Effect of Seismicity on Infrastructure Pipelines

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ABSTRACT

One of the important conditions of sustaining a healthy life is the quality of city water in residential environments and removal of wastes from living spaces. Therefore it is necessary that infrastructure systems we use in providing drinking water and removing wastewater always operate without leakage. Especially post-disaster epidemics will decrease sharply when infrastructure facilities continue to operate after disasters. Thus, infrastructure facilities and pipelines should continue to operate safely without sustaining any damages after earthquakes and/or application of high loads. However, pipelines do suffer damage and fail after almost every earthquake in Turkey.

Post-earthquake damage conditions of pipelines have been examined in this study according to earthquake magnitude, soil condition and type of pipeline, and suggestions have been made regarding construction of pipelines for future probable earthquakes, in which the soil conditions and infrastructure of Küçükçekmece district in Istanbul was considered.
Keywords: *Infrastructure Systems, Pipelines, Earthquake Risk, Istanbul, Damages*

INTRODUCTION

Infrastructure systems such as drinking water distribution pipelines, wastewater and rainwater systems are as important as buildings, bridges, roads and pavements in constituting living spaces, cities and streets. On the other hand, it is necessary that these systems do not get damaged and continue to operate after disasters.

Post-earthquake damages in superstructures are observed as structural damages, loss of human lives and injuries. However, although infrastructure damages do not cause such results, they become very important in terms of continuing human life if they become non-operational. Also, mitigation of superstructure damages can be carried out fasted compared to infrastructure damages.

Natural gas pipelines, oil pipelines, drinking water and sewer lines, electrical and communication lines are imperative for everyday life. Any damage in these lines (natural gas and electricity cuts, energy shortages, inability to respond to fire, failure of drinking water pipelines, inability to coordinate due to failure of communication lines) could halt daily life.

It was not possible to respond to fires that erupted as a result of the 1906 San Francisco earthquake (M=8.3), because three reservoirs were damaged. A similar case was observed at the 1925 Santa Barbara earthquake (M=6.3). Other infrastructure systems have suffered damage in the 1971 San Fernando earthquake (disruptions of electricity, water, and natural gas distribution network; a dam barely avoiding collapse; difficulties at emergency aid facilities and hospitals). Research on earthquake behavior of infrastructures have gained pace and increased in the US especially after the 1971 San Fernando earthquake. Therefore, much has been accomplished on earthquake behavior, repair and strengthening of infrastructures. Nevertheless, infrastructure damages occurred in the 17 October, 1989 Loma Prieta and January 17, 1994 Northridge, California earthquakes, even though it was at a smaller scale. There has been extensive infrastructure damage and fire in the January 17, 1995 Kobe earthquake in Japan. Damage has been rather high at the Kobe port, which was built on an earth fill. Electricity and communication systems were not much damaged, because they were constructed to be earthquake resistant. The works of fire brigades have been difficult due to lack of water [3].

Earthquake and fault conditions have been ignored during installation of underground pipelines in most countries, and therefore infrastructure damages have been very high. Earthquake conditions are not considered in selection of pipeline type, form of connection and material. However, significant research has been conducted in order to better assess and to provide a solution to this situation.

Earthquake damages inflicted on buried pipelines result in failure of vital services such as transportation, electricity, oil, natural gas, water and sewage systems. Terrain studies and various researches have shown that type and position of damage depend on soil conditions, placement conditions, pipe type and type and magnitude of earthquake [21], [22].

The 1985 Michoacan, Mexico earthquake is a good example of a case that required high rates of pipeline repair. This earthquake resulted in high damages in the water distribution pipelines of Mexico. Researchers have reported these losses and reached the conclusion that damages in pipelines have basically been a result of earthquake waves, having observed that there has been no liquefaction [23].

Repair was necessary at 74 points in the water transmission pipelines (pipe diameter ≥ 600 mm) of the Los Angeles Department of Water and Power (LADWP) and Metropolitan Water District of Southern California (MWD) and at 1013 points in the distribution pipelines (pipe diameter < 600 mm) of LADWP [24].

