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Cover Letter

ISTITUTO DI RICERCHE SULLA COMBUSTIONE

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Date: Marzo 5, 2014

To the kind attention of the Editor of

Safety Science

Elsevier

Dear Editor,

Please receive the manuscript:

EVALUATING THE STRUCTURAL PRIORITIES FOR THE SEISMIC VULNERABILITY OF CIVILIAN AND INDUSTRIAL WASTEWATER TREATMENT PLANTS

By A. Panico, A. Basco, G. Lanzano, F. Pirozzi, F. Santucci de Magistris, G. Fabbrocino, E. Salzano, to be submitted for publication on your journal on the special issue "Risk analysis and land-use planning: managing safety on the short and long range".

I thank you for your kind attention.

Yours sincerely

dott. Ernesto Salzano

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HIGHLIGHTS

- Seismic vulnerability of municipal or industrial wastewater treatment plants is needed
- New vulnerability functions based on damage observation of available earthquake reports
- Risk states based on loss of waste to the environment are given
- Municipal WTTPs are more vulnerable to earthquakes with respect to the industrial systems
- Non-structural components (sedimentation basins and digesters) are less resilient

TITLE PAGE

EVALUATING THE STRUCTURAL PRIORITIES FOR THE SEISMIC VULNERABILITY OF CIVILIAN AND INDUSTRIAL WASTEWATER TREATMENT PLANTS

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Abstract

Wastewater disposal systems are complex systems composed by several interconnected elements. In the aftermath of dramatic natural events, such as the earthquake, the failure of any of these elements can result in the deterioration of the environment as well as in the risk for the exposed population, due to leakage of untreated or un-properly treated wastewater on soil and/or its discharge into superficial waters.

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Keywords: Wastewater treatment plant; Earthquake; Na-Tech; Critical infrastructure; Vulnerability; Industrial risks

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1. INTRODUCTION

Past and recent strongest earthquakes (e.g. Loma Prieta 1989, Kobe 1995, Tohoku, 2011) affected dramatically either civil or industrial infrastructures. Wastewater Treatment Plants (WWTPs) also suffered severe damages, ranging from the temporary shutdown of the installation due to power outage to more significant structural failure. In some cases, the earthquake produced the collapse of the infrastructure, followed by the uncontrolled release of harmful and/or hazardous materials on soil and superficial waters, with undesirable consequences due to the decay of the environmental quality, public health and safety (Tang 2000; Zare et al 2010; Tang et al 2011). A significant example is the case of the seismic sequence in Christchurch (New Zealand) on February 22nd and June 13rd, 2011. There, untreated municipal wastewater was massively discharged into Avon River, Heathcote River, Avon-Heathcote Estuary and sea. Two years later, the Environment Canterbury Regional Council still recommended to avoid the dermal contact with superficial water (ECRC, 2013). Eventually, the assessment of the seismic hazard and more in general the analysis of vulnerability of WWTPs is highly recommended in order to pro-actively predict, prevent and mitigate the most relevant consequences for the workers and for the population (Krausmann et al 2011; Salzano et al 2013). To this aim, structural priorities and other management options are needed (Kameda 2000, Tugnoli et al 2012). The obtained vulnerability functions can be adopted in existing tools for quantitative risk assessment and land use planning, which must include natural events as earthquake (Fabbrocino et al 2005; Campedel et al 2008).

Quite clearly, the effects of the earthquake on WWTP are quite difficult to be evaluated due to the complexity of WWTPs, which are composed by nodes (e.g. tanks) and links (pipes) with large differences in the seismic response. Furthermore, WWTPs are often part of the wider and more complex disposal system, which include other vulnerable lifelines as power supply

and transportation systems. This complexity is shown in Figure 1. There, WWTP is only an intermediate component of a highly hierarchical system.
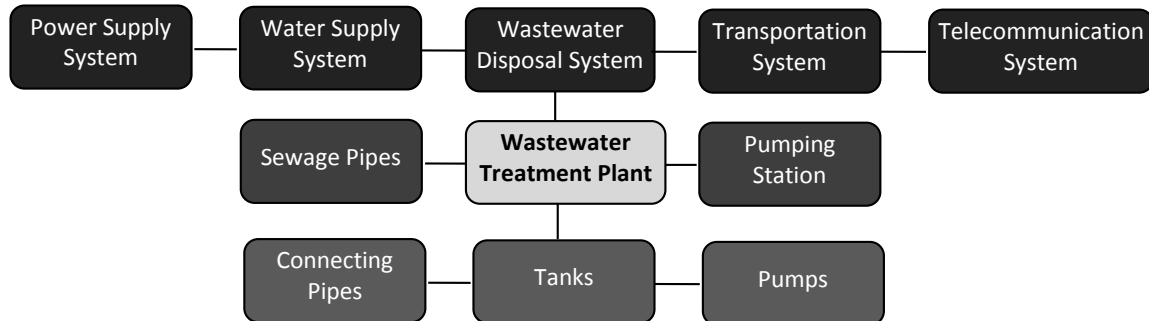

Figure 1. Hierarchical system of lifelines.

