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Na-Tech in Wastewater Treatments due to Volcanic Ash Fallout: Characterisation of the Parameters Affecting the Screening Process Efficiency

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In the contest of the study of Natural-Technological hazard (also named Na-Tech), some works investigating the effects of the volcanic ash fallout on chemical plants were published. The literature highlighted that volcanic ash emissions can endanger human health by means the inhalation of solid particles or can cause damage on critical structures, infrastructures, transport systems, chemical plants and lifelines due to the ash accumulation. In some cases, the impact on chemical plants and lifeline networks could also be significant for the environment. The effects of volcanic ash accumulation on primary wastewater treatment equipment have been recently analysed with the aim to determine the conditions leading to malfunctions of fine screens. The study highlighted that the critical ash thicknesses, causing damages, depend on the specific surface area and the voidage of the emitted material. To complete the previous investigation, in this paper the effects of these parameters are dealt and, then, the critical thresholds of volcanic ash deposit causing equipment malfunctions are updated. The area surrounding Mt. Etna is investigated.

1. Introduction

Natural events can cause damages to lifelines (electrical power grids, water distribution systems, gas and oil pipelines, etc.). The lifelines' disruption affects whole cities and even entire countries: some electrical power outages occurred during the Kocaeli (Tang, 1999) and Kobe (Erdik, 1998) earthquakes and also during several floods occurred in France (Cruz, 2004); a significant impact on wastewater treatment plants was due to the eruption of St. Helen in 1980 (Zais, 1980). Recently De Rademaeker et al. (2014) indicated, amongst several prioritised research topics related to the process safety, the category *"Natural hazard triggering technological disasters"* as an emerging issue; in this frame the literature shows some approaches addressing the quantification of Na-Tech risks caused by several natural events in the chemical and process industry, such as lightning, earthquakes, floods, volcanic eruptions, etc. (Antonioni et al. 2009; Girgin and Krausmann, 2013; Ancione et al., 2014a). The research dealing with the study of the impact of volcanic ash fallout starts growing after the eruption of the Eyjafjallajökull volcano (Iceland), some key contributions are due to: Spence et al. (2004), which used a deterministic approach to evaluate the vulnerability of buildings; Baxter et al. (1982), which analysed the functionality reduction of water treatment systems and the hazards related to the transportation of hazardous materials; Ancione et al. (2014b) which identified the most vulnerable equipment of typical wastewater treatment plants and defined the causes of damage and their potential effects through an extensive literature review; Milazzo et al. (2014a) used the volcanic event tree method to identify failure modes of fuel storage tanks and, finally, the same authors analysed the fragilities of atmospheric storage tanks (Milazzo et al., 2012), filtering systems (Milazzo et al., 2013b), fine screens (Milazzo at al., 2014a) and grit removals (Ancione et al. 2014c).
This paper focuses on volcanic Na-Techs in primary wastewater treatments and gives a further contribution to the work of Milazzo et al. (2014a) by means of a detailed analysis of the effects of the specific surface area,

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the voidage and the particles' size. The paper is structured as follows: Section 2 provides a brief overview on wastewater treatments; Section 3 summarises the approach for the estimation of the critical ash thickness on fine screens; Section 4 describes the application of the approach to a case-study; and, finally Section 5 shows the results, followed by a brief discussion.

2. Wastewater Treatments

Wastewater Treatments (WWT) aim to achieve improvements in the wastewater quality based on three levels of treatment:

- *Primary (mechanical) treatment* deals with the removal of gross, suspended and floating solids from raw sewage. It includes screening to trap objects and sedimentation by gravity to remove suspended solids.
- *Secondary (biological) treatment* removes the dissolved organic matter by means of microbes consuming it as food and converting in carbon dioxide, water and energy for their own growth.
- *Tertiary treatment* is an additional treatment, which can remove more than 99% of all the impurities from sewage, producing an effluent of almost drinking-water quality. Related technologies are very expensive.

The main equipment in primary treatments is screens, comminutors/grinders and grit removal. As reported by Ancione et al. (2014b), common failure modes associated with the presence of volcanic ash in the sewage are: (1) *screen clogging* due to a deposit formation, occurring when the particles' size is greater than their openings and causing a flow-rate reduction; (2) *incomplete grit removal* due to an incomplete ash deposition the channels, it causes abrasion and wear of mechanical equipment, grit deposition in pipelines and accumulation in anaerobic digesters and aeration basins.

3. Methodology

This paper focuses on screening processes, such treatments sometimes use both coarse screens and fine screens. Coarse screens have 6 mm openings or larger and remove large solids. Fine screens (opening sizes are 1.5 to 6 mm) are typically used to remove material that may create operating and maintenance problems in downstream processes, very fine screens have openings of 0.2 to 1.5 mm. Given the dimension of volcanic ash particles, the effects of accumulation should be study for fine and very fine screens. The variability of flow-rate due to the solid accumulation is correlated to the screen's pressure drop (ΔP), which is the main indicator to underline malfunctions. The length of deposit causing the critical pressure drop can be quantified as indicated in the following sections.