Material of a pipeline has as much effect as soil and placement conditions on damage inflicted from earthquakes. Detailed research has been carried out on damages of underground pipelines from recent earthquakes to determine which type of pipe material is more suitable/endurable. For example, the relation between pipeline material and damage ratio of pipelines is investigated at the cities of Kobe, Nishinamiyo and Ashiya, following the January 1995 earthquake in Japan; and as a result, the damage ratio (damage/km) was found to be 0.0 for polyethylene pipelines, whereas it was 0.437, 1.430, 1.508 and 1.782 for PVC, cast iron and concrete pipes with asbestos, respectively.

In this study, an overview of post-earthquake infrastructure damages in Turkey have been presented and the probability of such damages has been examined for the case of one district in Istanbul.

DAMAGES IN INFRASTRUCTURE PIPELINES AFTER EARTHQUAKE

It is indispensable and a very important requirement in emergency situations, that drinking water facilities, wastewater facilities and energy transfer lines remain in an operational state after an earthquake. However in Turkey both infrastructure systems and energy transfer lines have shut down after almost all recent earthquakes (Figure 1) within the last two decades: 1992 Erzincan (M= 7.9), 1995 Dinar (M= 6.0), 1999 Gölcük (M= 7.8), 2002 Afyon (M= 6.2), and 2011 Van (M= 7.2).

Figure 1. Infrastructure pipeline and energy transfer line damages and the rearranged water transmission lines

Damages in infrastructure pipelines have been observed mostly at alluvial deposits, soft soils, and in joints and shafts of pipes. Most infrastructure suffer damages in zones close to earthquake focus, while damage occurs mostly in weak soil as one moves away from focal earthquake zone. The whole infrastructure was damaged in the region including the fault zone in the Gölcük Earthquake (M = 7.4) on August 17, 1999, and damage ratio dropped only to 70% at distances further from the earthquake focus [1, 2, 3]. In fact, pipe damages were observed even in districts at 100-150 km distances. Similarly all pipeline systems of the district of Erciş have been damaged in the 2011 Van Earthquake and water was provided to the district through surface water supply pipes and tankers [4] (Figure 2).

Figure 2. Post-Earthquake Water Distribution

Among concrete, steel, polyethylene, cast iron and PVC types of pipes used in the region, concrete and cast iron pipes suffered more damage compared to PVC pipes.

EFFECT OF SEISMICITY ON PIPELINES AND DETERMINATION OF EARTHQUAKE DAMAGE PROBABILITY

Magnitude, focal depth and local soil conditions of earthquakes determine their intensity and quality of buildings and facilities determine the amount of damage. Pipeline damages are higher in zones close to the earthquake and in weak soil, and type and material of pipelines also increase the damage ratio. However, placement of pipelines before an earthquake and construction considering earthquake conditions will resolve drinking water and wastewater problems. Having pre-earthquake information about likely pipeline damage is important in order to take prior measures and thereby reduce any shortcomings.

Many researchers have shown a correlation between seismic parameters such as pipeline damages and peak ground acceleration (PGA) or peak ground velocity (PGV). Kubo and Katayama (1975), Isoyama et al. (1998) have developed a correlation between pipeline damage and earthquake parameters. Sarikaya and Koyuncu (1999), Tang (2000), Tankut et al. (1995) have carried out an examination of post-earthquake damages of drinking water and wastewater pipelines. Toprak and Yoshizaki (2003), Balkaya et al. (2003), Sağlamer and Balkaya (2005) have worked on pipeline behavior during earthquakes and effects of earthquake loads on pipelines.

FEMA 1999 has developed a function for estimation of pipeline damages in case of earthquake in their HAZUS 99 Technical Manual, based on work carried out by O'Rourke and Ayala in 1993. On the other hand, a damage function has been developed for cast iron (CI) water pipelines by Japan Water Works Association (JWWA) (1998) and Toprak (1998) (Figure 3).