In this work, a procedure for the assessment of seismic vulnerability of municipal and industrial treatment plants, taking into account the following assumptions:

− municipal and industrial WWTPs are similar from the physical and structural viewpoint: They are usually designed and built up according to the same construction technologies and structural analysis criteria (Hiks 2007);

− municipal WWTPs do not deal with hazardous materials as in the case of the industrial systems (Metcalf & Eddy Inc 2002);

− industrial operations may be interrupted if the installation is affected by the earthquake, however with additional economic consequences due to business interruption other than and repairing actions;

− municipal WWTPs cannot cope with the natural disaster: Before returning to service, untreated or partially treated wastewater is unavoidably released into superficial waters or on soil, because the public sewage systems cannot be interrupted.

In this framework, a description of the main operational units of WWTPs and a characterisation of the earthquake hazard is needed, as in the following section.

1.1. Wastewater treatment plants

Municipal and industrial treatment processes have the aim of removing pollutants from the wastewater by means of physical, chemical and biological processes. The process may take place in open or closed tanks, which can be buried, semi-buried, ground or elevated (above-ground). In the tanks, physical (baffles) and mechanical devices (scrapers) are typically installed, and chemicals are added. In addition, they are interconnected by pressurized pipes or free surface channels, according to the specific treatment system. Additional elements include storage tanks for chemicals (e.g., chlorine, biogas), dewatered sludge tanks compressor units, and others.

Figure 2 shows the main components of WWTP in more details. There, units 3 and 4 are adopted for the preliminary treatment of wastewater, for the removal of coarse and floating solids as well as grit. Hence, in unit 6, a primary (settleable, solid removal) and a secondary treatment (unsettleable, solid removal by biological conversion into settleable solids) is performed. These treatments are followed by disinfection (unit 18) before being discharged into the receiving water bodies. When the effluent quality from secondary treatment is unacceptable if compared to quality standards established by law or regulation, a third level of treatment by means of advanced processes (e.g. advanced oxidation, micro/ultra/nano-filtration by membranes, activated carbon filtration) is commonly used. Other units and more details information are described extensively elsewhere (Metcalf & Eddy Inc 2002; Hiks 2007).
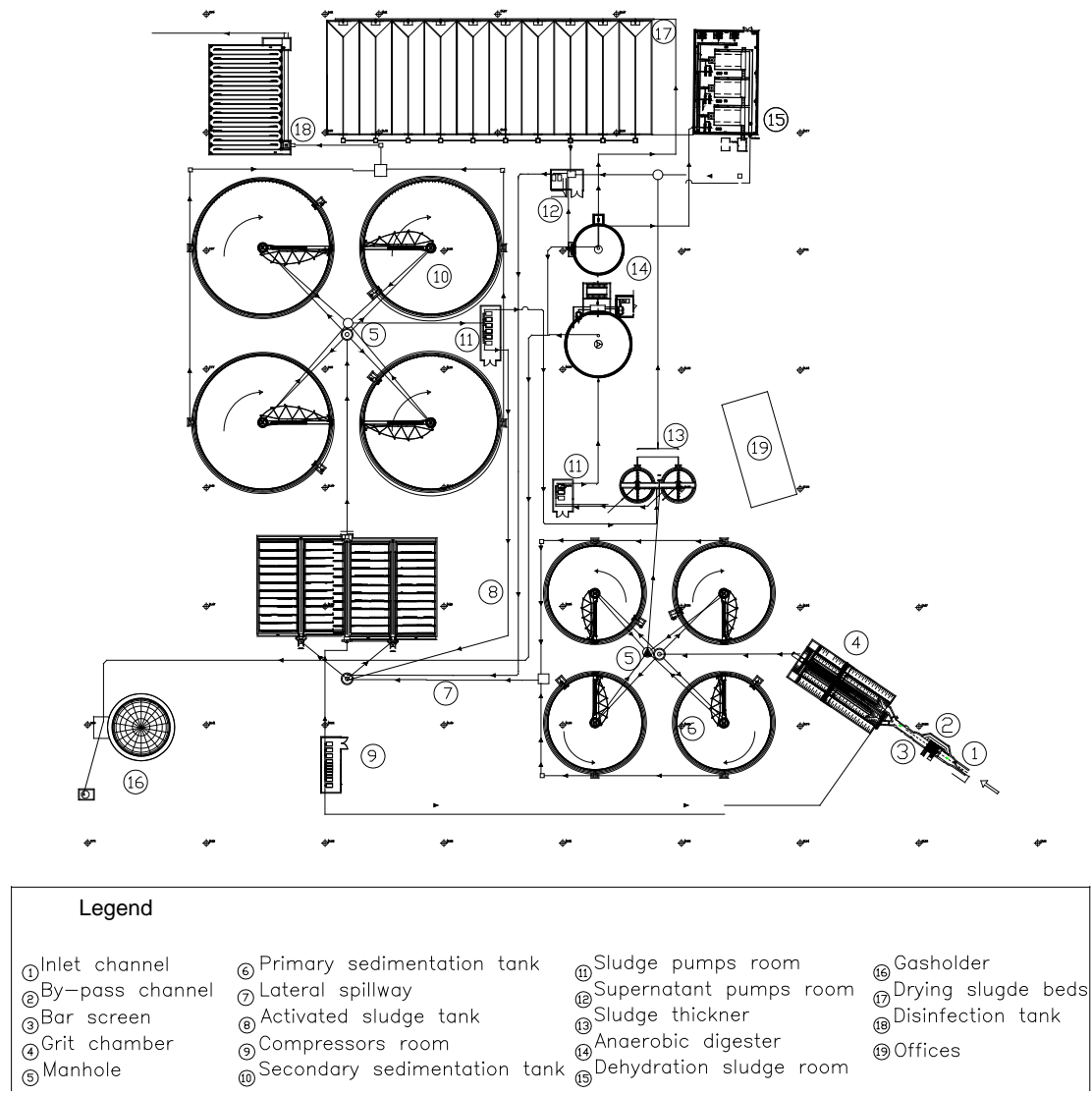
Figure 2. The main process units of a wastewater treatment plant.

