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Seismic Vulnerability of Wastewater Treatment Plants

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Wastewater treatment systems are complex networks composed by several interconnected elements, each of them characterized by specific seismic vulnerability. In the aftermath of an earthquake it is essential that such systems are fully or at least partially operating for the correct operation. Furthermore, the system failure can result in the deterioration of the environment by leakage of untreated wastewater on soil and/or its discharge into superficial water bodies.
This paper deals with the assessment of seismic vulnerability of wastewater treatment plants by analyzing the effects of past earthquakes and taking into account the following factors: (i) plant size (small, medium and large); (ii) typology of wastewaters treated (municipal and industrial); (iii) treatment level performed (primary, secondary and tertiary); (iv) main causes of damages (soil/structure dynamic interaction and inertial overload); (v) elements damaged (structural, e.g. tank walls and bottom, and non-structural, e.g sludge scrapers, baffles, aerators, mechanical mixers).
Historical seismic data for each combination of the previously listed factors will be given when available, in order to highlight common features and differences.
The final aim of this work is to provide fragility curves and threshold values with respect to the main seismic intensity parameters and considering either the loss of control or the leak of wastewater in the ground from containment system. Once validated such curves could be successfully and easily used implemented into existing or new Quantitative Risk Analysis (QRA) tools or for land-use planning methodologies.

1. Introduction

Wastewater treatment plants (WWTPs) are well known facilities located at the end of sewage systems and used to remove contaminants from wastewaters in order to avoid water pollution and consequently damages to the environment and public health. A WWTP is a complex system composed by structural (e.g. tanks, pipes, open channels, etc…) and not-structural elements (e.g. mechanical devices, pumps, aerators, valves, buffers, etc..) so closely connected that the success of the entire wastewater cleaning process depends on the correct operation of all elements composing the system.
On the base of wastewater source, WWTPs are commonly classified in 2 categories (Metcalf and Eddy, 2003): namely industrial WWTPs, when they only treat wastewaters produced by factories, and municipal WWTPs when they treat household wastewaters or a mixture of them with slightly polluted and not dangerous industrial wastewaters. Each countries set own rules to allow discharges of industrial wastewaters into public sewage. Whereas, on the base of size, WWTPs are distinguished in small (less than 10000 people equivalent-P.E. served), medium (from 10001 to 100000 P.E. served) and large (more than 100000 P.E. served) plants.
On the base of the required efficiency in removing contaminants, WWTPs can be designed to conduct a primary treatment or secondary and tertiary. In the first case WWTP removes only the suspended solids suitable to naturally settle in settling tanks, whereas in the second and third case also dissolved organic

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matter and nutrients are removed, with the aim to further improve (where tertiary treatment is more performing than secondary) the effluent quality before it is discharged to the receiving environment.
If a failure occurs in industrial WWTPs, dangerous consequences to the environment and to public health may occur, due to the release of untreated or not properly treated wastewater containing suspended and/or dissolved hazardous materials, on soil or into superficial water bodies. Besides, on the basis of the building techniques improved to realize WWTPs, no considerable difference can be found comparing industrial WWTPs with municipal ones. Such aspect is important since it makes rightful to extend to industrial WWTPs all results in terms of seismic vulnerability obtained for municipal WWTPs by analysing the effects caused on them by past earthquakes.
Aim of this work is to provide fragility curves for municipal and Industrial WWTPs with respect to a seismic intensity parameter, which is significant for the seismic response of the plant. This fragility curves presented in this paper represent a novelty compared to existing fragilities, which are generally intended to analyse the return-to-service thus neglecting the specificity of industrial WWTP with respect to the municipal installations.