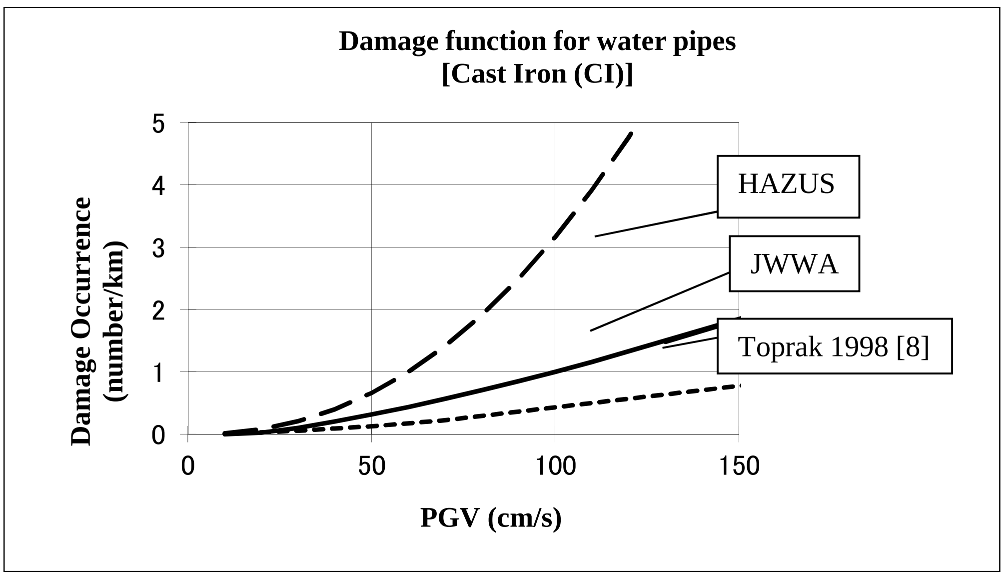

Figure 3. Relation between cast iron (CI) water pipeline damages and PGV [15]

Yüzügüllü and Uğurlu (2005) have used for Istanbul the average of graphs used in ATC 25 (Christopher 1991), developed for conditions of the US, and have used the vulnerability graphs developed for pump stations of the drinking water distribution network, to estimate damage.

Although damage in pipelines depends on earthquake movement and magnitude, the essential earthquake parameter that causes damage is the peak ground velocity (PGV) and local soil conditions. Japan Water Works Association (JWWA) estimates pipeline damage rate through the following relation;

$$Rm\ (PGV) = R\ (PGV) \times Cp \times Cd \times Cg \times CI \qquad (1)$$

Variables in this formula stand for the following:

Rm (PGV) : Pipeline Damage Ratio (points / km)
PGV : Peak Ground Velocity (cm / s)
R (PGV) : $3.11\times10^{-3} \times (PGV-15)^{1.3}$

Damage ratios according to type of pipeline and ground are presented in Table 1, based on the correlation provided by JWWA (1998). As it can be observed in Table 1, number of damages (breaks) are less in polyethylene pipelines in all types of soil. On the other hand, damage is higher at soils with high shear wave velocity.

Table 1. Damage rates of underground pipelines in Küçükçekmece, according to peak ground velocity (PGV)

R(PGV)	Pipe Type	Soil Condition (Turkish Earthquake Regulation, 2007)	Pipe Diameter (mm)	Rm (PVG)	Number of damages per 100 km
20	Concrete Pipe and Galvanized Iron Pipe	Group 1	300	0.060	60
			600	0.038	38
		Group 2	300	0.040	40
			600	0.025	25
		Group 3	300	0.008	8
			600	0.005	5
	Steel Pipe and Ductile Iron Pipe	Group 1	300	0.018	18
			600	0.011	11
		Group 2	300	0.012	12
			600	0.008	8
		Group 3	300	0.003	3
			600	0.002	2
	Polyetylene Pipe	Group 1	300	0.006	6
			600	0.004	4
		Group 2	300	0.004	4
			600	0.003	3
		Group 3	300	0.001	1
			600	0.001	1
120	Concrete Pipe and Galvanized Iron Pipe	Group 1	300	3.166	3166
			600	1.979	1979
		Group 2	300	2.111	2111
			600	1.319	1319
		Group 3	300	0.422	422
			600	0.264	264
	Steel Pipe and Ductile Iron Pipe	Group 1	300	0.950	950
			600	0.594	594
		Group 2	300	0.633	633
			600	0.396	396
		Group 3	300	0.127	127
			600	0.079	79
	Polyetylene Pipe	Group 1	300	0.317	317
			600	0.198	198
		Group 2	300	0.211	211
			600	0.132	132
		Group 3	300	0.042	42
			600	0.026	26