3.1 Condition for the Screen Clogging

Metcalf et al. (2004) suggested calculating the pressure drop in fine screen by using the following equation:

$$\Delta P = \frac{\rho}{2 \cdot C} \cdot \left(\frac{Q}{A_s} \right)^2 \tag{1}$$

where: ΔP = pressure drop [Pa]; C = coefficient of discharge (typically 0.60 for clean screens, 0.4 for dirty screens and 0.25 for very dirty screens); A_s = effective open area of submerged screen [m^2]; ρ = fluid (wastewater) density [kg/m^3].

The methodology to identify the amount of ash deposit on a fine screen causing the clogging is based on the assumption that the accumulation is a granular bed and the sewage is the fluid passing through it. Coulson et al. (2002) suggests estimating the bed dimension by using the Darcy's equation for streamline flows and the Carman's equation for transition and turbulent flows. The flow regime is determined using a correlation for the Reynolds number (Re), which expresses it as a function of the flow velocity in the channel and the characteristics of granular bed (i.e. the specific surface area and the voidage):

$$\mathrm{Re} = \frac{u \cdot \rho}{S \cdot \mu \cdot (1 - e)} \tag{2}$$

where: μ = fluid viscosity [kg/m·s]; e = voidage or porosity (fraction of the volume of the bed which is not occupied by solid material) [dimensionless]; S = specific surface area of the particles (surface area of the particles divided by their volume) [m^{-1}]; u = average velocity of the flow [m/s].

According to Darcy's law, the average velocity is directly proportional to the driving pressure and inversely proportional to the thickness of the bed:

$$Q = \frac{K}{\rho \cdot g} \cdot A_s \cdot \frac{\Delta P}{l} \quad (3)$$

where: Q = volumetric flow rate [m^3/s]; l = thickness of the porous medium [m]; g = gravity acceleration [m/s^2]; K = constant depending on the characteristics of the porous medium and of the fluid [m/s].
If the flow regime is transition or turbulent, Eq.(4) has to be used (Carman's equation), in which the dimensionless term ($R'/\rho \cdot u_l^2$) is the friction coefficient and is correlated to the Reynolds number (see Coulson et al., 2002):

$$\frac{R'}{\rho u_l^2} = \frac{e^3}{S \cdot (1-e)} \cdot \frac{(-\Delta P)}{l} \cdot \frac{1}{\rho \cdot u^2} \quad (4)$$

where: R' = drag force component per unit particle's area in the direction of motion; u_l = average velocity through the pore channels of the granular bed [m/s].

3.2 Ash Characterisation

To apply the above methodology, the volcanic ash was characterised with the following methods (1) Analysis of the size distribution; (2) Density (*solid* and *loose bulk* density) determination; and (3) Determination of the permeability. Then the specific surface area and the voidage were calculated.
The sieving was used to determine the particle's size distribution of the volcanic ash. The method makes use of sieves arranged in a column in such a way that the top has the larger mesh and the others have a gradually smaller mesh going down to the bottom. Each of them retains the fraction of granules having larger dimensions compared to the sieve opening. The column is placed on a mechanical shaker for 20 min and, then, the solid fractions retained by each sieve are weighted.
The *loose bulk density* of each fraction was determined according to the EN 1097-3 standard by using a container, whose volume and weight are known. It was filled with the volcanic ash and, subsequently, weighed. The *loose bulk density* is the mass of the dried particles (not compressed) divided by the volume they occupy (tank volume). The *solid density* was determined by means of a pycnometer.
The permeability (K) was determined by using the constant head (load) test method (according to the standard ASTM D 2434). A homemade constant head permeameter was assembled (Milazzo et al. 2014a).
Finally, the specific surface area and voidage were determined by using:

$$S = \frac{6}{d \cdot 1000} \quad (6)$$

$$e = 1 - \frac{\rho_{loose\ bulk}}{\rho_{solid}} \quad (6)$$

where: d = particle's diameter [m]; $\rho_{loose\ bulk}$ = loose bulk density [kg/m^3]; ρ_{solid} = solid or true density [kg/m^3].

