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Vulnerability Assessment of Drinking Water Treatment Plants

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In the aftermath of an earthquake it is essential that drinking Water Treatment Plant (WTP) and the relative distribution network keep their full, or at least, partial functionality. Indeed, a complete failure of such systems, associated to a long restoration time can result in serious damages to facilities and services depending on water supply as well as harmful consequences for the population. Actually, a WTP shutdown can amplify the damages caused by an earthquake in terms of economical and human losses by failing the supply of fire fighting network and consequently the extinguishment of potential fires, as well as getting worse the hygienic and sanitary conditions of population affected by the natural events, thus favouring the outbreaks of epidemics as it happened in Haiti, where cholera killed hundreds of thousands of people after the earthquake of January 12th, 2010. This paper deals with the assessment of seismic vulnerability of WTPs that constitute the first element of the water distribution network by analyzing the effects of past earthquakes on them with the aim of determining the main causes of damage (ground failure, sloshing phenomenon, structural weakness, etc…) as well as the weaker elements and then, on the base of risk analysis theory, drawing fragility curves that can be useful tools for designing reliable new WTPs and controlling the resilience of those already in service.

1. Introduction

Water treatment plants (WTPs) are facilities used to treat groundwater as well as raw water from surface sources (i.e. lakes and rivers) to make them suitable for drinking purposes, i.e. to satisfy the local public health standards, as well as for household, commercial and industrial uses. They constitute a complex system, made of a flexible number (the number inversely depends on raw water quality level) of process tanks equipped with mechanical, electrical and control devices coupled with other essential elements, such as plant piping, pumps, chemical storage, laboratory and office buildings (Figure 1). Their vulnerability to natural hazards, e.g. earthquakes, is the effect of the simultaneous presence of several critical factors (Kameda, 2000), mainly: (i) their full operational as well as restoration capacity after an earthquake actually depend on the seismic performance of other lifelines (e.g. power supply system, transportation system) as WTPs belong to the water distribution systems that are interdependent on the other lifelines; (ii) they are usually built near the water intake sources, i.e. lakes and rivers where the ground is made of alluvial soils that more than others are subject to liquefaction phenomenon in case of earthquake; (iii) they are often the result of upgrading operations conducted, over the years, on an existent and old WTP to gradually meet the growing water supply demand and more restrictive quality standards regulations, thus they could be composed of new and old structures with different seismic resilience since they have a differently long service life and have been built in different times and therefore according to different seismic codes; (iv) each element (e.g. tanks, pipes, pumps,...) composing the WTPs is characterized by a specific seismic vulnerability. The role of WTPs in the society is strategic (Oregon Seismic Safety Policy Advisory Commission-OSSPAC, 2013) as prove the social and economic serious consequences that can be caused by their shutdown:(i) the water distribution system could experience a loss of volume and pressure that could critically limit the availability of water supply for conventional urban fire fighting and consequently complicate the fire suppression operations as already happened in the aftermath of Loma Prieta earthquake (1989); (ii) water for healthcare facilities such as

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hospitals could be severely restricted; (iii) water emergency supply provided by the distribution network could even not meet after only few days the subsistence needs (direct consumption and bathing), thus worsening the hygienic situation of population, (iv) manufacturing facilities, hotels, restaurants and even office buildings that depend on water supply will be closed. The heaviness of consequences is expected to increase with the time required to restore the WTP and get it back to full service. Solutions usually adopted to face situations of emergency, such as to produce water through improvised temporary WTP, as happened in Haiti (2010), or to deliver it by tanker lorries could even be more risky for the public health than the shortage of water because this water cannot have appropriate quality controls and therefore can be not safe.

