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Vulnerability of Wastewater Treatment Plants to Volcanic Na-Tech Events

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Volcanic hazards caused by explosive eruptions could cause a wide range of Na-Tech risks (technological risks triggered by natural events), followed by negative effects for people and/or environment. In particular, volcanic ash fallout can directly endanger human health, structures and critical infrastructures (wastewater treatment plants, electricity networks, etc.). It is well known that even relatively moderate emissions often cause significant damages and economic losses. This work illustrates a preliminary study to approach the vulnerability estimation of wastewater treatment plants, which are located in areas with potential volcanic ash fallouts. It represents the first step for the further implementation of a recent methodology for the vulnerability mapping based on the use of a Geographical Information System (GIS).

1. Introduction

Many natural events caused several damages to lifeline systems (electrical power grids, water distribution systems, gas and oil pipelines). The disruption of lifelines can affect whole cities or even entire countries (Cruz et al., 2004). Some examples are given in the literature, such as the electrical power outages occurred during the earthquakes of Kocaeli in 1999 (Tang, 2000), of Kobe in 1995 (Erdik, 1998), other significant blackouts were due to the floods occurred in France in 1999 and 2002 (Cruz et al., 2004) and to the volcanic ash fallout in 1980 in Yakima (USA) (Kish, 1980). The eruption of St. Helen in 1980 had a catastrophic impact on the wastewater treatment plants (Zais, 2001). Reports on these events highlighted that measures taken to protect lifelines are still not sufficient.
Technological risks triggered by natural events are commonly named Na-Tech events. The literature shows some approaches estimating the failure probability of industrial facilities caused by many types of natural events, such as lightning, earthquake, flooding, etc, but only few works investigate the effects of volcanic eruptions on industrial structures and infrastructures. The most significant works are the following: Spence et al. (2004) evaluated the vulnerability of buildings by using a deterministic approach; Rasà et al. (2007) described, from a qualitative point of view, the effects of volcanic ash fallout from Etna on building, electric motors and other systems; Baxter et al. (1982) analysed the reduction of functionality of water treatment systems (either industrial or civil installation) and the hazards related to the transportation of hazardous materials due to slippery road conditions. Among different natural technological scenarios, this paper focuses on events triggered by volcanic ash emissions. After the recent eruption of the Eyjafjallajökull volcano (Iceland), the research activity, dealing with study of the potential impact of volcanic ash fallout, is growing. In this context, Milazzo and co-authors analysed the fragilities of atmospheric storage tanks (Milazzo et al., 2012a) and filtering systems (Milazzo et al., 2013b), then they developed procedures for vulnerability mapping (Milazzo et al., 2013c).
The aim of this paper is to implement a previous approach quantifying the vulnerability of industrial facilities, including the potential damage of wastewater treatment plants due volcanic ash fallout. Results

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of this study, in future, could be implemented on a Geographical Information System (GIS) in order to achieve a vulnerability mapping.

2. Wastewater Treatment Plants

After its use, the water often becomes polluted due to many contaminants, including organic and inorganic substances, nutrients and pathogenic micro-organisms, most substances could also be toxic. The contaminated water is named wastewater. It must be properly treated because both the ecosystems and human health can be negatively impacted after its release in the environment.
The basic principle of the wastewater treatment (WWT) is to remove pollutants from the water, by getting them either to settle or to float, and then to dispose of this material. Some pollutants are easily removable. Others must be converted to a settleable material. Treatment facilities are designed in stages, each one either removes particles from the wastewater or changes dissolved and suspended material to a form that can be removed. A flow-chart of a wastewater treatment process is given in Figure 1, it includes:

- primary treatment
- secondary treatment
- tertiary treatment (sometime included in the general layout)