2. Observation of the seismic damages occurred to the WWTPs

In the last decades, the damages caused by earthquakes on WWTPS have been collected and registered through direct observations and analyses of the consequences produced. Many papers and reports have been published describing the main features of the seismic event and its environmental, social and economic impacts Well-documented post-earthquake reports are available in the literature (ASCE-TCLEE, 1998,1999 and 2010; Erdik, 1999; USGS, 2007; EERI, 2010; Evans and McGhie, 2011) starting from Californian earthquake of Loma Prieta (1989), till the recent event of Darfield (2010) in New Zealand.
WWTPs are frequently located in coastal zones and/or near rivers since their effluents are discharged into the sea or other superficial water bodies (i.e. rivers and lakes). Such zones are usually constituted by soft sedimentary deposits or saturated loose sand layers and, for this reason, the seismic response of the plants could be strongly influenced by the geotechnical effects (O'Rourke and Liu, 1999).
An earthquake can affect directly or indirectly the WWTP operation. Tsunamis, flooding and long power shortage are examples of indirect causes of failure for WWTPs produced by an earthquake, whereas examples of direct causes are breaks and deformations of structural elements (e.g. pipes, tank walls and bottom) as well as detachments of non-structural elements (e.g. sludge scrapers, baffles, aerators, mechanical mixers). Such physical damages are mainly consequences of strong ground shaking (SGS), ground failures (GF) and inertial overloads (IO).
SGS is the common seismic effect due to the waves passage: the result is a deformation of the soil layer. GF effects are failure phenomena induced by earthquake and they could be divided in 3 categories: i) fault displacement; ii) liquefaction; iii) earthquake-induced landslide. Generally, the permanent movement of soil is predominantly horizontal, except for the liquefaction cases, which are differently treated when it is considered 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. Inertial overloads, instead, are responsible for beaks of structural elements and detachments for non-structural ones.
Based on the analysis of available reconnaissance reports, a collection of damage cases has been carried out, focusing the attention on the typology of damages due to earthquake occurrence. Nine earthquakes were considered and damages produced on seventeen WWTPs were accurately studied.

3. Performance-based analysis of the seismic behaviour of WWTPs

The vulnerability analysis of the WWTPs was investigated by a systematic and thoughtful collection of the damage data based on the post-earthquake reports results. The aim of this data collection was the construction of new fragility curves for the WWTPs where industrial and municipal plants are first considered separately. Fragility curves are functions used to describe the resistance of an element by evaluating the probability to attain or exceed a damage level given a peak value of a considered seismic parameter. Each fragility curve is modeled as log-normal density probability functions characterized by its median and dispersion factor (standard deviation). The procedure used to obtain the fragility curves was based on observational data, according to an approach described by our previous works (Salzano et al., 2003; Fabbrocino et al., 2005; Lanzano et al. 2012; 2013a, 2013b), specifically oriented for industrial tanks and pipelines respectively, which requires special tools (Campedel et al. 2008; Krausmann et al.

2011) in order to carry out quantitative analysis (QRA) of the risk induced by natural catastrophic events (NaTech risks).
Each collected datum concerning damages to municipal WWTPs was associated to a set of synthetic seismic parameter, in terms of Modified Mercalli Intensity MMI, maximum acceleration PGA and velocity PGV (Table 1). Data were generally obtained from the Shaking Maps of the relative earthquakes, knowing the exact location of the WWTPs. These maps are produced, for instance, by USGS (USGS, 2012) and the synthetic data were checked using attenuation laws, which are specific for the site under examination. Considering the uncertainties of shaking maps and attenuation laws, the reference synthetic parameters are just an indication of the magnitude order of seismic action.

Table 1: Seismic parameters associated to municipal WWTPs for several earthquakes

Earthquake	WWTP name	MMI	PGA (g)	PGV (cm/s)
Loma Prieta (1989)	EBMUD	VIII	0.28	50
Kobe (1995)	Higashinada	IX	0.76	88
Kobe (1995)	Chubu	IX	0.72	78
Kobe (1995)	Seibu	IX	0.72	78
Kocaeli (1999)	Izmit	VIII	0.40	56
Kocaeli (1999)	Düzce	VI	0.10	12
Atico (2001)	Moquegua	VII	0.28	24
Niigata (2007)	Kashiwazaki	VII	0.24	20
L' Aquila (2009)	Ponte Rosarolo	VIII	0.36	31
L' Aquila (2009)	Pile	VIII	0.38	31
L' Aquila (2009)	Corfinio	V	0.08	4,0
L' Aquila (2009)	Arischia	VIII	0.28	22
Cile (2010)	Bio Bio	VIII	0.32	34
El Mayor (2010)	Calexico	VIII	0.32	40
El Mayor (2010)	El Centro	VIII	0.36	34
El Mayor (2010)	Herber	VIII	0.36	40
El Mayor (2010)	Holtville	VII	0.24	24
Darfield (2010)	Christchurch	VII	0.16	18
Darfield (2010)	Kaiapoi	VII	0.20	16

