SEISMIC VULNERABILITY OF TREATMENT PLANTS IN ISTANBUL

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ABSTRACT

Water treatment plants are critical components of infrastructure systems and their failure during earthquakes can result in significant damages to the environment and interruption of services in addition to financial losses.

This paper investigates the seismic vulnerability of water treatment plants in Istanbul, which is one of the most populated cities in the world with a population of approximately 13.85 million people and is located on a seismically active region. Seismic vulnerability evaluation will help to understand the potential threads originated from the chemicals used in water treatment process units to ambient environment. The seismic vulnerability assessment takes into account the construction year of the facilities, local soil conditions and the seismicity of the treatment plant sites. Results of the seismic assessment of these facilities are presented in the conclusions along with the implications on the environment and post-earthquake services.

Keywords: Seismic Vulnerability, Water Treatment Plants, Contamination, Chlorine byproducts, Disinfection products

İSTANBUL’DAKİ ARITMA TESİSLERİNİN SİSMİK HASSASİYETİ

ÖZET

Su arıtma sistemleri altyapı sistemlerinin kritik elemanlarındandır. Bu sistemlerde olası deprem durumlarında meydana gelecek hasarlar çevreye verecekleri zararların yanı sıra sunulan altyapı hizmetinde aksamalara ve beraberinde maddi kayıplara da sebep olacaktır.

Bu çalışmada yaklaşık 13,85 milyon nüfusuyla dünyanın en kalabalık şehirlerinden ve sismik açıdan aktif bölgelerden birisi olan İstanbul’da bulunan su arıtma tesislerinin sismik hassasiyetleri değerlendirilmiştir. Sismik hassasiyet değerlendirmesi su arıtma tesislerinde arıtma amaçlı kullanılan çeşitli kimyasalların tesislerde meydana gelecek yapısal hasarlarla çevreye yayılmasıyla oluşacak zarar potansiyelinin anlaşılmasına yardımcı olacaktır. Sismik hassasiyet değerlendirmesinde tesislerin yapılış tarihleri, zemin koşulları ve tesislerin bulunduğu bölgelerin depremselliği dikkate alınmıştır.

Anahtar Kelimeler: Sismik Hassasiyet, Su Arıtma Tesisi, Kontaminasyon, Klor, Dezenfeksiyon

1. INTRODUCTION

1.1. Seismic Vulnerability of Water Treatment Plants

Recent earthquakes have shown that these structures are quite vulnerable to earthquakes. The water treatment plant serving the city of Concepcion which has a population over 1.300.000 people suffered severe damages due to liquefaction and ground shaking after the M_w 8.8 Chile earthquake of 2010. As a result, there were water outages in the city and the water treatment could not serve some of its customers for over a month (Eidinger et al., 2012). Damaged components of the water treatment plant included the intake structure, clarifier (baffles, settlers and supporting elements) and suspended ceilings in the control room and water quality laboratory.

Nonstructural damage at the plant also included the toppling of computers, water quality test equipment and glassware on the countertops (Tang, 2011).. Two water treatment plants suffered extensive damage during the M_w 9.0 Tohoku earthquake of 2011 due to liquefaction (Eidinger and Davis, 2012). Two of the three steel water storage tanks were severely damaged due to sloshing and one of the two clarifiers was destroyed at the Calexico Water Treatment Plant, which supplies all the water to the city of Calexico, after the M_w 7.2 Sierra El Mayor earthquake of 2010. The capacity of the Calexico water treatment plant was reduced by 50% following the earthquake. The same earthquake also caused significant damages to the two clarifiers and the main steel water storage tank of the water treatment plant of the city of El Centro (EERI, 2010; Hutchinson, *et al.,* 2010). A water treatment plant in Feng Yuen suffered significant damage during the M_w 7.4 Chi-Chi, Taiwan earthquake of 1999. Extensive sloshing due to ground shaking has dislocated the baffles and caused the partial collapse of the reinforced concrete roofs of two reservoirs. Underground piping at the plant was also damaged due to earthquake ground motion (Schiff and Tang, 2000). The Maltepe water treatment plant which provides potable water by gravity to Adapazari and Erenler lost raw water supply immediately after the M_w 7.4 Kocaeli, Turkey earthquake of 1999 due to power supply failure at the Sapanca pumping plant, the damaged trash rack at the intake structure and the damages at downstream distribution system pipeline. The full raw water capacity was stored in 5 days after the earthquake. There was also minor nonstructural damage at the unanchored components. The Yalova water treatment which serves the communities between Çınarcık and Gölcük also lost raw water supply shortly after the Kocaeli earthquake due to downstream pipeline damage. The Yalova treatment plant was inoperational for 2 days due to power outages (Tang, 2000). Two reinforced concrete potable water storage tanks in the Christchurch, New Zealand were seriously damaged during the M_w 7.1 Darfield earthquake of 2010. One of these tanks was damaged at the roof-wall junction due to the inertial force applied by the roof. The roof of the other damaged tank collapsed due to the uplift forces caused by the sloshing of the contained liquid.