4. Case-study

The case study is the surrounding Mt. Etna (South Italy). The volcano has five main craters: North-East Crater (NEC), Voragine (VOR), Bocca Nuova (BN), South-East Crater (SEC) and the very recent New South-East Crater (NSEC). The volcanic activity was characterised by an explosive style (in particular during 2001, 2002-2003 and 2013) and produced stable tephra and gas columns in the atmosphere. Two samples of ash produced by explosive eruptions of Mt. Etna were characterised in this study. The first sample (ID=A) was collected at 5.5 km from the main crater (Southern direction) and the second one (ID=B) at ~ 20 km from the main crater (Northern direction). The particles' size distribution (weighted percentage for each class w), ρ, S, e and K were obtained for both samples. The study was based on two assumptions: (i) the sewage characteristics were those of water, and (ii) the particles were smooth and spherical.Then, the Reynolds number for the wastewater stream, flowing in the granular bed (ash deposit), was calculated to make possible the choice of the approach for the computation of the thicknesses of the deposit (Darcy or Carman approach). A square opening fine screen was assumed in this study, its characteristics are given by Milazzo et al. 2014a.

5. Results

The particles' size distribution and the density (Tables 1 and 2) were determined only for the sample B, those related to the sample A were previously given by Milazzo et al. (2014b). The permeability was close to 10^{-5}

m/s both samples, whereas the intrinsic permeability (B) was ~ 10^{-12} m^2. The specific surface area and voidage as a function of the range of diameters for the particles' are given in Figures 1 and 2, from these the weighted S and e were obtained (see Table 2).

Table 1: Particle size distribution for the samples

$d \cdot 10^{-3}$ (m)	<0.075	0.075÷0.1	0.1÷0.15	0.15÷0.2	0.2÷0.3	0.3÷0.6	0.6÷1.18	1.18÷2	>2
Weight (%)	w_1	w_2	w_3	w_4	w_5	w_6	w_7	w_8	w_9
Sample A	2.85	1.63	3.76	4.64	11.82	35.25	35.52	4.5	absent
Sample B	absent	0.05	0.11	0.31	3.34	45.44	43.79	4.29	2.67

Table 2: Ash densities

Sample ID	Bulk density (kg/m^3)	Solid density (kg/m^3)	Specific surface area (m^{-1})	Specific surface area (m^2/g)	Voidage (dimensionless)
A	1430	2830	~ 22570	15.19	0.48
B	1390	3050	~ 14995	9.75	0.49

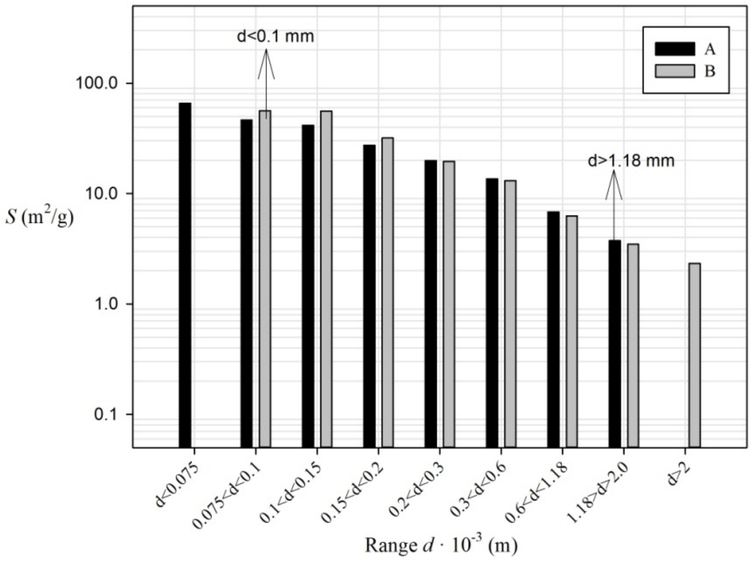

Figure 1: Specific surface area of samples with respect to the class of particles' size

