on electric motors are mentioned from a qualitative point of view. Nothing has been reported concerning industrial installations near to the volcano.

2. Methodology

According to the type of roof, atmospheric storage tanks are classified as fixed roof or floating roof. Floating roofs are used to minimize the losses of the product by evaporation and to increase safety by

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minimizing the amount of vapor between the roof and liquid. These roofs can be single deck or double deck. Single deck roofs consist of a series of pontoons (closed compartments) around the outer edge of a central plate and double deck roof are two continuous decks with internal bulkheads forming buoyancy compartments (API 650, 2007).
The potential damage to fixed roof storage tanks due to ash deposits can be estimated using the method developed for snow load. This methodology defines thickness threshold limits causing defined structural faults. In this paper we study the potential damage to double-deck floating roof storage tanks. We have made calculations for a cylinder with radius (R) of 20 m, depth (δ) of 1 m and weight (M_{roof}) of 1.5 10^5 kg which may be considered to be a reasonable approximation to a double deck floating roof. The study of the problem of floating bodies and their stability has a history dating back to the work of Archimedes. The fundamental physics continues to receive attention (Kliava and Mégel, 2010; Mégel and Kliava, 2010) and the topic also has educational value (Mungan and Emery, 2011). The extreme damage that volcanic ash deposition could cause to a floating roof would be to sink or capsize it. Studies on ships lead to a distinction between longitudinal stability (pitching) and lateral stability (rolling) but for a cylinder because of its symmetry the two are equivalent. In the case of the stability of floating roofs, where a non-uniform ash deposit may occur, it is convenient in setting up Cartesian axis systems to choose the positive x direction as the downwind direction and the positive z direction as vertically upwards. The positive y direction is chosen to come towards the observer. It will be necessary to consider axis systems fixed in the floating roof and others with respect to the surface of the liquid. We have found it useful to verify experimentally some calculations by floating laboratory beakers in water adding weights or salt to mimic the volcanic ash fallout.

2.1 Sinking a floating roof

In order to sink the 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 (V_{disp}) greater than that of the roof. The weight of displaced liquid must be equal to the combined weights of the roof and the deposit:

$$M_{roof} + M_{ash} = \rho_{liquid}\pi R^2\delta = V_{disp}\rho_{liquid} \quad (1)$$

where ρ_{liquid} is the density of the liquid. Assuming the ash deposit to have a density ρ_{ash} and to be a cylinder with radius R and height h:

$$M_{ash} = \rho_{ash}\pi R^2 h \quad (2)$$

$$M_{roof} = \rho_{liquid}\pi R^2\delta_{roof} \quad (3)$$

where δ_{roof} is the depth of immersion of the roof in the absence of ash. Equation (1) may be written as:

$$h = \frac{\rho_{liquid}}{\rho_{ash}}(\delta - \delta_{roof}) \quad (4)$$

2.2 Capsizing a floating roof

The stability of floating bodies for small displacements from equilibrium was treated by Bouguer in 1746 who introduced the concept of the metacentre (Mégel and Kliava, 2010). Euler in 1749 (Euler, 1749) gave a general criterion for ship 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 ship remains stable if this couple produces a restoring moment. A change in sign of this couple leads to capsizing and the point where it is zero in an inclined position gives the angle of capsizing. First we will apply the metacentre concept and then use Euler's method to calculate the minimum weight that must be added to the floating roof in order to capsize it. We will consider the floating body to be in a state of equilibrium with the gravity and buoyancy forces acting along a vertical line with $x=0$ where the origin is located at the centre of the bottom of the floating roof. The distance between the coordinates of the metacentre (z_M) and the centre of buoyancy (z_B) is:

$$z_M - z_B = \frac{I}{V_{imm}} \quad (5)$$

where I is the moment of inertia of the body ($I=\pi R^4/4$, for a cylinder) and V_{imm} is the immersed volume ($V_{imm}=\pi R^2\delta_{imm}$ where δ_{imm} is the depth of immersion). The buoyancy centre (Z_B) is located at $\delta_{imm}/2$:

$$z_M = \frac{R^2}{4\delta_{imm}} + \frac{\delta_{imm}}{2} \quad (6)$$

The body is stable if the metacentre is above its centre of gravity (z_G).