Cp : Coefficient for pipeline material (Concrete and Galvanized Iron: 1, Steel and Ductile Iron: 0.3, Polietylene: 0.1)
Cd : Coeficient for pipeline diameter (<90 mm: 1.6, 100-175 mm: 1.0, 200-450 mm: 0.8, >500 mm: 0.5)

Cg : Coefficient for soil condition (Yd, Sd, Ym : 1.5 (Group 1); Qal, Ksf, Oa, Q: 1.0 (Group 2); Others: 0.4 (Group 3)
CI : Liquefaction coefficient (Ym, Yd, Sd, Qal, Ksf, Oa, Q:2.0; Others: 1.0)

Flexible pipelines suffer lesser damage or none at all, as they become deformed during earthquakes and can thus endure pressure concentrations. Utilization of flexible connections increases endurance of pipelines against external and internal forces and reduces failure risk. Therefore, effects that could cause possible damages on pipelines are eliminated by complying with placement and bearing conditions.

Research shows that PE pipes, used as water and natural gas pipes, have better performance against earthquake forces compared to other pipe materials. Therefore utilization of flexible pipelines such as polyethylene, steel, ductile iron and glass fiber reinforced plastic pipelines is recommended. On the other hand, as materials with asbestos cement are brittle and weak against different placements and earthquake forces, pipes manufactured from such materials are the worst type of pipe for earthquake zones.

SEISMICITY OF ISTANBUL DRINKING WATER AND WASTEWATER PIPELINES AND ESTIMATE OF DAMAGE IN A PROBABLE EARTHQUAKE

Istanbul is one of the most important metropolises of the world, with a population of 17 million. Accommodating a significant portion of Turkey's population, industry and commerce, Istanbul is also under an earthquake risk. Many researchers have carried out work on the earthquake risk of Istanbul and concluded that a very high damage may be expected [15, 18, 19, 20]. In addition to superstructure damages, expected damage in infrastructure pipelines is also considerably high. In this study, drinking water and wastewater damages have been determined from the JICA-IMM (Istanbul Metropolitan Municipality) report according to peak ground velocity (PGV) (Figure 4) for the expected Istanbul earthquake (Table 2).