As these field reports suggest, the wide array of components used in water treatment plants such as liquid storage tanks, computer systems, pipes, testing equipment and clarifiers contribute to the complexity of these facilities. Therefore, the operability of water treatment plants not only depends on the performance of the structural systems but also depends on the individual performance of all their components and the performance of other infrastructure system components such as power plants, pumping stations and pipelines, as well. The fact that water treatment plants are usually located on liquefiable alluvial deposits near rivers and lakes and that many of them were built prior to the development of modern seismic design codes further increase the seismic vulnerability of these facilities. Analysis of the seismic vulnerability of water treatment plants is therefore a challenging task due to these complexities.

Over the last few decades, various methodologies have been developed to help decision makers and planners to make quick and realistic estimates on the seismic vulnerability of water distribution systems and components. HAZUS , originally released by FEMA in 1997, is one of the most widely used methodologies for assessing the seismic vulnerability of water treatment plants (HAZUS, 2004; NIBS, 1997). HAZUS methodology classifies water treatment plants based on their capacity and the anchorage conditions of their components. Water treatment plants with capacities range as follows:

- **Small water treatment plants** **:** 37854 - 189270 m^3/day (10 - 50 mgd)
- **Medium water treatment plants** **:** 189270 - 757080 m^3/day (50 - 200 mgd)
- **Large water treatment plants** **:** > 757080 m^3/day (200 mgd)

Larger capacity water treatment plants are simulated by increasing the redundancy of smaller capacity water treatment plants. The water treatment plants with anchored components are assumed to be less susceptible to seismic damage.

According to HAZUS methodology, water treatment plants and storage tanks are assumed to be most vulnerable to Peak Ground Acceleration (PGA) and sometimes to Peak Ground Displacement (PGD) if the treatment plant is located in liquefiable of landslide zones. Therefore the damage states of water treatment plants and liquid storage tanks are estimated using these two ground motion parameters. HAZUS uses five damage states, form ds_1 to ds_5, which are consistent with the damage states expressed in ATC-13- Applied Technology Council, nonprofit research organization based in California (ATC, 1985) (Table 1).

Table 1. HAZUS Damage states

ds_1	ds_2	ds_3	ds_4	ds_5
none	slight/minor	moderate	extensive	complete

Occurrence probability of a certain damage state for a particular water treatment plant at a certain PGA level can be assessed using the fragility curves based on treatment plant capacity and component anchorage conditions. Restoration functions, which are primarily used to estimate the number of days required to make a component at a particular damage state fully operational, are also consistent with ATC-13.

1.2. Water Treatment Plants

Water treatment plants are designed to remove contaminants, sediments and pathogens from water to a certain level that can be safely consumed without posing any health, economical or ecological risk. Water treatment processes must meet water quality standards including consumption of water for drinking water, industrial, medical or other consumption purposes by using physical, chemical and biological processes. In this context, specifically for potable water treatment, generally combination of many processes such as pre-chlorination, aeration, coagulation, sedimentation, filtration, desalination, and disinfection processes are applied.