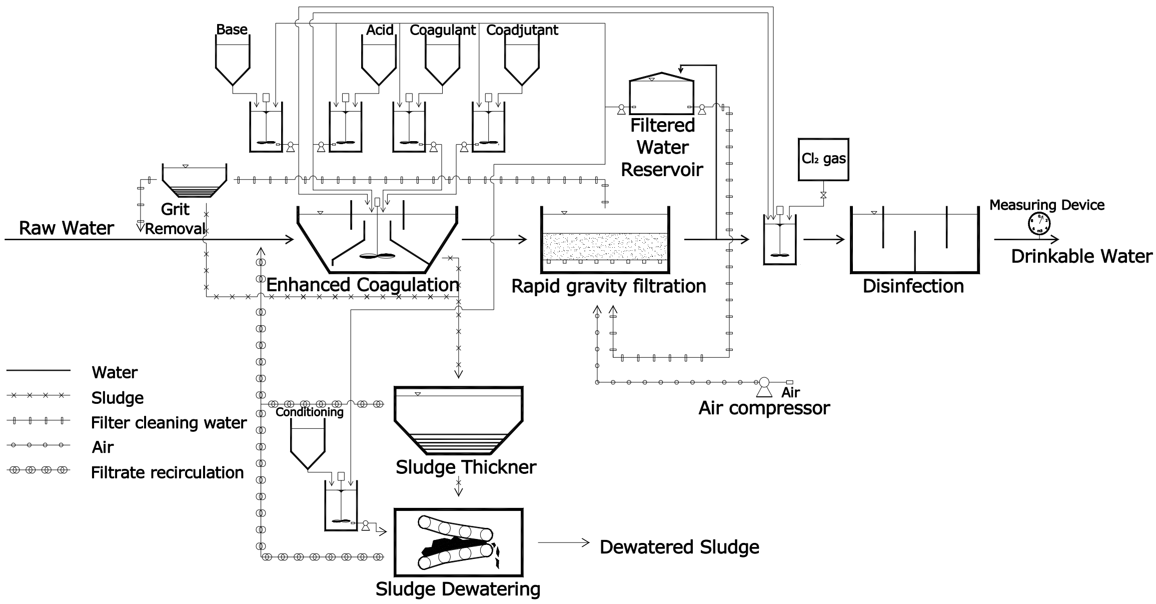

Figure 1: Cycle of a drinking water treatment plant.

All these considerations make essential to take measures to prevent the shutdown of WTPs in case of earthquake making them seismic resilient through structural upgrading. To achieve this aim, the use of tools that can predict the expected damages to a WTP after an earthquake could be extremely useful and, taking into account the complexity as well as heterogeneity of elements that compose a WTP, such tools cannot be the result of a deterministic study, but necessarily have to be the outcome of a statistical approach, and this work is actually focused on presenting the fragility curves for WTP obtained processing statistically data collected from the analysis of damaged caused by past earthquakes to WTPs.

2. Reconnaissance of seismic damages occurred to WTPs

Damages caused to WTPs by the main earthquakes occurred in the last 25 years have been collected from the technical literature and analysed. The main source of data is represented by reconnaissance reports of earthquakes edited few days after the event and describing the main features of the seismic event and its environmental, social and economic impacts starting from Californian earthquake of Loma Prieta (1989), till the recent event of Tohoku (2011) in Japan. An earthquake can affect directly or indirectly the WTP operation. Tsunamis, flooding, quality decay of raw water reservoirs and long power shortage are examples of indirect causes of failure for WTPs 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, mechanical mixers). It is not infrequent that the shutdown of WTP produced by indirect causes is the result of a domino effect as proves the 2011 Tohoku earthquake (Miyajima, 2012) when the outage of a WTP was caused by the inundation of surface water used as intake for the plant with sea water: the high concentration in salts of the water made it not suitable to be treated. But more frequent failure events are caused by physical damages to WTP mainly due to inertial overloads (IO) and ground failures (GF). The sloshing phenomenon is the main consequences of the IO; it produces hydrodynamic forces responsible for damages to process tank cover, baffles and other submersed equipments (Ballantyne & Coruse, 1997). Visible effects of sloshing on process tanks are damages to roof and buckling in walls (it happens in metallic wall tanks), e.g. the well known elephant’s foot buckling. GF consequences 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 (e.g. saturated fine loose sand, an active fault, a potentially unstable slope, ...), which could induce the soil failure for a given earthquake loading (Santucci de Magistris et al. 2014). Visible effects of GF on WTP are damages to inlet and outlet pipes connecting tanks as well as opening of the process tank construction joints due to liquefaction induced permanent ground displacements. Based on the analysis of available reconnaissance reports, a collection of damage cases has been carried out, focusing the attention on the type and quality of damages due to the seismic action. Fourteen earthquakes were considered and damages produced on thirty-one WTPs were accurately studied.