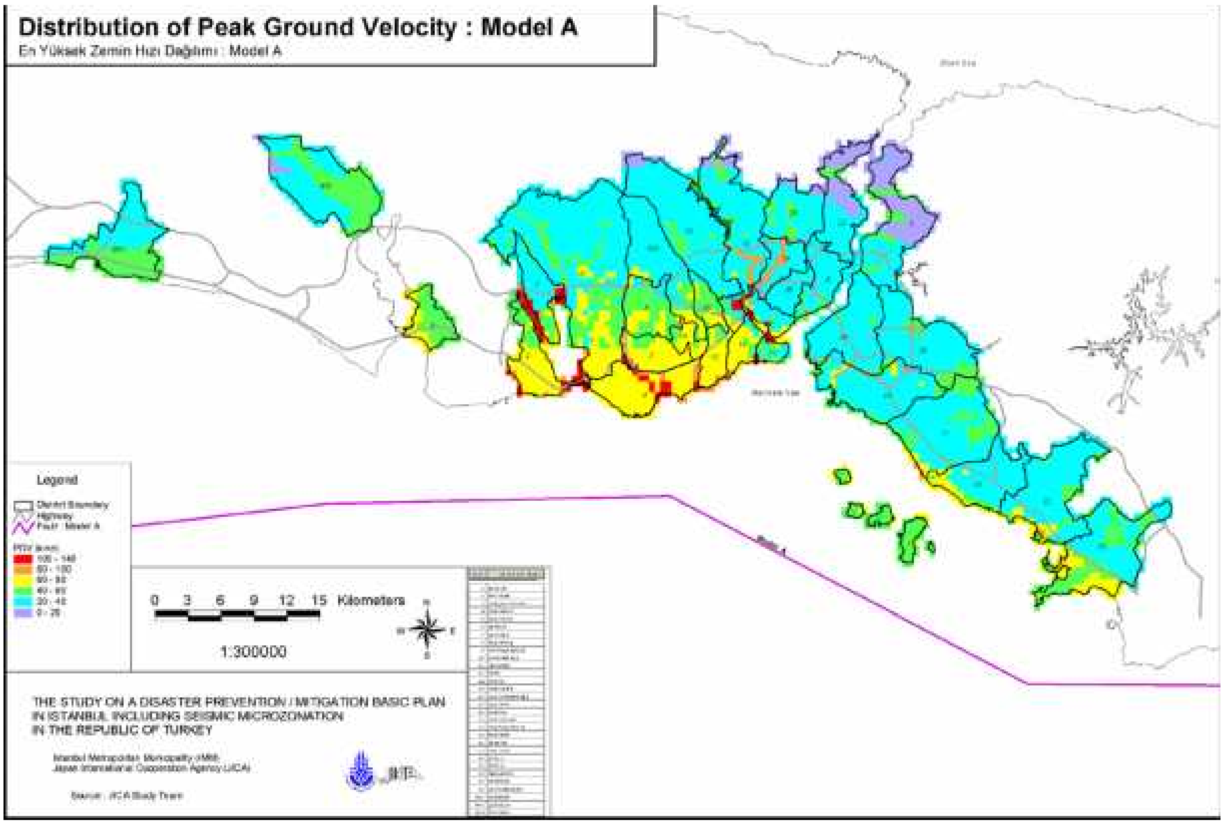

Figure 4. Peak Ground Velocity Values in a Probable Istanbul Earthquake

Table 2. Drinking Water and Wastewater Pipeline Damages in Some Districts of Istanbul after a Probable Earthquake

Code No.	District Name	Length of Pipeline for Drinking Water (km)	Number of Damages	Length of Pipeline for Wastewater (km)	Number of Damages
2	Avcılar	59	20	229	85
3	Bahçelievler	321	107	422	152

4	**Bakırköy**	**207**	**98**	**183**	**93**
5	Bağcılar	391	87	474	121
6	Beykoz	189	16	318	20
7	Beyoğlu	220	46	271	48
8	Beşiktaş	234	24	286	28
17	Kadıköy	527	71	613	87
18	Kartal	394	62	398	71
19	Kağıthane	264	21	28	57
20	**Küçükçekmece**	**523**	**130**	**525**	**152**
21	Maltepe	352	48	402	63
22	Pendik	432	59	245	44
23	Sarıyer	276	13	307	12
26	Şişli	247	15	261	17
28	Tuzla	138	29	145	44
29	Ümraniye	293	14	343	21
30	Üsküdar	471	32	463	36
32	Zeytinburnu	180	66	-	-
33	Esenler	205	31	-	-

Küçükçekmece and Bakırköy are the top districts in terms of highest likely drinking water and wastewater pipeline damages.

ESTIMATION OF EARTHQUAKE DAMAGE PROBABILITY ON DRINKING WATER AND WASTEWATER PIPELINES IN THE DISTRICT OF KÜÇÜKCEKMECE

Distribution of infrastructure systems within the boundaries of the district of Küçükçekmece, according to pipeline diameter, has been provided in the table below as a percentage distribution (Table 3).

Table 3. Distribution of infrastructure systems in the district of Küçükçekmece according to pipeline diameters.

PIPE DIAMETER	WASTEWATER	RAINWATER	DRINKING WATER
< 90 mm	-----	-----	-----
100-175 mm	-----	-----	% 79
200-450 mm	% 88	% 41	% 14
> 500 mm	% 12	% 59	% 7

Amounts of damage are listed in Table 4, by taking into consideration the distribution of underground pipes according to peak ground velocity (PVG) and the distribution of pipe diameters used in infrastructure systems in the district of Küçükçekmece.

Table 4. Distribution of infrastructure damages according to pipeline diameters in the district of Küçükçekmece.