Legend

①Inlet channel ⑥Primary sedimentation tank ⑪Sludge pumps room ⑯Gasholder
②By-pass channel ⑦Lateral spillway ⑫Supernatant pumps room ⑰Drying slugde beds
③Bar screen ⑧Activated sludge tank ⑬Sludge thickner ⑱Disinfection tank
④Grit chamber ⑨Compressors room ⑭Anaerobic digester ⑲Offices
⑤Manhole ⑩Secondary sedimentation tank ⑮Dehydration sludge room

1.2. Earthquake characterization

The design of civil and industrial structures in seismic areas is commonly based, among others, on the estimation of the level of shaking induced by an expected earthquake selected on a probabilistic basis. A typical measurement of the seismic scale is the Magnitude (Local Magnitude or Moment Magnitude), which is a unique value that is related to the quantitative estimation of the released energy. In the past, however, the seismic scale was measured on the basis of its intensity, which is related to the damaging effects of the earthquake, as in the

Modified Mercalli Scale (MMI or Macroseismic Intensity). Quite obviously, this is not an objective scale because it is not based on a unique site-independent parameter but on the observation of the damages.

More recently, the presence of seismic network stations has led to the use of instrumental and objective parameters for the description of earthquakes. For the simplified (pseudo-static) earthquake engineering analyses, synthetic parameters are often preferred rather than whole time histories of the seismic motion (in terms of acceleration, velocity or displacement) (see e.g. Kramer (1996) for details). In this framework, the most significant parameter for structural analyses has been recognised in the Peak Ground Acceleration (PGA), which is the peak of the horizontal component of an acceleration time history. In fact, for aboveground civil engineering structure, the PGA is directly related to the structural damage, due to the importance of inertial effects in the seismic loadings.

Quite clearly, the PGA is a synthetic description of the seismic motion and do not give a complete description of the ground motion, which should be also characterized by frequency content and signal duration. However, despite of this limitation, this parameter is frequently adopted as reference for designing earthquake-resistant structures.

2. METHODOLOGY

The methodology proposed in this work is based on an observational method, and is composed by four steps as follows: damage data collection; damage state definition; risk state definition; and fragility curves plotting. Each of these steps is discussed in the following sections.

2.1. Damage data collection

An earthquake can affect either directly or indirectly the WWTP. That is, tsunamis, flooding and power shortage are indirect causes of failure for WWTPs produced by an earthquake. Direct

causes include breaks and deformations of structural elements (e.g. pipes or tank walls) as well as detachments and breaks of non-structural elements (e.g. sludge scrapers, baffles, aerators, mechanical mixers). Such physical damages are the main consequences of Strong Ground Shaking (SGS), Ground Failures (GF) and Sloshing Waves (SW). Strong Ground Shaking is the common seismic effect due to the passage of waves: the result is a transient deformation of the soil layer. Aboveground structures respond to the accelerations associated to the ground shaking through the foundation. The inertia of the construction causes the shearing of the structure, which can concentrate stresses on the weak walls or joints, thus resulting in failure or even total collapse. Similar damages occur for buried or semi-buried constructions. In this case, the eventual failure is a function of a complex process of soil-structure-fluid interaction. Ground Failures (GF) are failure phenomena in the soil that could be divided into three categories: i) fault displacement; ii) liquefaction; iii) earthquake-induced landslide. Generally, the permanent movement of soil is predominantly horizontal, except for the liquefaction, which may be characterised by both lateral spread (horizontal) or seismic settlement (vertical). These effects are site dependent, because they depend on specific soil conditions (saturated fine loose sand for liquefaction, an active fault or a potentially unstable slope), which could induce the soil failure for a given earthquake loading (Santucci De Magistris, 2013). Finally, sloshing waves (SW) are consequences of fluid/structure interaction. This phenomenon is produced by motion of a fluid with free surface inside tanks and is responsible for additional forces on the roof and tank walls as well as on physical and mechanical devices placed in tanks to perform water cleaning processes. Usual consequences of SW are spillage of liquids from the top of open tank, deformation and failure of structures and detachments and breaks of non-structural elements.

