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Consequences of Liquid Tank Explosions Caused by Lava Flow

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This contribution aims at the study of technological accidents triggered by natural phenomena, so-called Na-Techs (Natural Technological events). In particular the focus is on those triggered by volcanic events. The impact of eruptions is significant in the Southern Italian territory, where the volcano Etna is located. Volcanic eruptions could threat structures, critical infrastructure, lifelines and human health. Even if volcanic eruptions are less frequent and devastating than earthquakes, they give high potential risks for population. In this context, local emergency plans have to be extended to protect people and structures also from Na-Tech hazards. An event occurred in Sicily in 2002, which was an explosion of a liquid tank involved in a lava flow during an eruption of Mt. Etna, addressed towards the need to analyse such Na-Tech scenarios with the aim to include them within the emergency plans.

1. Introduction

Natural disasters (i.e. earthquakes, floods, tsunamis, landslides, volcanic eruptions, etc.) are able to affect the integrity of industrial facilities and lifelines, whose vulnerability should be evaluated (Vališ, 2013; Vintr et al. 2012). These events can cause several accidents in chemical plants, such as fires, explosions or toxic dispersions and may involve both workers and population living close to these facilities. Scenarios deriving from the interaction between natural and technological disasters are generally defined as Na-Tech events (Cruz et al., 2004). Amongst many natural phenomena a growing attention recently has been paid to Na-Techs caused by volcanic eruptions, in particular those caused by volcanic ash fallout due to the large impact area (Milazzo et al. 2012), some examples are the following: Baxter et al. (1982) analysed the hazards related to the transportation of hazardous materials due to slippery road conditions; Ancione et al. (2014a) analysed the reduction of functionality of water treatment systems; Rasà et al. (2007) qualitatively described the effects of the ash fallout on building, electric motors and other systems; Milazzo et al. (2013a) analysed the fragilities of atmospheric storage tanks, whereas Milazzo et al. (2013b) malfunctions of filtering systems; Milazzo et al. (2014) also showed that the damage can be more severe in presence of ash aggregation phenomena due to the water rain; finally, Ancione et al (2014b) defined a methodology for the representation of the vulnerability of equipment to volcanic Na-Tech scenarios.
Lava flows appear less dangerous for human life than other volcanic hazards; the impact on structures, traffic and communication are even also more manageable because the slow movement of the flows (usually metres per hour rather than kilometres per hour) allows mitigation strategies to be employed (i.e. diversion measures, cool advancing front with water or disruption of source or advancing front of lava flow by explosives may be taken in principle). However, such measures sometimes do not turn out successful the problem. In 2002 Italian national newspaper reported about a large explosion triggered by a lava flow that involved a liquid tank during an effusive eruption from Mt. Etna (La Repubblica, 2002; Il Corriere della Sera, 2002). This event was likely due to the overheating of the tank trapped under the flow (Barnard, 2004). The tank proximity to the lava with high temperature (or the contact with it) created the conditions originating the BLEVE (Boiling Liquid

Expanding Vapour Explosion). As a result 32 people near the building were injured and a car was destroyed. People exposed to the hazard posed by the flow and the consequent Na-Tech was more than the local population, due to the increase of tourists arrived to admire the spectacular eruption of Mt. Etna getting too close to the flow. This accident highlighted a lack of these scenarios in the emergency plans. A review of local emergency plans showed that some documents take into account the hazard due to the presence of tanks and give a probability of damage for these facilities, but they do not analyse the potential consequent scenarios, which may be different because of the number of people involved.
The present paper focuses on the potential damage scenarios of water and fuel tanks used in civil activities and produced by thermal radiation derived from lava. The aim is to contribute to the improvement of the emergency planning. Thus, the first part of this paper gives a short overview on BLEVEs; the second part reports a brief description of the adopted methodology; then a case study is presented; some results are finally given with a short discussion.