3. Results and discussion

Concerning the sinking of a floating roof, Figure 1 shows how the height of the ash deposit varies with the immersion depth for two typical liquid densities and two ash densities. The right ordinate shows the ratio of the weight of ash to the weight of the roof, and it can be seen that, in order to sink the roof, the weight of the ash deposit must be several times larger than the weight of the roof.

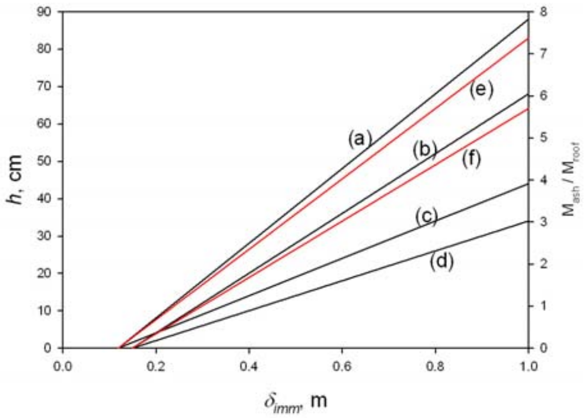


Figure 1: Thickness of the ash deposit required to sink the floating roof for ρ_{liq}=1000 kg·m^{-3} (a) ρ_{ash}=1000 kg·m^{-3} (c) ρ_{ash}=2000 kg·m^{-3} and ρ_{liq}=800 kg·m^{-3} (b) ρ_{ash}=1000 kg·m^{-3} (d) ρ_{ash}=2000 kg·m^{-3}. The right ordinate shows the ratio M_{ash}/M_{roof} for (e) ρ_{liq}=1000 kg·m^{-3} and (f) ρ_{liq}=800 kg·m^{-3}.

To study the capsizing of a floating cylinder, we have applied Equation (6) to the floating of two laboratory beakers in water and also to the model of floating roof. The characteristics of the systems and a summary of the calculation of their flotation stability are shown in Table 1.

Beaker A is predicted to be stable if it is immersed in water (z_M-z_G>0) and, if it is pushed slightly down at a point on its edge and then released, it returns to its stable position. Beaker B is predicted to be unstable if it is immersed in water (z_M-z_G<0) and we have never been able to get it to float without capsizing, filling with water and sinking. The beaker is not a perfect cylinder because of the lip and the vertical lines through the centres of gravity (G) and buoyancy (B) do not coincide and so there is a destabilizing couple and the beaker capsizes.

The metacentre heights for the model floating roof are very large compared to those of ships which are generally a few meters. The great stability of floating bodies with a large ratio of the waterline area to the immersed depth has been noted by (Mégel and Kliava, 2010) and they term such structures rafts. An ash deposit on top of the roof will raise the centre of gravity and immersion depth leading to a reduction in z_M-z_G as shown in Figure 2. On the scale of Figure 2 the curves for the liquid and ash densities considered in Figure 1 are indistinguishable. Even when the roof is fully immersed it is still very stable. It will be shown below that this stability is reflected in the large minimum weight required to capsize the roof.

Table 1: Characteristics and calculations related to two laboratory beakers and the floating roof model.

Parameters	Beaker A	Beaker B	Parameters	Floating roof	
R (cm)	4.708	3.436	R (m)	20	
δ (cm)	5.490	9.642	δ (m)	1	
M (g)	92.27	96.01	M_{roof} (10^5 kg)	1.5	
z_G (cm)	1.963	4.135	z_G (m)	0.5	
ρ_{liquid} (10^3 kg·m^{-3})	1.0	1.0	ρ_{liquid} (10^3 kg·m^{-3})	1.0	0.8
δ_{imm} (cm)	1.325	2.589	δ_{imm} (m)	0.119	0.149
z_M (cm)	4.843	2.434	z_M (m)	837.58	670.32
(z_M-z_G) (cm)	2.880	-1.701	(z_M-z_G) (m)	837.08	669.82