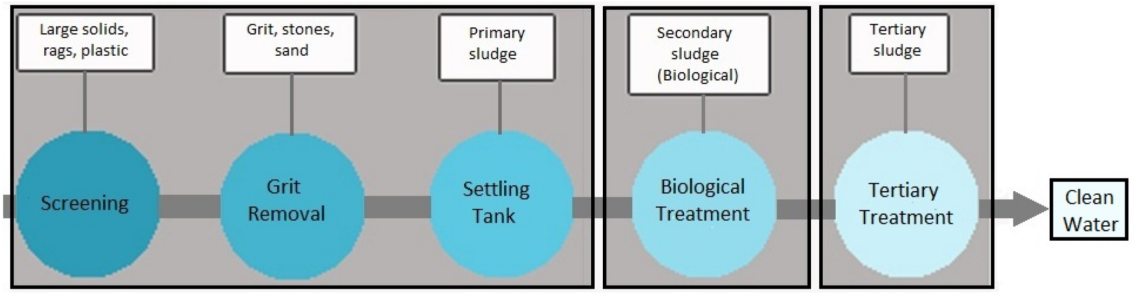

Figure 1: Flow-chart wastewater treatment process

2.1 Primary treatment

The primary treatment provides a mechanical separation of most of suspended and floating solids from raw sewage. In the first step, wastewater passes through raked bar screens to remove large debris, such as rags, plastics, sticks and cans. Smaller inorganic material, such as sand and gravel, is removed by a grit removal system. The lighter organic solids remain suspended in the water and flow into large tanks, called primary clarifiers. Here, the heavier organic solids settle by gravity; the settled solids (named primary sludge) are removed with floating foam and are pumped to anaerobic digesters for further treatment.
This treatment sometimes is referred to as *mechanical treatment*, although chemicals are often used to accelerate the sedimentation process. Wastewater-treatment plants usually are located on low ground, often near a river into which treated water can be released.

2.2 Secondary treatment

The secondary treatment (named also *biological treatment*) removes the dissolved organic matter that escapes primary treatment. The process is achieved by bacteria, consuming the organic matter for their sustenance and converting it in carbon dioxide, water and energy for their own growth and reproduction. The biological process is then followed by additional settling tanks (secondary sedimentation) to remove more of the suspended solids. Secondary treatment technologies include the basic activated sludge process, the variants of pond and constructed wetland systems, trickling filters and other forms of treatment which use biological activity to break down organic matter.

2.3 Tertiary treatment

The tertiary and/or advanced wastewater treatment is used for specific contaminants which cannot be removed by secondary treatment. Sometimes, individual treatment processes are necessary to remove nitrogen, phosphorus, additional suspended solids, refractory organics, heavy metals and dissolved solids. The equipment to be used depends on the contaminants which must be removed, these could be filters and separation membranes, systems for dechlorination and disinfection, reverse osmosis systems, ion exchangers, activated carbon adsorption systems and physical-chemical treatments.

3. Potential damages of wastewater treatment: literature review

When an eruptive scenario with a significant emission of volcanic ash occurs, the material is transported by wind and falls on the ground at a certain distance. After the rain, most of the ash will be collected by the drainage system. Rain water (or stormwater) and wastewater, carried away by different drainpipes, are often collected in the same treatment system; this connection causes the entrance of the volcanic ash into the waste treatment plants. The main problem associated with the volcanic ash fallout is related to the overload of the treatment system, which could occur during severe eruptions and due to the increase of solid to be removed. The literature provides some reports related to these problems.

As mentioned above, a wastewater treatment plant consists of different typologies of equipment, thus many component can be damaged due to the volcanic ash deposition. Day and Fisher (1980) reported that serious problems occur with deposit >10 mm, although these are rare events. The same authors reported about the effects on the wastewater treatment in Yakima, which followed to the explosive eruption of St. Helens (United States) in 1980. The city was covered by about 10 mm ash, the plant underwent to a pH change, which dropped from 6.7 to 5.7. The day after, a quantity equal to 15 times the usual amount of solid particles began to be received (but only partially removed) in the pre-treatment stage causing the damage of the grit classifier and the gearbox of the cleaned bar screen and the blockage of some pumps; during the following days, also the bacteria contained in the biofilters stopped their growth. The cost of the repairs and cleanup was very expansive (White et al., 1980).

Blong (2003) reported about the eruption of Mt. Spurr in Alaska, where 3 mm of volcanic ash fell on Anchorage in 1992 and caused many pipe blockages. In Rabaul (Papua New Guinea) in 1994, two pump stations and the treatment plant were damaged by the amount of ash entering into the drainage system, due to the eruptions of Mt. Tavurvur and Vulcan; consequently to the event they were decommissioned.

The ash fallout, following the eruption of Mt. Copahue (Argentina) in 2000, caused many power outages to the water treatment plants and cut off drinking water supplies (Smithsonian-Institution, 2000)

In 2002, during the eruption of Mt. Etna (Italy), small amounts of ash caused the blockages of the rainwater drainage systems in the city of Catania (Barnard, 2004), due mainly to the formation of not easily pumped material.