Among these units, disinfection process and sludge dewatering processes (including sedimentation and coagulation) may need risk assessment evaluations since during these processes tons of chemicals have been used. For instance, depending on the capacity of the treatment plant, disinfection unit require consumption of tons of chlorine. Contamination of chlorine in excess amounts with water may result with the formation of byproducts, such as trihalomethanes and haloacetic acids, which may pose health risks (WHO, 1996). On the other hand, pathogens found in tons of water such as total coliforms, which are potentially harmful, Fecal coliform and Escherichia coli (E. coli) may pose a health risk for young children, and people with vulnerable immune systems; and other many viruses or bacteria groups.

Similar with the disinfection unit, sludge dewatering process require utilization of sludge thickeners which are found as complex compounds, such as Aluminum Sulfate, Iron-3-Chloride, Polyelectrolyte, Activated carbon and Potassium permanganate (Lazur & Yanong, 1992).

In any case of failure in the stability of these risky units in a water treatment plant due to an earthquake may result with the contamination of these compounds to ambient environment. Contamination of these complex compounds in huge amounts to receiving water bodies, may cause health risk in short or long periods. For instance, although Aluminium sulphate is accepted as relatively nontoxic, it is irritant to the skin and eyes, and increased aluminium absorption and retention in bone is reported following acute ingestion without apparent adverse sequelae [Url 1]. Additional to acute exposure, Chronic exposure to aluminium sulphate in drinking water may be involved in the pathogenesis of Alzheimer's disease though this remains a highly contentious issue.

2. AN OVERVIEW OF THE WATER TREATMENT PLANTS IN ISTANBUL

Istanbul is one of the most populated cities in the world with a population of approximately 13 million people. Recent strong earthquakes along the North Anatolian Fault Line, a strike-slip fault line almost identical to the San Andreas Fault Line in California, has raised concerns over the seismic vulnerability of lifelines in the city of Istanbul which is in close proximity to this fault line. This study focuses on the seismic vulnerability of water treatment plants which serve the city of Istanbul.

There are currently 10 water treatment plants in Istanbul, Turkey (Table 2). The geographic distribution of these water treatment plants is shown in Fig. 1.

Celebi Mehmet Han and Orhaniye water treatment plants are the oldest water treatment plants in Istanbul. Although, rest of the water treatment plants can be considered as relatively new, only four of these water treatment plants were constructed after 1998, when the Turkish Seismic Design Code had a significant revision.

Table 2. List of Water Treatment Plants in Istanbul

Plant ID	**Water Treatment Plant**	**Construction Year**	**Latitude**	**Longitude**	**Seismic Zone (Turkish Seismic Design Code 2007)**	**Capacity (mgd)**	**HAZUS 99 Capacity Classification**
1	Fatih Sultan Mehmet Han	1998	41.088891	28.764418	Zone 2	106	Medium
2	II. Beyazıt Han	2003	41.088706	28.764688	Zone 2	106	Medium
3	Büyükçekmece	1989	41.043152	28.591883	Zone 2	106	Medium
4	Çelebi Mehmet Han	1978	41.088190	28.966474	Zone 2	132	Medium
5	Yıldırım Beyazıt Han	1995	41.087917	28.964699	Zone 2	53	Medium
6	Orhaniye	1979	40.999467	29.327897	Zone 1	100	Medium
7	Osmaniye	1996	40.997282	29.326265	Zone 1	53	Medium
8	Muradiye	1995	41.001466	29.329927	Zone 1	79	Medium
9	Emirli Yavuz Sultan Selim	2001	40.998674	29.331498	Zone 1	132	Medium
10	Elmalı	1994	41.074196	29.099921	Zone 2	11	Small