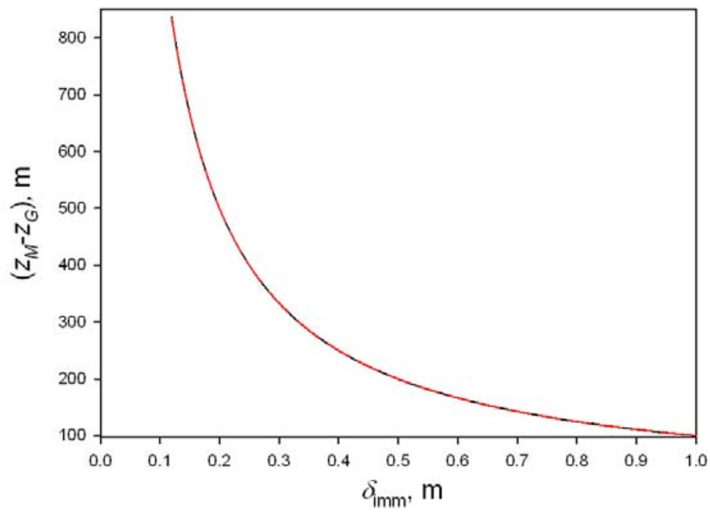


Figure 2: Variation of (z_M-z_G) with the depth of immersion of a double deck floating roof.

The minimum weight necessary to capsize the roof (M_{min}) occurs when it is concentrated at a point on its edge in order to give the greatest moment about the point of floatation. The calculation starts in the body fixed axis system as shown in Figure 3(a). When M_{min} is placed at x=0 the depth of immersion is

$$\delta_{imm} = \frac{(M_{roof} + M_{\min})}{\pi R^2 \rho_{liquid}} \tag{7}$$

In Figure 3(a) the volume with section PQR must be equal to the displaced volume of liquid ($\pi R^2 \delta_{imm}$). The intersection of the horizontal line $z = \delta_{imm}$ with the line PQ is the centre of buoyancy. Rotation about this point in the y direction puts P and Q on the surface of the liquid. The coordinates of the point P and those of the centre of buoyancy which is located at the centre of gravity of the displaced liquid are calculated in the (x,y,z) frame using standard integrals. The final set of axes (X,Y,Z) is often referred to as the earth fixed system in the case of ships. For a floating roof tank the flotation plane must move upwards because of the displaced liquid and we will refer to this as the liquid surface fixed frame. Figure 3(b) shows the liquid surface fixed frame with the points P and Q on the surface of the liquid and Figure 3(c) a picture of the experiment.

In order to apply the Euler criterion for the capsizing of the roof it is necessary to have the X coordinates of the centre of gravity of the roof G (X_G), of the centre of buoyancy B (X_B) and of the point Q (X_Q). Then we can apply the condition that when the roof is on the point of capsizing (Figure 3(b)) from which M_{min} can be calculated:

$$M_{roof} X_G - M X_B + M_{\min} X_Q = 0 \tag{8}$$

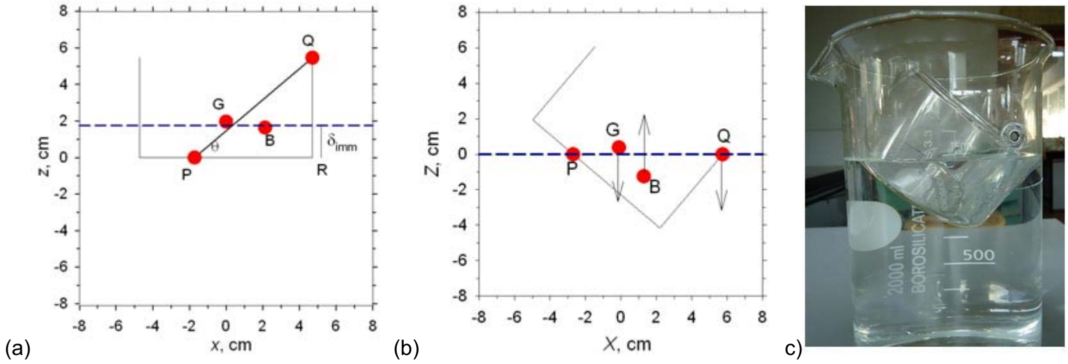


Figure 3: (a) Location of the points P and Q, the points G and the B of the beaker in fixed axis system (x,y,z). (b) The same points located in the liquid surface fixed axis system (X,Y,Z), (c) Beaker A with the minimum weight (30 g) located at the point Q

We first illustrate the calculation of the weight which must be applied to a point on the edge of Beaker A when it is immersed in water in order to capsize it and, then, the same calculation has been made for the floating roof. The results are summarized in Table 2.