Each collected set of data concerning WWTPs was then associated to a specific PGA value calculated for the exact location of the WWTPs by using Shaking Maps of the relative

earthquakes provided by national services as e.g. United States Geological Service (USGS 2012) or by Ground Motion Prediction Equations, for the specific region of interest (Douglas, 2004).

2.2. Damage state definition

For each collected datum, the severity of damage was analysed in terms of post-seismic operating conditions of WTTPs and fluid leakage from basins and pipes. This step was functional for the assignment to five damage states (DS_i), according to the following classification derived by HAZUS (FEMA 2004):

i) DS_1 (no damage): no significant damage occurred;

ii) DS_2 (slight/minor damage): damage is related to the malfunction of plant for a short time (less than three days) due to loss of electric power and backup power, considerable damage to equipment, light damage to sedimentation basins, light damage to chlorination tanks, or light damage to chemical tanks. Decay of treated water quality may occur;

iii) DS_3 (moderate damage): damage is related to the malfunction of plant for about a week due to loss of electric power and backup power, extensive damage to equipment, considerable damage to sedimentation basins, considerable damage to chlorination tanks with no loss of contents, or considerable damage to chemical tanks. Decay of treated water quality is imminent;

iv) DS_4 (extensive damage): extensive damage of pipes connecting the different basins and chemical units. This type of damage will likely result in the shutdown of the plant and loss of contents;

v) DS_5 (complete damage): damage is related to the complete failure of piping, or collapse of equipment, extensive damage to the WWTP structures, followed by loss of contents.

2.3. Risk state

Risk assessment is based on hazard and consequences. When natural - technological interactions are of concern, the structural failures classified by the Damage State, as given in the Hazus methodology, have been mainly addressed to return-to-service or business interruption, with few attentions to the consequences. With the aims of filling this gap, we have arranged the damage state into a Risk State (RS) focused on the occurrence of wastewater release into the environment, as described in the following.

When a municipal WWTP experiences a malfunction, wastewaters flowing through the sewage system, either untreated or un-properly treated, are irreparably discharged into the superficial waters used as receiving water bodies, because the flow of public wastewaters continues despite the earthquake. Hence, it is reasonable to set a Risk State for municipal WWTP corresponding to the malfunctioning of the system, i.e. $RS_{municipal} = DS \geq DS_2$.

When industrial WWTPs are considered, any malfunctioning of the treatment plant induces the temporarily or long-term interruption of the process, whereas a contaminating event can occur only when the structural damage to WWTPs units are relevant in terms of loss of containment in the environment. That is, serious damages to piping system and basins, or structural failures of tanks. Eventually, a Risk State for industrial system can be set as soon as the damage state DS is larger than DS_4, i.e. $RS_{industrial} = DS \geq DS_4$).

2.4. Fragility curves

Once the damage and risk states have been set, the corresponding fragility curves with respect to the seismic intensity parameter (the PGA) can be obtained. Each fragility curve is modelled as log-normal density probability functions characterized by its median μ and dispersion factor (standard deviation) β. The procedure used to obtain the fragility curves is based on

observational data, according to the approach described by previous works (Salzano et al 2003; 2009). The experimental data were fitted by using a cumulative log-normal distribution:

$$P(RS_i) = \frac{1}{2}\left[1 + erf\left(\frac{\ln PGA - \ln \mu}{\beta\sqrt{2}}\right)\right] \tag{1}$$

where μ and β are the median value and the standard deviation of the distribution respectively. The two terms μ and β are obtained by setting Pearson residuals to zero, as indicates from the following expression (X):

$$\sum_i^n \frac{y_i - o_i}{\mathrm{var}\, o_i / n} = 0 \tag{2}$$

where y_i is the ith predicted value from the fragility curves (g); o_i is the ith observed value from empirical studies (g); n is the number of cases investigates.

Finally, following Salzano et al (2003; 2009), threshold values for the intensity seismic parameter for either of DS or RS states can be obtained by probit analysis on fragility, by the following dose-response model:

$$Y = k_1 + k_2 \ln V \tag{3}$$

where Y is the measure of a certain damage possibility in function of the variable "dose" V. In detail, the considered "doses" are the values of PGA used to plot the fragility curves. A zero probability is related to values of Y equal to 2.71.