The damaging levels were calibrated considering the entity of damage in terms of service stop and loss of containment. These criteria were derived and extended from HAZUS (FEMA, 2004). Five damage states (DS) for WWTPs according to FEMA (2004) were defined.
These are none (DS1), slight/minor (DS2), moderate (DS3), extensive (DS4), and complete (DS5), where:

- DS1 means no damage;
- DS2 is defined by malfunction of plant for a short time (less than three days) due to loss of electric power and backup power if any, considerable damage to various equipment, light damage to sedimentation basins, light damage to chlorination tanks, or light damage to chemical tanks. Loss of treated water quality may occur;
- DS3 is defined by malfunction of plant for about a week due to loss of electric power and backup power if any, extensive damage to various equipment, considerable damage to sedimentation basins, considerable damage to chlorination tanks with no loss of contents, or considerable damage to chemical tanks. Loss of treated water quality is imminent;
- DS4 is defined by the pipes connecting the different basins and chemical units being extensively damaged. This type of damage will likely result in the shutdown of the plant and loss of contents.
- DS5 is defined by the complete failure of all piping, or extensive damage to structures composing the WWTP.

According to such a classification, a damage state was associated to each datum collected and the occurrences number, are reported in the histogram chart of Figure1 on the basis of PGA and of the different damage states.

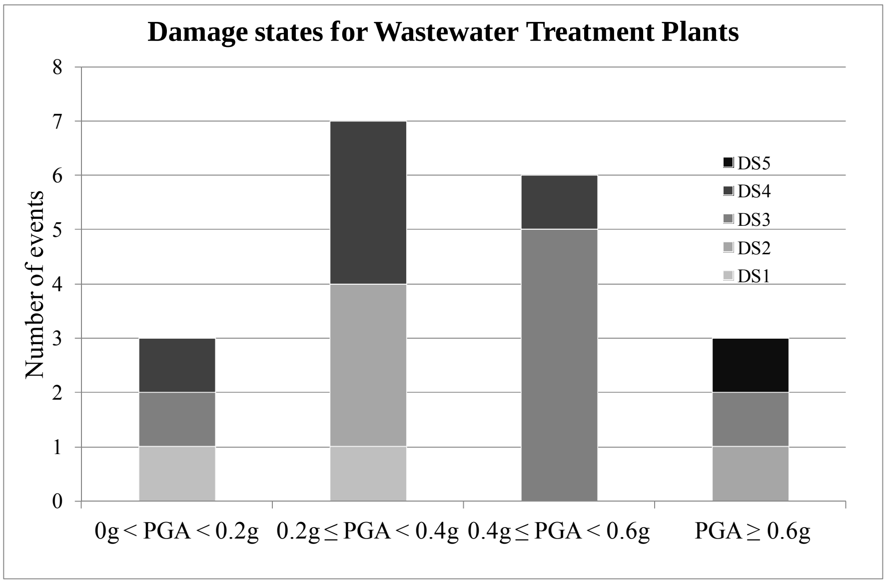

Figure 1: Number of events of damage states DS for WWTPs.

Despite of the limited amount of data, it can be observed that most of the damage data are included in the range of peak ground acceleration PGA=0.2-0.4g and the complete failure of the plant was observed only for very high acceleration values (PGA>0.6g).
In order to carry out different and specific quantitative risk analyses both for industrial and municipal WWTP, the damage states were reorganized in order to identify new risk states, RS, based on the amount and consequence of wastewater fluid release, rather than the severity of damage. Our proposal is given in Table 2.

Table 2: Risk State RS for WWTP.

State	Types	
	Industrial	Municipal
RS	DS ≥ DS4	DS ≥ DS2

When a municipal WWTP stops working, untreated wastewater, flowing through the sewage system, is irreparably discharged in the environment, contaminating soils and/or water bodies. Then, it is reasonable to set a risk state for municipal WWTP as soon as a damage state not lower than DS2 occurs (DS ≥ DS2). Whereas, for an industrial WWTP, the consequence of a failure can be controlled by interrupting temporarily the manufacturing production and for this reason a contaminating event for the environment can occur only when tanks in the WWTPs lose their content. That means that the WWTP is affected by serious damages to piping system and basins, with loss of contents or even by a structural collapse. For this reason a risk state can be set as soon as a damage state not lower than DS4 occurs. (DS ≥ DS4).