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

The vulnerability analysis of the WTPs 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 fragility curves for these facilities. 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 modelled 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 in other manuscripts produced by the same authors (Salzano et al., 2003; Fabbrocino et al., 2005; Lanzano et al. 2012; 2013; Panico et al. 2013), 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 WTPs was associated to a set of synthetic seismic parameter, in terms of Modified Mercalli Intensity MMI, maximum acceleration PGA and velocity PGV (Table 1).

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

Earthquake	WTP name	MMI	PGA (g)	PGV (cm/s)
Loma Prieta (1989)	Rinconada de Los Gatos	VIII	0.44	58
Loma Prieta (1989)	Penitencia	VII	0.16	22
Loma Prieta (1989)	Santa Teresa	VIII	0.40	52
Valle de la Estrella (1991)	Limón	VII	0.24	19
Northridge (1994)	Joseph Jensen	IX	0.80	88
Northridge (1994)	Los Angeles A.F.P.	VII	0.28	24
Kobe (1995)	Uegahara	IX	0.72	76
Kobe (1995)	Hanshin	IX	0.72	76
Kobe (1995)	Motoyama	IX	0.64	38
Kocaeli (1999)	Maltepe	IX	0.45	64
Kocaeli (1999)	Yalova	VII	0.28	30
Kocaeli (1999)	Kullar	VIII	0.41	58
Düzce (1999)	Düzce	VI	0.20	16
Atico (2001)	Arequipa	VII	0.20	20
Atico (2001)	Moquegua	VII	0.28	24
Atico (2001)	Tacna	VI	0.16	14
Denali (2002)	Golden Heart Utilities	IV	0.04	2
Boumerdes (2003)	Boudouaou	VIII	0.6	50
Sumatra (2004)	Phang Nga N.Base	IV	0.04	6
Kashmir (2005)	Muzaffarabad	IX	0.68	68
Niigata (2007)	Kashiwazaki	VII	0.24	22
Cile (2010)	Mochita	VII	0.28	24
El Mayor (2010)	Calexico	VIII	0.32	38
El Mayor (2010)	El Centro	VIII	0.40	40
Tohoku (2011)	Wanagawa	VII	0.40	30
Tohoku (2011)	Moniwa	VII	0.28	26
Tohoku (2011)	Kunimi	VII	0.40	28
Tohoku (2011)	Fukuoka	VII	0.24	22
Tohoku (2011)	Nakahara	VII	0.24	26
Tohoku (2011)	Hebita and Abuta	VIII	0.40	46
Tohoku (2011)	Sueyama	VIII	0.36	42

Data were generally obtained from the Shaking Maps of the relative earthquakes, based on the location of the WTPs. These maps are actually produced by USGS (USGS, 2015) 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 the seismic action. The damaging levels were set 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 WTPs according to FEMA (2004) were defined. These are: none (DS_1), slight/minor (DS_2), moderate (DS_3), extensive (DS_4), and complete (DS_5), where (i) DS_1 means no damage; (ii) DS_2 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. Light decrease in volume of the treated water; (iii) DS_3 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. Significant reduction in volume of treated water; (iv) DS_4 is defined by extensive damage to pipes connecting the different basins as well as chemical units and shutdown of the plant; (v) DS_5 is defined by the complete failure of all piping, or extensive damage to structures composing the WTP. 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 Figure 2 on the basis of both PGA and different damage states. No DS_5 occurred.

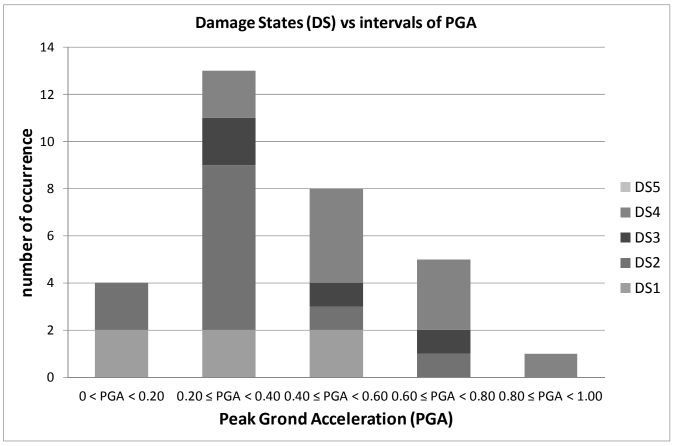

Figure 2: Number of damage states events DS for WTPs.