3. RESULTS AND DISCUSSION

Aiming at the construction of fragility curves and threshold values for the seismic intensity parameter, a collection of damage cases for WTTPs subjected to seismic action has been carried out, through the analysis of available reconnaissance reports. Fifteen earthquakes were considered and damages produced on thirty-nine WWTPs were accurately studied.

The 1989 Loma Prieta earthquake resulted in relevant damages to non-structural submerged equipment, and tanks, due to sloshing liquid (Schiff 1998a). The earthquake of Kobe in 1995 resulted in catastrophic consequences, including the Higashinada WWTP (Schiff 1998b). The plant experienced damages to non-structural elements caused by sloshing (sludge scrapers came off their sprockets in sedimentation tanks), and structural components (e.g. separation of the aeration basin joints) caused by differential ground settlements. The municipal WWTPs of Izmit experienced severe damages to the mechanical equipment in the clarifier after the earthquake in 1999 (Tang 2000), which then resulted off-duty. WWTPs in Calexico and El Centro in Mexico experienced relevant structural damages from El Mayor-Cucapah earthquake on 2010: primary and secondary clarifiers were heavily damaged by sloshing and further damages were caused by liquefaction and lateral spreading (EERI 2010). The 2010-2011 Canterbury earthquakes caused mainly non-structural damages to the WWTP of Christchurch. Although some water tanks experienced some cracks, none was damaged to leaking. However, mechanical devices were seriously damaged and six weeks after the second earthquake the sewage treatment system was reported to be processing only 30% of its normal hydraulic load and he removal efficiency was only 30% of the expected quantities of BOD (Biochemical Oxygen Demand) on a daily basis (Evans & McGhie 2011). The result of damage data collection from the reported earthquakes is shown in Table 1.

Table 1. Collected data of WWTP damages due to earthquakes.

Seismic event (year)	WWTP location	Measured PGA (g)	Damaged process unit	DS	Ref
Loma Prieta (1989)	East Bay Municipal District	0.28	digester	2	Seed et al 1990; O'Rourke 1992; Schiff 1998a
Northridge (1994)	Los Angeles-Glendale	0.28	no data	2	NIST 1994; Dewey et al 1995
Kobe (1995)	Higashinada	0.76	filters and aeration unit	5	EERI 1995; Kuraoka & Rainer 1996; Schiff 1998b
	Chubu	0.72	sedimentation basin	4	
	Seibu	0.72	sedimentation basin	4	
Kocaeli (1999)	Izmit	0.40	sedimentation basin	4	Erdik 1999; Tang AK 2000
	Düzce	0.10	sedimentation basin	4	
Nisqually (2001)	Lacey, Olympia, Tumwater, Thurston County	0.20	no data	1	EERI 2001
	Chambers Creek	0.12	no data	1	
	Tacoma Central	0.12	no data	1	
	Tacoma North End	0.16	no data	1	
	Puyallup	0.20	no data	1	
	Port Ochard	0.16	no data	2	
	Bremerton	0.16	no data	1	
	West Point	0.08	no data	2	
Atico (2001)	Moquegua	0.28	aeration unit	3	Eidinger J 2001; Rodriguez-Marek et al 2003
Denali (2002)	Golden Heart Utilities	0.04	no data	1	Eidinger & Yashinsky 2004
San Simeon (2003)	Oceano	0.04	sedimentation basin and digester	2	Yashinsky 2004
	San Simeon	0.24	no data	2	
	Paso Roble	0.28	sedimentation basin	1	
	Morro Bay-Cayukos	0.12	sedimentation basin	1	
	Prismo Beach	0.08	no data	1	
	Cambria	0.12	no data	1	
	Guadalupe	0.04	no data	1	
Sumatra (2004)	Kata Noi Beach	0.04	no data	1	Strand & Masek 2007
	Patong	0.04	no data	1	
Niigata (2007)	Kashiwazaki	0.24	sedimentation basin	3	Kayen et al 2007; Tang & Schiff 2010
L'Aquila (2009)	Ponte Rosarolo	0.36	digester	3	Tang & Cooper 2009
	Pile	0.38	no data	3	
	Corfino	0.08	no data	1	
	Arischia	0.28	no data	2	
Chile (2010)	Bio Bio	0.32	sedimentation basin	4	Evans &, McGhie 2011; Tang et al 2011
El Mayor-Cucapah (2010)	Calexico	0.32	sedimentation basin and aeration tank	4	EERI 2010
	El Centro	0.36	sedimentation basin	4	
	Herber	0.36	no data	3	
	Holtville	0.24	no data	1	
Darfield (2010)	Bromley	0.16	aeration unit	3	Eidinger & Tang 2012
	Kaiapoi	0.20	no data	2	
Christchurch (2011)	Bromley	0.50	sedimentation basin and aeration unit	5	Warehama & Bourkeb 2013

From the analysis of damages caused by earthquakes on WWTP it comes out that sedimentation basins and sludge digesters are the process units that are more likely affected by seismic stresses. Their low resistance is explainable taking into account that these units are equipped with non-structural elements (e.g. baffles, mixer, sludge scrapers), which are not standardized by any specific seismic code (Schiff 1998a).