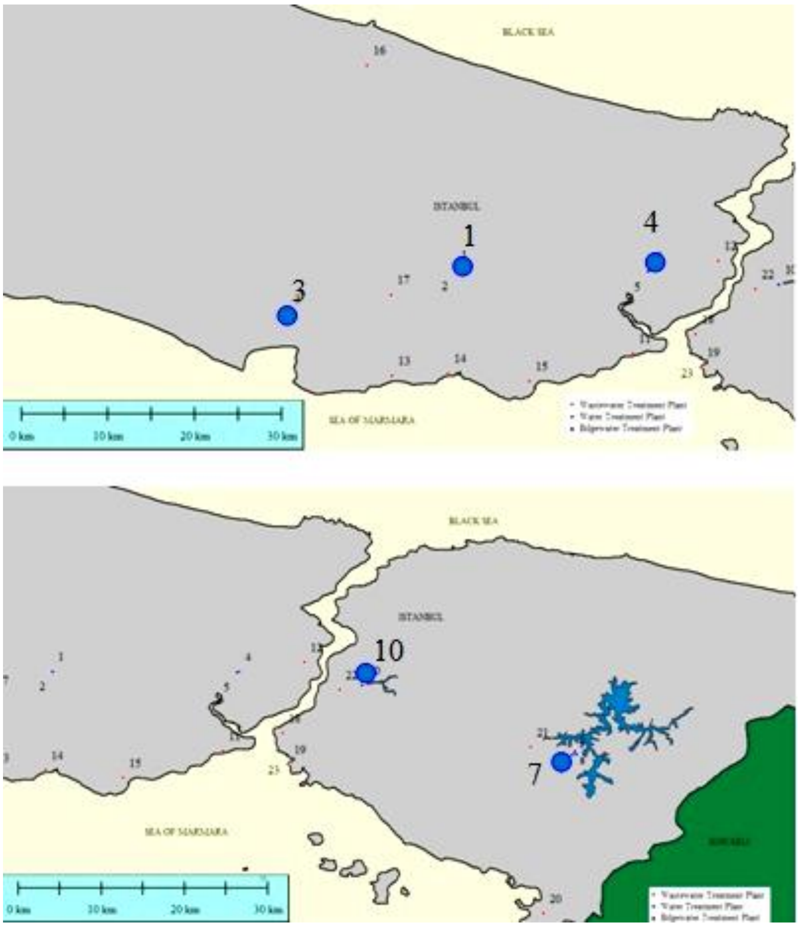

Figure 1. a. Water Treatment Plants on the European Side of Istanbul
b. Water Treatment Plants on the Asian Side of Istanbul

The water treatment plants are located on seismic zones 1 and 2 according to the 2007 Turkish Seismic Design Code. The peak ground acceleration for stiff soil seismic zones 1 and 2 are indicated as 0.40g and 0.30g, respectively. A quick evaluation of the PGA map of Turkey (10% probability of exceedance in 50 years), shows that the expected PGA varies between 0.30g and 0.60g at the water treatment plant sites in Istanbul (KOERI, 2014). Upper and lower limits of expected PGA values at the water treatment plant sites are presented in Table 2.

Table 3. Expected PGA limits obtained from the PGA map of Turkey for the 475 year return period earthquake

Plant ID	**Water Treatment Plant**	**PGA Lower Limit (g)**	**PGA Upper Limit (g)**
1	Fatih Sultan Mehmet Han	0.40	0.60
2	II. Beyazıt Han	0.40	0.60
3	Büyükçekmece	0.40	0.60
4	Çelebi Mehmet Han	0.40	0.60
5	Yıldırım Beyazıt Han	0.40	0.60
6	Orhaniye	0.40	0.60
7	Osmaniye	0.40	0.60
8	Muradiye	0.40	0.60
9	Emirli Yavuz Sultan Selim	0.40	0.60
10	Elmalı	0.30	0.40

Anchorage of components significantly decreases the probability of minor and moderate damage states but does not have a profound effect on reducing the probability of extensive and complete damage states. There are no strict regulations on the anchorage of components for water treatment plants in Turkey. Since, there is limited information on the anchorage of water treatment plant components, exceedance probability of damage states were obtained for anchored and unanchored conditions from HAZUS fragility curves which are presented in Tables 4 and 5, respectively. Tables 3 and 4, show that the occurrence probabilities of "minor" and "moderate" damage states are quite high, especially for water treatment plants with unanchored components.