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 no complete failure of the plant was observed even for very high acceleration values (PGA>0.8g). In order to carry out specific quantitative risk analyses for WTPs, the damage states were reorganized to identify the risk states, RS, based on the volume of water that the WTP is capable to supply after the earthquake. Our proposal is given in Table 2.

Table 2: Risk State RS for WTP.

Risk State	Damage state	Expected effect
low risk (RS_1)	$DS \geq DS_1$	Regular water supply with lower quality
moderate risk (RS_2)	$DS \geq DS_2$	Reduction in water supply and quality
high risk (RS_3)	$DS \geq DS_3$	No water supply

The social and economic consequences of a WTP reduced capacity of treating water are different on the basis on the amount of water that is supplied. If this volume approximately meets the total demand the consequences are limited and therefore for this event is set a RS equal to low, on the contrary, if no water is supplied the social and economic effects could be really serious and therefore a high RS is set for $DS \geq DS_3$

4. Fragility curves and PGA thresholds for WTPs

The experimental data were fitted using a cumulative log-normal distribution, whose relevant parameters are the median value μ and the standard deviation β. The fragility curves, see Figure 3a, have been derived for each of the relevant risk state mentioned in the previous section. Table 3 reports the values of μ and β.

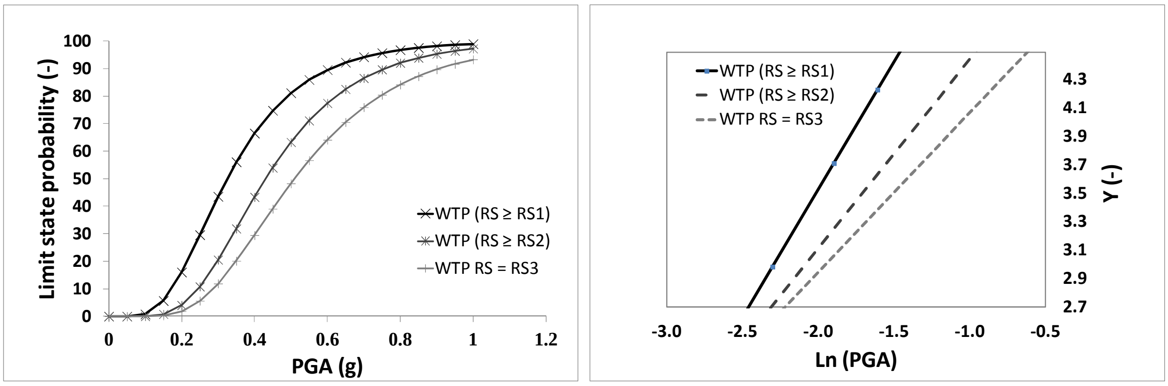

Figure 3: Fragility curves (left, a) and probit coefficients (right, b) for WTPs.

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

RS	Fragility parameters		Probit coefficients		PGA threshold
	μ (g)	β	k_1	k_2	(g)
RS1	0.33	0.49	7.1	1.8	0.09
RS2	0.43	0.44	5.6	1.3	0.10
RS3	0.51	0.45	5.2	1.1	0.11

The results of fragility estimation were also expressed in terms of probit parameters (Finney, 1971), k_1 and k_2. The probit functions are plotted in Figure 3b, 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 lines in Figure 3b, are also given in Table 3. The PGA thresholds on the ground surface below which the given RS is unlikely to occur were derived from the above probit coefficients. The thresholds are reported in the last column of Table 3 pointing out the availability of an useful reference, but also the need of further development of the work and database enlargement.

5. Conclusions

The present paper reviewed the performance of water treatment plants located in seismic areas. Different limit states associated to selected levels of consequences (Risk State, RS) were identified and the corresponding fragility curves have been processed. Interesting and promising results have been obtained, even though available data are not numerous as those available for other types of structures and infrastructures. Nevertheless, the relationships between the probability of occurrence of a given risk state (RS) as well as the threshold values of the peak ground acceleration expressed can be profitably assumed as reference for fast seismic assessment of WTPs and management of such infrastructures during seismic emergencies.

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