2. BLEVEs

Boiling liquid expanding vapour explosions (BLEVEs) are included amongst the most severe accidents that usually can occur in chemical and process industry or in the storage and the transportation of hazardous materials (Fabiano and Currò, 2012). In most cases the substance involved is a fuel that causes a severe fireball after the explosion or a rapid vaporisation of the liquid, mainly in case of liquefied gasses. Usually, a BLEVE refers to the combination of these two phenomena, i.e. BLEVE and fireball (Van den Bosch and Weterings, 2005), meaning that the accident simultaneously involves mechanical and thermal effects. Thus, the combined action of these scenarios can be summarized in the following effects: (1) thermal radiation, (2) pressure wave and (3) flying fragments. If the substance involved is not flammable, the pressure wave and the missiles will be the only effects of the explosion. While the explosion of a tank containing a pressurized flammable liquid will almost always lead to a fireball, the explosion cannot always be considered strictly a BLEVE, as the following conditions must occur (Casal et al., 2001):

- significant liquid *superheating*: most liquefied gases under fire attack fulfil this condition, also liquids stored in containers that undergo anomalous heating.
- instantaneous *depressurization*: this phenomenon is usually related to the type of failure of the vessel. The sudden pressure drop in the container upon failure causes the liquid superheat, if the liquid superheat is significant, the flash may be explosive.

A BLEVE occurs in a very short time (10^{-3} s). The significant increase in the liquid's volume when it vaporizes (1,750 times in the case of water and 250 times in the case of propane) plus the expansion of the previously existing vapour will give a strong pressure wave (explosion, bursting of the container) as well as to the breaking of the container into several pieces, which will reach considerable distances (see the studies of Lisi et al. (2015) for cylindrical tanks and Lisi et al. (2014) for spherical tanks).

3. Methodology

A simply scheme of the methodology used in this paper is shown in the Figure 1. First, the method consists in identifying potential Na-Tech scenarios due to lava inundations, thus it is necessary to analyse the lava flow map and to take a census of territorial elements (i.e. people, infrastructure, storage tanks, etc.). This work focuses on the analysis of BLEVE of fuel tanks (liquefied propane at ambient temperature), thus both thermal radiation and overpressure scenarios have to be simulated. The modelling of the phenomenon has been made as suggested by Casal et al. (2001) and the representation of the damage zones on cartography has been made by means of a GIS (Geographical Information System) software. The use of the GIS allows suggesting actions to mitigate the effects and to prevent the accident (Ancione et al., 2015).

3.1 Thermal radiation effects

Analyzing effects due to fires, the evaluation of the flame extent is essential (Palazzi and Fabiano, 2012). Concerning fireballs, the diameter and duration are the initial parameters to be evaluated given the mass of fuel, several correlations are reported in CCPS (1994); it should be taken into account that the size and position of the fire continuously change, thus the calculation of the radiation received by the target is usually performed supposing that the fireball immediately reaches its maximum size. To estimate the radiation received by a surface located at a given distance, the solid body model can be applied, therefore the emissive power, the view factor, the atmospheric trasmissivity and the distance between the flame and the target are needed. To know this distance, it is necessary to estimate the height at which the fireball is located, which is a function of the specific volume and the latent heat of vaporization of the fuel. As the fraction of the energy released emitted as thermal radiation is known, the energy radiated can be deduced.

The thermal radiation effects involve a portion of the territory which is included in the damage zones identified for the explosion; thus given the higher severity of the explosion, thermal effects were not estimated.

3.2 Blast effects

To estimate blast effects associated to the BLEVE, the initial amount of vapour in the vessel must be known. The energy released in its expansion (from the breaking pressure in the vessel up to the atmospheric pressure) is given by the model of Prugh (1991):

$$E_v = 10^2 \cdot \left(\frac{P \cdot V}{g - 1} \right) \cdot \left(1 - \left(\frac{P_o}{P} \right)^{(g-1)/g} \right) \quad (1)$$

where: P_o = atmospheric pressure (bar); V = initial volume of vapour (m^3); γ = ratio of specific heats; P = pressure in the vessel just before the explosion.

The energy calculated by Eq. (1) can be expressed as TNT equivalent mass (W_{TNT}) by means of:

$$W_{TNT} = \left(\frac{0.021 \cdot P \cdot V}{g - 1} \right) \cdot \left(1 - \left(\frac{P_o}{P} \right)^{(g-1)/g} \right) \quad (2)$$

If the vessel contains superheated liquid, the released energy can be estimated approximately by using the same method. In this case the mass of liquid will partly vaporise suddenly when reaching atmospheric pressure. The fictitious volume of this vapour at the pressure in the vessel (just before the explosion) must be calculated and added to the real one.