In order to significantly represent data collected, we have considered 3 range of PGA (PGA < 0.30 g, 0.30 g ≤ PGA < 0.60 g; 0.60 g ≤ PGA<0.90 g). For each range, the number of events associated to each of the damage states DS has been then evaluated. Results are shown in Figure 3.
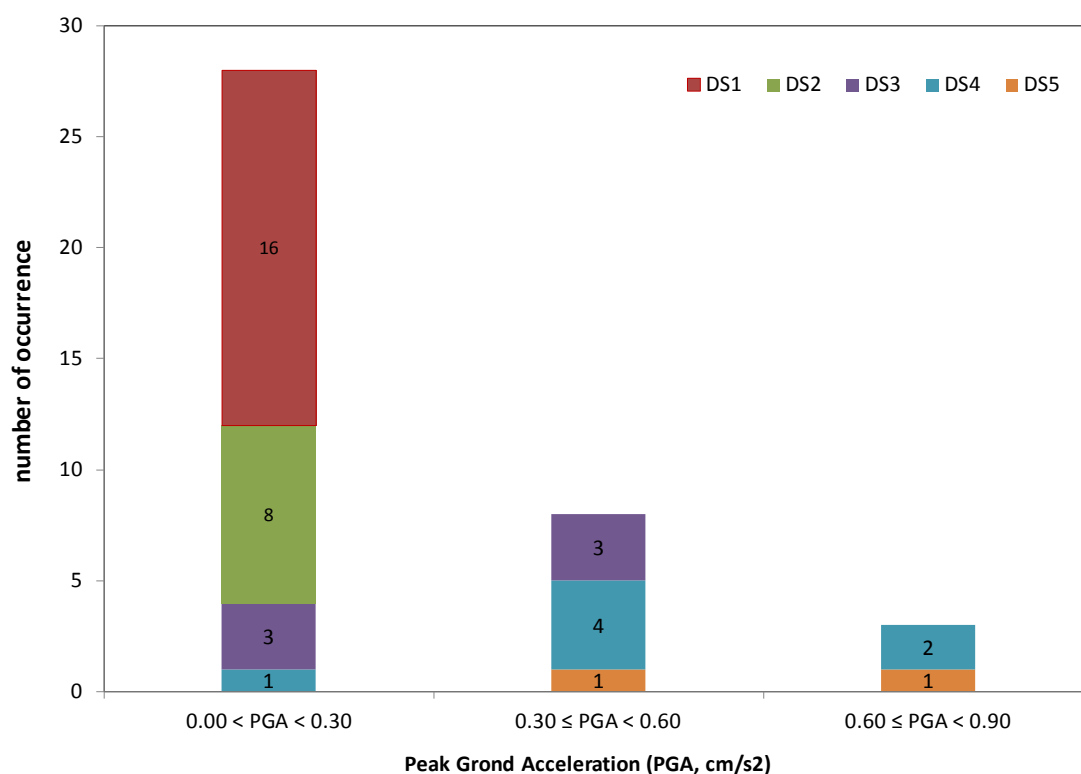

Figure 3. Number of events for the corresponding damage states with respect to PGA ranges.

Most of the damages are related to the lowest seismic intensity (PGA < 0.3 g). For higher PGA only DS>DS_3 can be observed.