4. Methodology

According to Milazzo et al. (2012b), to estimate the vulnerability (fragility) of equipment included in a wastewater treatment plant, the threshold limit of a physical parameter, related to the intensity of the ash emission and the probability of exceedance of this value must be determined. Figure 2 summarizes the procedure.

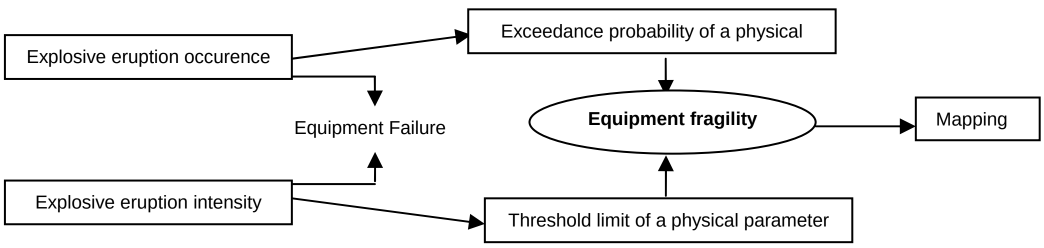

Figure 2: Methodology for the vulnerability estimation.

Firstly to estimate threshold values and exceedance probabilities, the eruptive phenomenon must be characterized, some difficulties are often associated due the poor data related to the natural phenomenon (see Milazzo et al. 2013a).

The probability of exceedance the threshold limits of the physical parameters are obtained from exceedance curves, their construction requires a huge number of simulations of the volcanic scenario to take into account each variable affecting the phenomenon. The volcanology does not permit to forecast with certainty the characteristics of the next eruptive event, thus to account the uncertainties in forecasting future eruptive events, it is suggested to perform Monte Carlo simulations of the event, each time assigning different input conditions, that can vary within pre-defined ranges.

After the estimation of the equipment's fragility, by using the concept of *geoevent* and Geographical Information System (GIS) software, the vulnerability mapping is possible. The use of these concepts is not a novelty as the literature gives the following examples: Milazzo et al. (2009) developed a specific approach for the emergency planning of terrorism attacks; whereas Demichela et al. (2013) used *geoevents* to estimate the vulnerability of people to volcanic ash emissions. In this case, the evolution of the ash emission can be represented using its geographical coordinates, these association event/coordinates allow to name the phenomenon *geoevent*. Then, the basic function of GIS software, named *geoprocessing*, permits the processing of the geographical data and the creation new information from input data; in this case the output is the vulnerability mapping.

5. Vulnerability of wastewater treatments

In order to apply the methodology described above to the wastewater treatments, the literature review cited in the section 2 has been exploited. The review allowed the identification of the vulnerable equipment, included in a typical plant, and the related causes of failure. Table 1 shows the results of the identification of the modes of damage of some facilities and the physical parameters causing the damage. It is possible to underline that the volcanic ash mainly causes mechanical screenings clogging (due to the overload of the lines due to the reduction of the flow-section caused by the particles), blockages and erosion of pumps and pH change in biological and chemical treatment tanks.
Table 2 reports the potential consequences associated with each failure mode of Table 1. In the following sub-sections details related to the data of Tables 1 and 2 are given.

Table 1: Main causes of damage in wastewater treatment

Equipment	Cause of damage	Physical parameter	Reference
Pump	Blockage Wear	Mass of the ash Ash concentration	Day and Fisher, 1980; Blong, 1984
Primary sedimentation tank	Dispersion of particles	Ash concentration	White et al., 2011
Biological treatment tank	Dispersion of particles	pH of the ash	White et al., 1980
Grit removal (screen)	Vibrations Clogging	Mass of the ash Mass of the ash	Blong, 1984
Gearbox	Vibrations	Mass of the ash	White et al., 1980
Biofilters	Dispersion of particles	Ash concentration	White et al., 1980
Metallic structures	Wear	Ash concentration	Johnston, 1997
Drainage system	Clogging/Blockage	Mass of the ash	Blong, 2003; Barnard, 2004; Stewart et al., 2006
Electric system	Ash infiltration	Ash concentration	Smithsonian-Institution, 2000
Disinfection (Chlorination)	Dispersion of particles	Ash concentration	Stewart et al., 2009