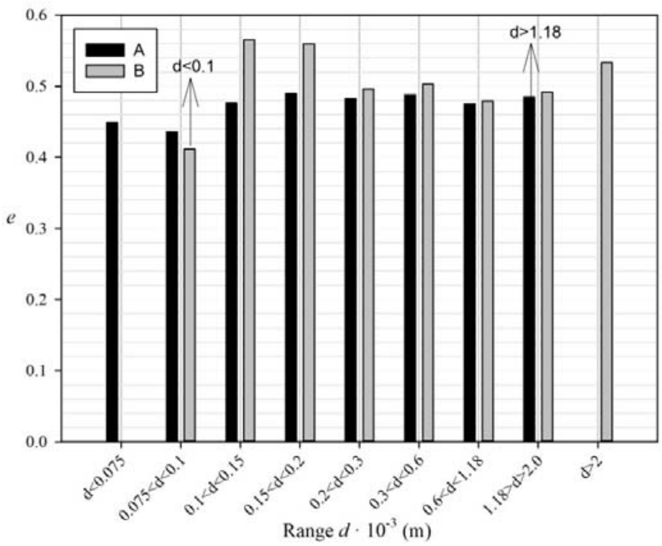

Figure 2: Voidage of samples with respect to the class of particles' size

By using some results from the ash characterisation and Eq.(2), the regime flow for the wastewater inside the pore channels was identified. Each case gave a transition regime flow, thus the Carman's equation was used to calculate the length of deposit causing the critical pressure drop: ΔP_1 ~ 9850 Pa is the dirty screen pressure drop and ΔP_2 = 15760 Pa is the very dirty screen pressure drop, l_1 and l_2 are the thicknesses of ash deposit causing a pressure drop, respectively, equal to ΔP_1 and ΔP_2. It is worth noting that the extreme event, which is the total screen clogging, was not considered in this work, since cleaning operations were assumed to be executed before the occurrence of a total blockage.
Figure 3 shows the critical thickness (l_1 and l_2) as a function of the d, it can be evidenced that a very small quantity of ash is enough to clog this type of screen. Taken into account the results of the analysis of the particles' size distribution, the weighted value for l_1 and l_2 were calculated for both the samples (Table 3).

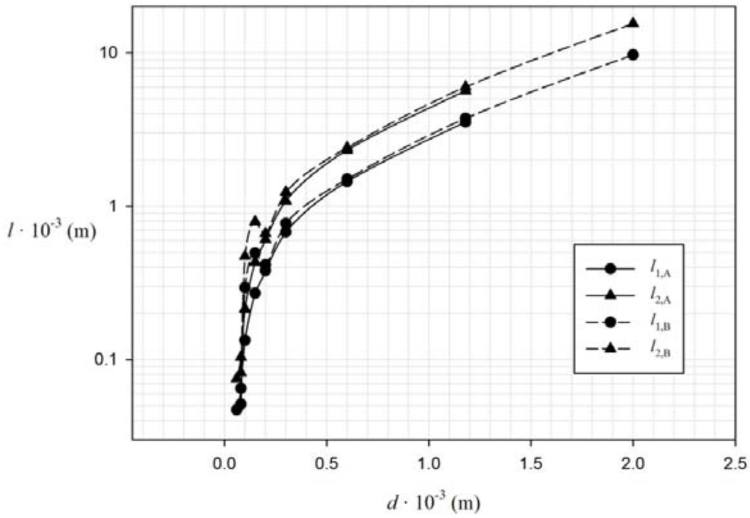

Figure 3: Critical thicknesses of ash deposit (l_1 and l_2) with respect to the particles' diameter

Table 3: Weighted critical thicknesses of ash deposit (l_1 and l_2)

Sample ID	l_1 (m)	l_2 (m)
A	$9.8 \cdot 10^{-4}$	$1.57 \cdot 10^{-3}$
B	$1.45 \cdot 10^{-3}$	$2.31 \cdot 10^{-3}$

The deposit thicknesses causing the critical pressure drops are very small and range between 1 and ~ 2.5 mm. This observation allows stating that the presence of few quantities of volcanic ash, with characteristics similar to those emitted by Mt. Etna, quickly causes the system clogging. Some comments about the ash characteristics of both the samples can be made.
The specific surface area was obtained by a numerical elaboration; S is very small and clearly increases as d decreases. By comparing the samples, S is greater for B when d<0.2 mm, given that the sample B has the lowest density, this reflects a higher porosity; whereas for d>0.2 mm, S is almost the same for both the samples (S_A is slightly higher than S_B, meaning that the porosity is comparable for both samples). These considerations are confirmed below.
The voidage of the sample A ranges between 0.46 and 0.49, with a prevailing contribution of the particles' class having 0.15<d<0.2 mm; while the sample B shows a greater voidage variability than the sample A, in this case e is higher (~ 0.56) for the classes having 0.1<d<0.15 mm and 0.15<d<0.2 mm, but the prevailing contribution to the weighted voidage is given by the classes 0.3<d<0.6 mm and 0.6<d<1.18 mm.
By applying the approach for the calculation of the critical thicknesses, it was observed that the flow was always in the transition regime; the increase of S (related to the decrease of the diameter of the particles) causes the decrease of the Reynolds number up to bring the flow close to the laminar regime. It must be recalled that S also increases as the porosity rises. As a consequence, the critical thickness increases with the decrease of S and, thus, with the increase of d. Finally a higher voidage determines greater ash accumulations.

6. Conclusions

This paper gives a further contribution to the determination of the conditions leading to failures or malfunctions of screens, with the respect to the phenomenon of volcanic ash emission. The amount of ash causing the reduction of functionality of fine screens was calculated for the surrounding of Mt. Etna. The contribution of each particles' class, derived by the analysis of the size distribution, was taken into account and gave a further improvement to the work of Milazzo et al. 2014a. The results provide a valid support in addressing alternative solutions for the ash removal and more efficient management (frequent cleaning operations).

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