Table 2: Summary of the calculation of the minimum weight.

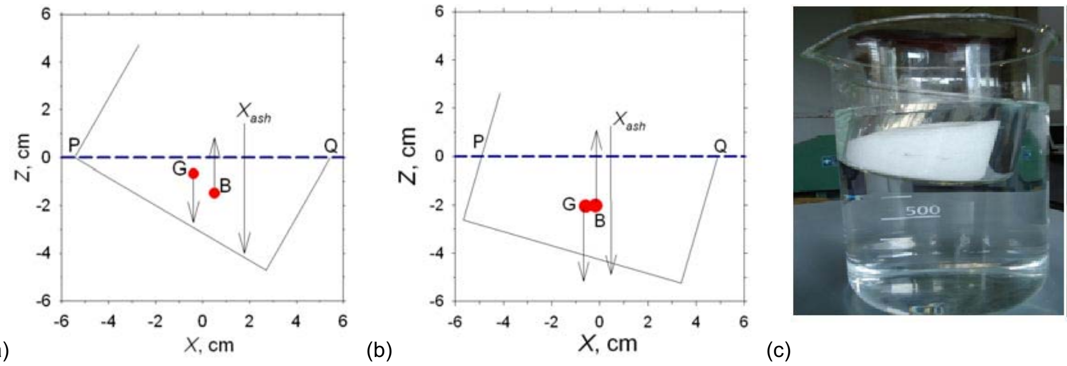
Beaker A	Values	Floating roof	Values
M_{min} (g)	29.30	M_{min} (10^5 kg)	1.704
V_{imm} (cm^3)	121.57	V_{imm} (m^3)	320.4
δ_{imm} (cm)	1.746	δ_{imm} (m)	0.255
θ (°)	40.35	θ (°)	2.50
X_G (cm)	-0.117	X_G (m)	-0.117
X_B (cm)	1.791	X_B (m)	7.737
X_P (cm)	-2.697	X_P (m)	-5.850
X_Q (cm)	5.734	X_Q (m)	5.734

The minimum weight necessary to capsize Beaker A when it is immersed in water is approximately one third of its weight and this has been verified experimentally by attaching a weight of 30 g to the point Q (Figure 3(c)). By contrast that necessary to capsize the floating roof when it is immersed in water is greater than its weight.

For a given immersion depth the X coordinate of the centre of mass of the ash deposit (X_{ash}) necessary to capsize Beaker A or the floating roof may be determined and the results are summarized in Table 3 and shown in Figure 4 for $\delta_{imm}=\delta/2$ and $\delta_{imm}=3\delta/4$.

Table 3: Summary of the principal results.

Parameters for Beaker A	(a)	(b)	Parameters for the roof	(a)	(b)
δ_{imm}/δ	0.50	0.75	δ_{imm}/δ	0.50	0.75
M_{ash} (g)	97.8	192.8	M_{ash} (10^5 kg)	4.78	7.93
X_G (cm)	-0.385	-0.593	X_G (m)	0.000	-0.003
X_B (cm)	0.505	-0.177	X_B (m)	4.994	1.662
X_{ash} (cm)	1.344	0.022	X_{ash} (m)	6.560	1.977



(a) (b) (c)

Figure 4: (a) and (b) To show Beaker A on the point of capsizing for the data given in Table 3. (c) Beaker A loaded with 193 g of salt.

4. Conclusions

The possibility of sinking or capsizing the roof of an external floating roof tank due to the fallout of volcanic ash has been considered. Simple experiments of floating laboratory beakers in water have proved useful in clarifying same of the concepts used. In order to sink a floating roof the weight of the ash deposit must be several times that of the roof. The metacentre concept shows that floating roofs are very stable structures compared to ships where the metacentre may be a few meter above the centre of gravity. The minimum weight of ash required to capsize a floating roof must be greater than that of the roof. Extremely large explosive eruptions are required to bring about this kind of damage.

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