Table 2: Main effects of damage in wastewater treatment

Equipment	Cause of damage	Effects
Pump	Blockage	Fluid is not pumped
	Wear	Unstable operating conditions (variability of flow-rate, water infiltration)
Primary sedimentation tank	Dispersion of particles	Uncompleted separation
Biological treatment tank (anaerobic)	Dispersion of particles	Bacteria death due to acidification followed by absence of organic matter removal
Grit removal (screen)	Vibrations	Unstable operating conditions (variability of flow-rate, water infiltration)
	Clogging	Flow rate reduction, Flow absence
Gearbox	Vibrations	Unstable operating conditions (variability of flow-rate, water infiltration)
Biofilters	Dispersion of particles	Bacteria death due to acidification and asphyxiation followed by absence of organic matter removal
Metallic structures	Wear	Damages depend on the equipment
Drainage system	Clogging/Blockage	Flow absence
Electric system	Ash infiltration	Power outage
Disinfection (Chlorination)	Dispersion of particles	Higher turbidity levels which causes the protection of micro-organisms by the effects of disinfection

5.1 Pumps

Pumping is necessary to move the wastewater from one point of the plant to another. Pumps operate through some mechanisms, typically reciprocating or rotary. The presence of a high amount of solids may affect moving parts and, then, determine the blockage. Furthermore, given that the volcanic ash leads an acidification increase of the liquid and the particles are very abrasive, an increase of the corrosion rate could be observed.
The vulnerability of pumps is correlated to the amount of the suspended solids and the acidity of the materials.

5.2 Screens

Screening is the first unit operation used at wastewater treatment plants. It removes materials into different size through grid with different mesh of sieve and prevents damage and clogging of downstream equipment and piping. Some modern wastewater treatment plants use both coarse screens and fine screens. Coarse screens remove large solids from wastewater, and typically have openings of 6 mm or larger. Types of coarse screens include mechanically and manually cleaned bar screens, including trash racks. Fine screens are typically used to remove material that may create operation and maintenance problems in downstream processes, particularly in systems that lack primary treatment. Typical opening sizes for fine screens are from 1.5 to 6 mm, whereas very fine screens with openings from 0.2 to 1.5 mm are sometimes placed after coarse or fine screens to reduce suspended solids to levels near those achieved by primary clarification. Under normal operation, the velocity of water through the screen should be sufficient to avoid the sedimentation of particles, but not so high to produce an excessive pressure drop or a complete clogging of the bars. The degree of clogging depends both on the water quality and the system used to recover the waste from the bar screen.
Following volcanic ash fallout, water quality is correlate by the amount of mass of ash enter into the drainage system, which in turn is correlated to the amount of the ash deposit on the ground.

5.3 Primary sedimentation tanks

This treatment consists in a simple settlement of the suspended solids and colloids contained in the sewage. The particles fall down due to the gravity. A particle, entering into the tank, is affected by a downward velocity and a horizontal velocity, then it will be deposited at the bottom to form the sludge. If its settling velocity is greater or equal to the critical velocity of sedimentation, the particle will settle to the bottom and then will be removed, otherwise it will pass in the next stage of treatment. The detention time is the average time that particles of water have stayed inside the tank. The efficiency of removal of solid matter depends on the depth of tank and on the flow-rate (Sincero et al., 2003).
If wastewater contains great amounts of volcanic ash, the removal becomes a problem, in particular in presence of hydrocarbons because emulsion water/oil obstacles the sedimentation of small particles.

5.4 Biological treatments

These treatments are used to convert soluble organic contaminant to insoluble material through biological oxidation. Soluble organics metabolized by bacteria are converted to carbon dioxide, water, energy and bacterial residues, which can be settled from solution.
If a great amount of volcanic ash is inside the system, it can affect the process mainly due to two reasons: (1) the increase of pH compromises the life of bacteria and (2) the presence of suspended solids reduced the assimilative capacity of oxygen of bacteria causing asphyxiation.

6. Conclusions

The analysis of the literature on volcanic NaTech risks related to lifelines has provided the base for the construction of the vulnerability maps related to these facilities located in the area affected by the fallout of volcanic ash. It has been seen that the impact of volcanic ash fallout can lead serious consequences on human health and local economy.
The study of the correlation between the physical parameters causing the damage and the intensity of the natural phenomenon, as addressed in this paper, will support the implementation of a recent methodology for the vulnerability mapping based on the use of a Geographical Information System (GIS).

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