Due to the fact that the volume initially occupied by the fuel, which release the calculated energy in the explosion, is much larger than that which would occupy the equivalent mass of TNT, a correction must be made on the distance from the explosion centre and the point in which the pressure wave must be estimated. This correction is carried out by using the scaled distance, based on the similitude principle proposed by Hopkinson (CCPS, 1994). This scaled distance graphically allows determining the trend overpressure vs. target distance.

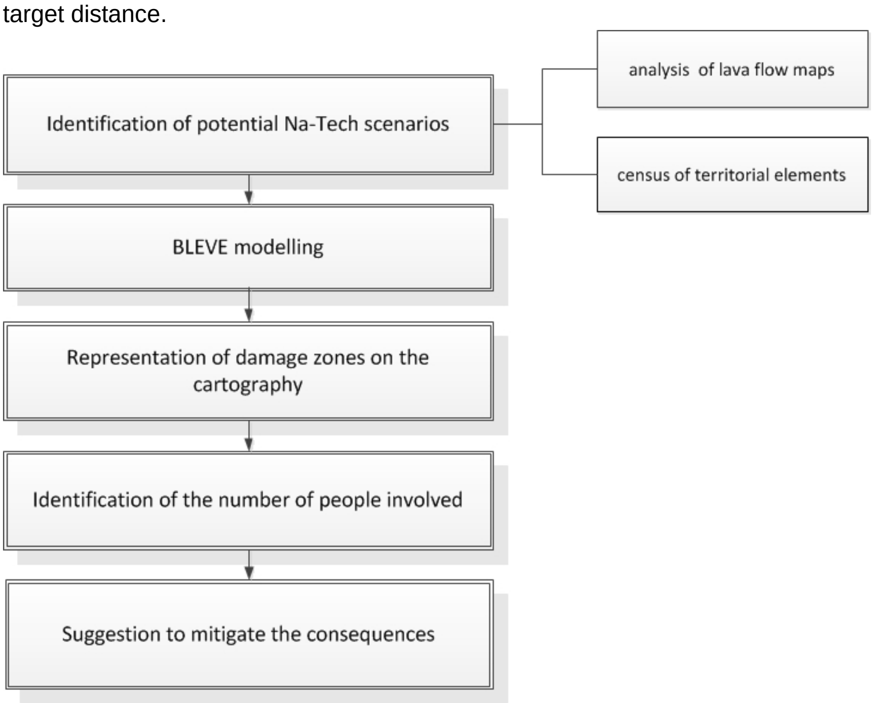

Figure 1. Methodology scheme

4. Case study

The study has been applied to the surrounding of Mt. Etna. The volcano is located in the South of Italy (Sicily), it is one of the most active volcano in Europe, high over 3300 m above the sea level. The surrounding of Mt.

Etna is characterized by the presence of the city of Catania with more than 300 thousand inhabitants, by many small urban centres and agricultural and industrial areas.

According to the D.P.C. - Regione Sicilia (2013) and Del Negro et al. (2013), a number of municipal areas were identified as potential exposed to lava flow and the proper hazard assessment due to lava inundations was made. Amongst these territories the most exposed is Nicolosi, a small city of about 7500 inhabitant with a surface of 42.48 km^2 (coordinates: lat. 37°41'25" N, long. 15°02'45" E); its local emergency plan includes a lava flow mapping (Figure 2).