Starting from the structural damage state DS and following the previously discussed assumption for the Risk State RS, we have calculated the fragility curves for WWTPs with respect to PGA (Figure 4). The values of μ and β (Eq. 1) for both curves are given in Table 2. In the same table, the threshold values (PGA$_0$) for the seismic risks of WWTPs are also reported, based on the corresponding values of the slope (k_2) and intercept (k_1) of the linear probit equations (Eq. 2).
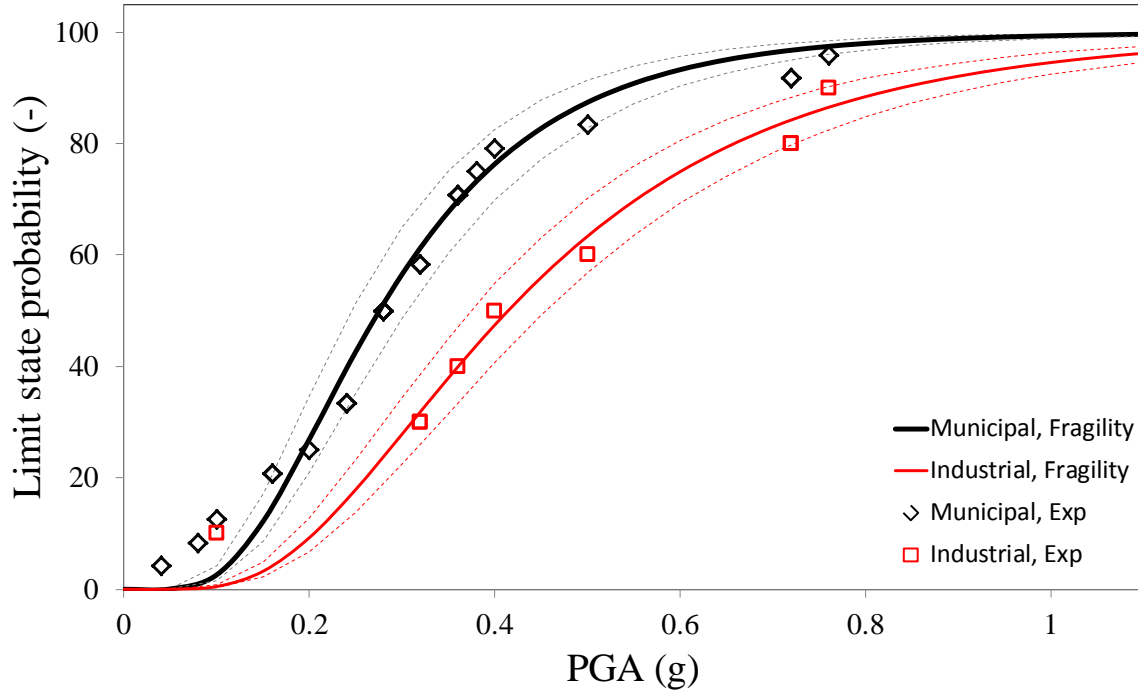

Figure 4. Fragility curves for the seismic risk state RS of municipal and industrial WWTPs. Dashed lines are the standard deviation.

Table 2. Parameters of Fragility curves and Probit functions for the seismic risk state RS of municipal and industrial WWTPs.

Type	RS Fragility		RS Probit		PGA$_0$
	μ (g)	β	k_1	k_2	(g)
Municipal	0.275	0.521	7.17	1.67	0.069
Industrial	0.414	0.550	6.02	1.32	0.085

Quite clearly, the vulnerability associated to municipal WWTPs is higher than industrial WWTPs. This difference depends only on the impossibility of stopping municipal wastewater flow through the sewage system. Finally, the threshold values of PGA (respectively 0.069 g and

0.085 g for the municipal and industrial WWTPs) represent the limit values of PGA for a negligible probability of environmental loss.

From the dataset, the influence of four macro-categories on the occurrence of malfunctions in WWTPs and more specifically: i) the damage to structural elements, such as tanks, reservoirs; ii) the damage to non-structural elements such as baffles, air diffusers, scrapers, pumps; iii) the damage to pipelines connecting tanks in the plant; and iv) the damage to power system, can be also evaluated (Figure 5). If neglecting the effects of power system shortage as risk factor (WWTPs are typically equipped with emergency system) it can be noted that the resistance of non-structural elements to seismic stresses is essential for the municipal WWTPs seismic performance, because they represent the weakest elements. For industrial WWTPs, instead, no element is resulted weaker than others.
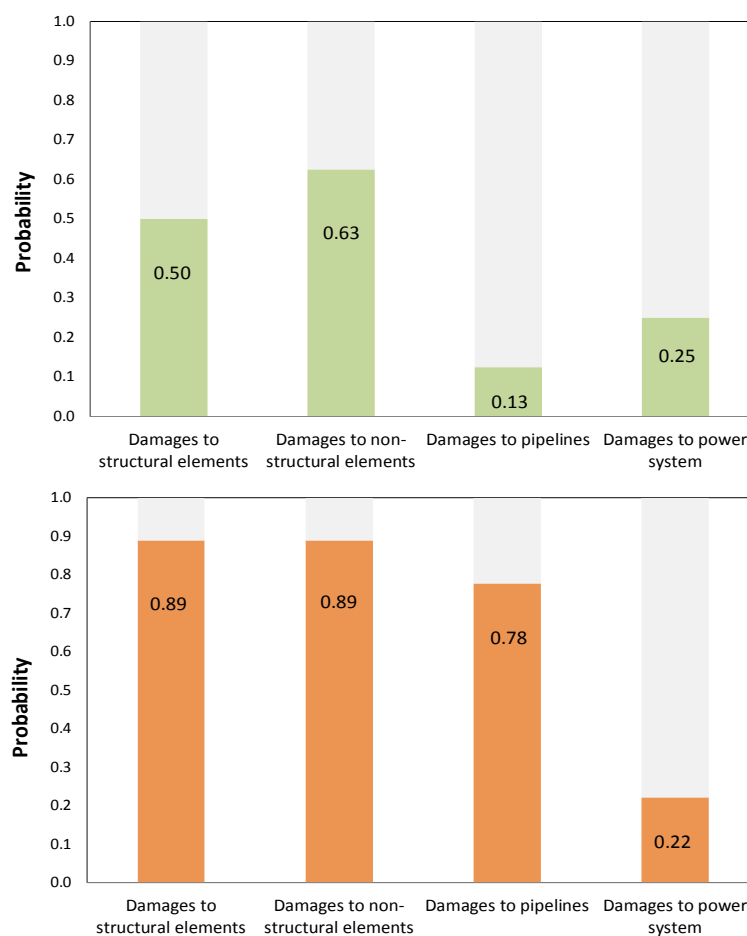