4. Preliminary fragility curves for WWTPs

The experimental data were fitted using a cumulative log-normal distribution:

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

where μ and β are the median value and the standard deviation of the distribution respectively. The fragility curves, shown in Figure 2a, have been actually obtained setting a different risk state for municipal and industrial WWTP on the base of the previous considerations. Observing the figure it can easily noted an unexpected crossing between the two curves. This result can be justified taking into account that the industrial WWTP fragility curve has been obtained using an extremely short data set. Then, the results can be considered preliminary reliable only for municipal WWTP: the values of μ and β are given in table 3.

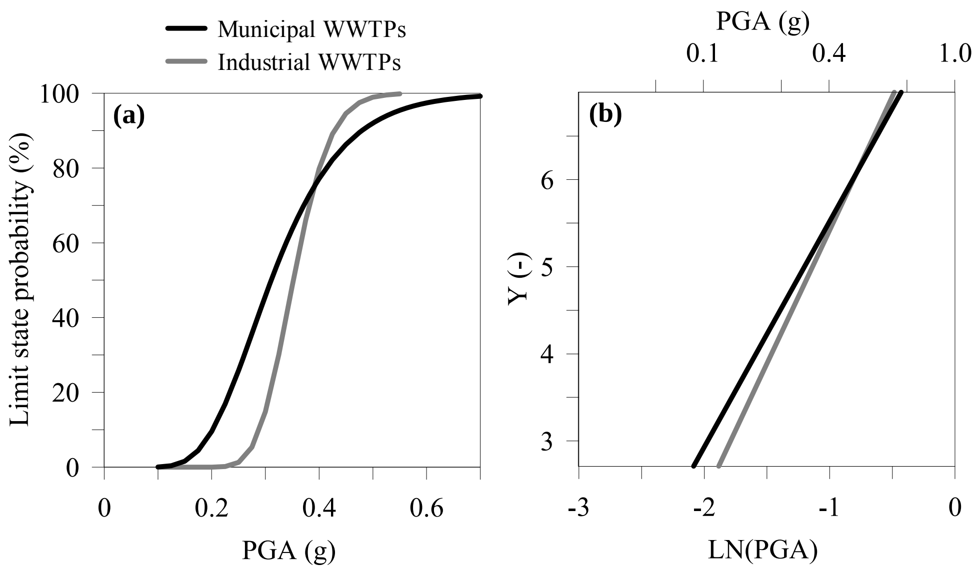

Figure 2: Fragility (a) and probit (b) curves for WWTPs.

Table 3: Preliminary fragility and probit coefficients for municipal WWTP.

Type	Fragility		Probit		PGA_0
	μ (g)	β	k_1	k_2	(g)
Municipal	0.311	0.338	8.11	2.59	0.124

The results of fragility estimation were also expressed in terms of probit parameters (Finney, 1971), k_1 and k_2, and a threshold value, PGA_0, in first instance, was estimated. The probit functions are plotted in Figure 2b, where Y(-) is the probability of damage in the logarithmic scale of PGA; the values of the slope (k_2) and intercept (k_1) of the black straight line in Figure 2b, are also given in Table 3. The threshold value PGA=0.124g represents the limit value of peak ground acceleration, below which the risk probability is practically null.

5. Conclusions

The research reported in this paper has been focused on the seismic vulnerability of wastewaters treatment plants, setting for municipal and industrial WWTPs same damage states but a different risk state. This difference is a consequence of their different operational conditions. Indeed, for an industrial WWTP the influent flow can be interrupted any time, while for a municipal WWTP it cannot be interrupted and therefore a release of contaminated water in the environment occurs as soon as the plant is affected by any malfunction that compromise its regular working. Instead for an industrial WWTP a release of contaminants in the environment is associated to loss of material from tanks as consequence of pipes or basin walls break. For this reason municipal WWTPs result to be more vulnerable than industrial ones when earthquakes occur. The fragility curves shown in this paper and obtained by processing collected data are affected by scarcity of available data, therefore such curves need to be refined and this operation is possible only if more data concerning past and next earthquakes are systematically collected. However, they can be usefully adopted for preliminary structural analysis of seismic resilience of WWTPs, in the framework of risk assessment tools and land use planning (Salzano et al., 2009)

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