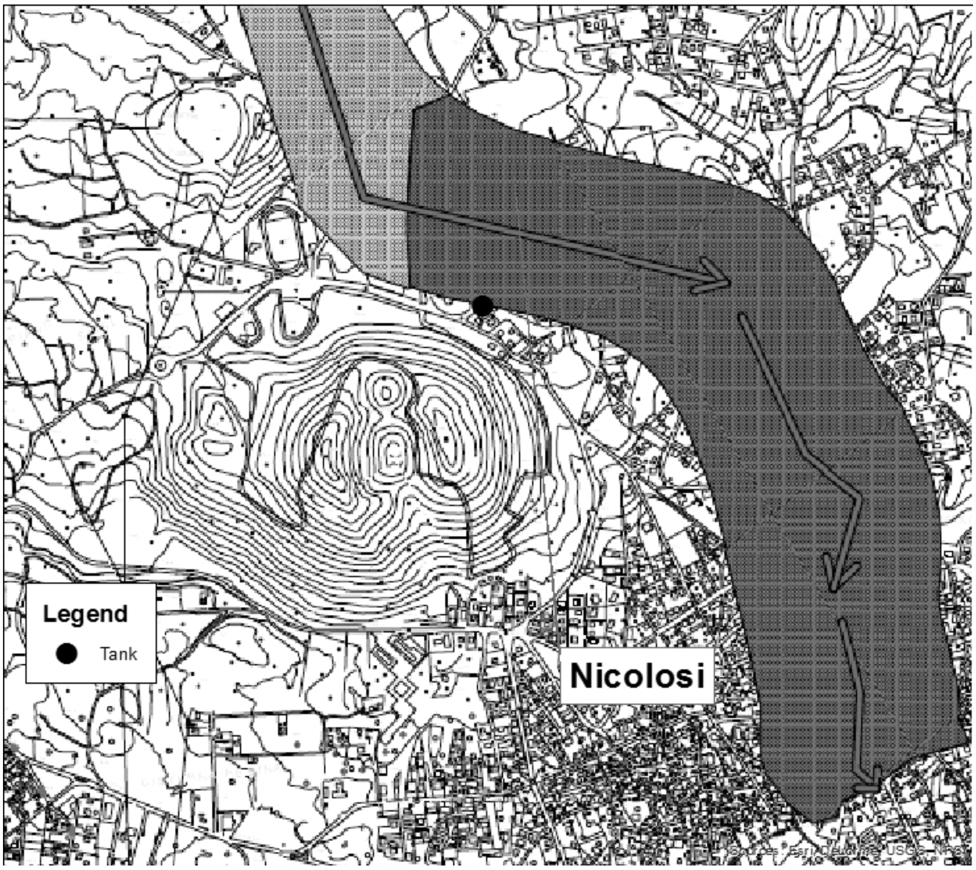

Figure 2. Lava flow scenario in Nicolosi, scale 1:25000 (Comune di Nicolosi, 2007).

A simulation of a BLEVE has been made for a tank containing propane, located as indicated in Figure 2. It is a small capacity tank, which is usually used in minor agglomerations. The characteristics of the tank are given in Table 1.

Table 1. Tank characteristics

Parameter	Value
Volume (m^3)	2.5
Diameter (m)	1.2
Height (m)	2.5
Length (m)	1.2
Temperature (°C)	20
Pressure (bar)	2
Filled percentage of the tank (%)	80

5. Results and discussion

Table 2 gives the dimension of each damage zone and the potential targets involved. The results of the simulation are shown in Figure 3.

Given the size of the damage zones, if the propane tank is completely involved by the lava (case 1), the consequence of the explosion are included in the impact area of the lava scenario. Thus the impact of the explosion is negligible compared to those due to the thermal radiation and disruption caused by the lava. If the propane tank is located close to the borderline of the lava flow scenario (case 2), the overpressure, generated by the BLEVE, can destroy structures and hit people that are located close to the front of lava.
In this example, the tank is located in the city of Nicolosi as in case 2. The results of the simulation show that the zone 4 has a radius of 40 m, it represents the area where 50 % of people suffer to be injured by the pressure wave. If the capacity of the tank is greater, the zone 4 will be greater and it will likely involve more people and territorial elements. If a water tank will be impacted by the lava, given that according to Casal et al. (2001) the vaporization of the liquid is 1,750 times higher than previously the existing vapour in the vessel (while in case of the propane it is 250 times), the consequence will be more severe.

Table 2. Damage zones and vulnerable elements

Zone	Threshold of overpressure (bar)	Distance (m)	Elements involved
Zone 1	0.30	10	none
Zone 2	0.14	20	2 buildings (4 people)
Zone 3	0.07	30	3 buildings (6 people)
Zone 4	0.03	40	6 buildings (12 people)

Figure 3. Damage zones (scenario mapping).

6. Conclusions

The review of local emergency plans for the municipalities surrounding Mt. Etna addressed to the need to improve these documents taking into account potential Na-Tech scenarios triggered by lava flows. The work performed has investigated explosive scenarios (BLEVEs) due to flammable and no-flammable substances and gave the base for the mapping of the related damage zones. The modelling of these explosions was made as suggested by Casal et al. (2001) and the representation of the damage zones on cartography was achieved by means of a Geographic Information System.
The overall scenario simulated for the propane involves 12 residents (which obviously greatly increased in case of water tank explosions), however it must been taken into account that, as reported for the event occurred in 2002, more people could be hit. In fact during such an event the presence of operators of Civil Protection and tourists must be considered, which could be more exposed to the scenario than the local population.

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