Table 4. Exceedance probability of damage state obtained from the HAZUS fragility curves for water treatment plants with unanchored components

Plant ID	**Water Treatment Plant**	**Probability Ds>ds for PGA lower limit**				**Probability Ds>ds for PGA upper limit**			
		Minor	**Moderate**	**Extensive**	**Complete**	**Minor**	**Moderate**	**Extensive**	**Complete**
1	Fatih Sultan Mehmet Han	0.97	0.72	0.1	0.01	1	0.95	0.35	0.06
2	II. Beyazıt Han	0.97	0.72	0.1	0.01	1	0.95	0.35	0.06
3	Büyükçekmece	0.97	0.72	0.1	0.01	1	0.95	0.35	0.06
4	Çelebi Mehmet Han	0.97	0.72	0.1	0.01	1	0.95	0.35	0.06
5	Yıldırım Beyazıt Han	0.97	0.72	0.1	0.01	1	0.95	0.35	0.06
6	Orhaniye	0.97	0.72	0.1	0.01	1	0.95	0.35	0.06
7	Osmaniye	0.97	0.72	0.1	0.01	1	0.95	0.35	0.06
8	Muradiye	0.97	0.72	0.1	0.01	1	0.95	0.35	0.06
9	Emirli Yavuz Sultan Selim	0.97	0.72	0.1	0.01	1	0.95	0.35	0.06
10	Elmalı	0.94	0.6	0.17	0.05	0.98	0.8	0.31	0.21

Table 5. Exceedance probability of damage state obtained from the HAZUS fragility curves for water treatment plants with anchored components

Plant ID	Water Treatment Plant	Probability Ds>ds for PGA lower limit				Probability Ds>ds for PGA upper limit			
		Minor	Moderate	Extensive	Complete	Minor	Moderate	Extensive	Complete
1	Fatih Sultan Mehmet Han	0,6	0,23	0,1	0,01	0,92	0,65	0,35	0,06
2	II. Beyazıt Han	0,6	0,23	0,1	0,01	0,92	0,65	0,35	0,06
3	Büyükçekmece	0,6	0,23	0,1	0,01	0,92	0,65	0,35	0,06
4	Çelebi Mehmet Han	0,6	0,23	0,1	0,01	0,92	0,65	0,35	0,06
5	Yıldırım Beyazıt Han	0,6	0,23	0,1	0,01	0,92	0,65	0,35	0,06
6	Orhaniye	0,6	0,23	0,1	0,01	0,92	0,65	0,35	0,06
7	Osmaniye	0,6	0,23	0,1	0,01	0,92	0,65	0,35	0,06
8	Muradiye	0,6	0,23	0,1	0,01	0,92	0,65	0,35	0,06
9	Emirli Yavuz Sultan Selim	0,6	0,23	0,1	0,01	0,92	0,65	0,35	0,06
10	Elmalı	0,65	0,3	0,17	0,05	0,85	0,55	0,31	0,1

Restoration functions provided in HAZUS and ATC-13 presented in Tables 6 and 7, show that it may take up to 7 days for the water treatment plants with “minor” and “moderate” damage states to be fully operational.

Table 6. Restoration Function (Normal Distribution) for (After ATC-13)

Damage State	Mean (Days)	σ(days)
slight/minor	0.9	0.3
moderate	1.9	1.2
extensive	32.0	31.0
complete	95.0	65.0

Table 7. Discretized Restoration Functions for Water Treatment Plants (After HAZUS)

Damage State	1 day	3 days	7 days	30 days	90 days
slight/minor	65	100	100	100	100
moderate	23	82	100	100	100
extensive	16	18	21	48	97
complete	7	8	9	16	47

3. CONCLUSIONS

Although, there is limited information on the local geotechnical conditions of the water treatment plant sites, almost all of them are located near river beds and lakes, which increase the risk of geotechnical problems such as liquefaction. Since, the damage state predictions presented in HAZUS primarily depend on the value of the expected peak ground acceleration; site specific geotechnical studies should be conducted in order to predict structural failures of these water treatment plants due to local soil conditions. Another issue that has to be considered in predicting the functionality of water treatment plants is their dependence on other water distribution system components such as pumping stations, pipelines and storage tanks, as underlined in the case studies presented in the introduction. Even a study focused on the sole performance of these facilities show that there is a significant probability of “minor” and “moderate” damage states which could translate into considerable loss of functionality of the water distribution system for up to 7 days following the event.

As seen on Tables 3 and 4, anchorage of the unanchored components of these water treatment plants can be quite helpful in reducing the disruption of services immediately after the earthquake.

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