INFRASTRUCTURE TYPE	**R(PGV)**	**Pipe Type**	**Pipe Diameter (mm)**	**Number of damages**
DRINKING WATER	20	Concrete Pipe and	100-175	42 / 316

		Galvanized Iron Pipe	200-450	6 / 45
			> 500	2 / 13
		Steel Pipe and Ductile Iron Pipe	100-175	16 / 95
			200-450	2 / 14
			> 500	1 / 4
		Polyetylene Pipe	100-175	5 / 32
			200-450	1 / 5
			> 500	0 / 1
	120	Concrete Pipe and Galvanized Iron Pipe	100-175	2224 / 16683
			200-450	319 / 2393
			> 500	90 / 673
		Steel Pipe and Ductile Iron Pipe	100-175	670 / 5006
			200-450	96 / 718
			> 500	27 / 202
		Polyetylene Pipe	100-175	221 / 1670
			200-450	32 / 240
			> 500	9 / 67
WASTEWATER	20	Concrete Pipe and Galvanized Iron Pipe	200-450	37 / 279
			> 500	3 / 24
		Steel Pipe and Ductile Iron Pipe	200-450	14 / 84
			> 500	1 / 7
		Polyetylene Pipe	200-450	5 / 28
			> 500	1 / 3
	120	Polyetylene Pipe	200-450	1962 / 14722
			> 500	169 / 1267
		Concrete Pipe and Galvanized Iron Pipe	200-450	591 / 4418
			> 500	51 / 380
		Polyetylene Pipe	200-450	195 / 1474
			> 500	17 / 127

Highest damage is observed in concrete or galvanized iron pipes (Table 4). Less damage is observed in steel pipes and ductile font pipes, and lowest damage is inflicted on polyethylene pipes.

Pipeline diameters between 100 and 200mm increase damage ratio by 25%, and pipeline diameters less than 100mm increase damage ratio by 100% for drinking water pipelines.

Since wastewater and storm water pipelines typically have diameters more than or equal to 300mm, damage ratios have been calculated according to these diameter values. However, damage is higher in wastewater pipelines as compared to storm water pipelines, since their diameters mostly are approximately 300mm. This is because, as storm water flow rate is considerably higher than wastewater and since pipes used in storm water lines have diameters larger than 500mm, damage ratios are lower as compared to wastewater pipes.

Research shows that PE pipes, such as water and natural gas pipes, have better performance against earthquake forces compared to other pipe materials. Therefore, it is recommended that flexible pipelines such as polyethylene and reinforced plastic pipelines be used in earthquake zones. On the other hand, as cement materials with asbestos are brittle and weak against displacements and earthquake forces, pipes manufactured from such materials should be avoided in earthquake zones.

CONCLUSIONS

1- It is possible to calculate earthquake damage probability in pipelines using the calculation methods provided above, taking into consideration soil conditions and peak ground velocity. This evaluation and calculation method has also been adopted in the Istanbul Earthquake Master Plan. It would be possible to determine the damage probability after an earthquake using a regional modeling based on this calculation.
2- According to the above formula, amount of damage increases in zones with peak ground velocity and liquefaction potential. Type of pipeline used also has a very large effect on the damage ratio. Less damage ratio is observed in plastic pipes such as PVC, GRP and Polyethylene, used extensively in water pipes when compared with concrete and steel pipes.
3- Concrete pipes with asbestos or concrete font pipes used in wastewater sewage systems can easily get broken and the resulting leaks can contaminate the groundwater. On the other hand, it has been observed that concrete pipelines with asbestos (AC) are damaged 4 times higher than CI (cast iron) pipelines during earthquakes. Therefore, especially types of pipes that are fragile and which could get damaged at an earthquake should not be utilized in an earthquake-prone area.
4- It has also been observed that the diameter of a pipeline also has a significant effect on infrastructure damages. Therefore, since pipe placement, type and density of filling material and construction workmanship become more important as pipe diameter gets lower, more attention should be given to small-diameter pipes.
4- Regardless of the value of the above mentioned damage ratio, pipeline systems (especially drinking water systems, which operate with pressure, and storm water and wastewater systems which have free water surface flow) will not be operational as a result of damage on a single point.

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