Figure 5. Cause of damages for Municipal (top) and Industrial (bottom) WWTPs.

The data in Figure 5 can be also explained by comparing the fragility and probit coefficients obtained by observational analysis in this work, and the corresponding threshold values in PGA, with data reported in the open literature for single equipment as storage tanks, pumps, pipelines, either with respect to the occurrence of structural damage (DS) states (as in HAZUS (2004) and Kakderi & Argyroudis (2014)) or with respect to the loss of containment of hazardous substances from the same equipment (RS state) as reported by Salzano et al. (2009), Campedel et al. (2009), Lanzano et al. (2013; 2014; 2015). Results are summarised in Tables 3 and 4.

Table 3. Fragility and probit parameters of WWTP subcomponents as reported in HAZUS (2004) and Kakderi & Argyroudis (2014). Seismic intensity parameter IM = PGA.

Component	Damage State DS	μ (g)	β	k_1	k_2	IM_0 (g)
Electric power (back-up)	DS_2	0.20	0.60	7.69	1.67	0.05
	DS_3	0.40	0.80	6.15	1.25	0.06
Chlorination equipment	DS_2	0.35	0.60	6.75	1.67	0.09
	DS_3	0.70	0.70	5.43	1.31	0.13
Sediment flocculation	DS_2	0.36	0.50	6.99	1.94	0.11
	DS_3	0.60	0.50	5.72	1.60	0.15
	DS_4	1.20	0.60	4.23	1.02	0.23
Chemical tanks	DS_2	0.25	0.60	7.32	1.67	0.06
	DS_3	0.40	0.60	6.53	1.66	0.10
Pipeline	DS_4	0.53	0.60	5.97	1.55	0.12
	DS_5	1.00	0.60	4.63	1.17	0.19

Table 4. Fragility and probit parameters of equipment for the risk state RS representing the moderate and extensive release of content from equipment, as reported by Salzano et al. (2003; 2009), Campedel et al. (2009) and Lanzano et al. (2013; 2014; 2015). No liquefaction effects have been taken into account. Seismic intensity parameter IM = PGA.

Component	Risk state RS	μ (g)	β	k_1	k_2	IM_0 (g)
Storage tank Atmospheric (unanchored)	Moderate	0.15	0.7	7.71	1.43	0.029
	Extensive	0.68	0.75	5.51	1.34	0.118
Storage tank Atmospheric (anchored)	Moderate	0.3	0.6	7.01	1.67	0.074
	Extensive	1.25	0.65	4.66	1.54	0.275
Storage tank Pressurised	Moderate	1.85	0.85	4.5	1.12	0.196
	Extensive	4.91	0.84	3.39	1.12	0.526
Pump	Moderate	0.81	1.29	5.31	0.77	0.032
	Extensive	2.44	1.00	4.30	1.00	0.195
Pipeline Aboveground (liquid)	Extensive	0.47	0.64	6.18	1.56	0.110

Comparing the data, it can be observed that the PGA threshold data obtained in this work for WTTPS intended as a whole, are more conservative on the safe side (lower PGA) of typical industrial equipment, either in terms of structural damage DS or in terms of release of content RS, with the exception of – if existing – unanchored atmospheric tanks, which should be excluded in the design of WWTPs or modified for safer anchored options.

4. CONCLUSIONS

The research reported in this paper has been focused on the seismic vulnerability of municipal and industrial Waste Water Treatment Plants (WWTPs), assessed by means of an observational method based on the analysis of damages caused by earthquakes.

Municipal WTTPs are more vulnerable to earthquakes with respect to the industrial systems if considering the release of content in the environment.

Specific vulnerable elements are represented by non-structural components and particularly the sedimentation basins and the digesters. These units are far less resistant than other standard equipment as chemical tanks or pipelines, which may be installed in the plant.

The obtained fragility curves can be usefully adopted for the seismic analysis of WWTPs, in the framework of risk assessment and land use planning.

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