Seismic Retrofitting Water and Wastewater Facilities in Metropolis

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SUMMARY:
Earthquakes damage pipeline systems in various ways, having significant consequences on the cities and their associated populations. Today, pipeline systems are used widely as most countries are industrially modernized; hence it is essential to improve the pipeline systems in fault areas. Displacements found at fault sites during an earthquake tend to change the intensity and type of the earthquake, create unpredicted loads, alter forces and tensions in water and water waste systems. Fault's displacement is one of malicious phenomenon on pipeline systems which many studies have been done in this area in recent years. Large deformations caused by failure slopes, earthquake, fault displacement and floating pipes in shallow trenches have caused major damages in buried pipeline network. Subsequently, Manhole's protrusion is mostly observed in sewage collection lines after the "KOBE" earthquake in various places in Japan. Also, after California's earthquakes, drinking water facilities including those of water treatment plants and major pipelines of transmission and distribution of water had fractures due to permanent damage of the ground. In this article, the current status of water treatment plants, drinking water, and waste water in Tehran (capital of Iran) will be described. Furthermore, the amount of vulnerability of water treatment plants, drinking water, and waste water along with its needed preventive maintenance, improvement, and retrofitting status post-earthquakes will be discussed below.

Keywords: Tehran metropolis – Retrofitting – Earthquake – Water and Wastewater Facilities

1. INTRODUCTION

Iran and its capital Tehran are located in one of the most earthquake-prone regions of the world; hence having increased risk of earthquakes so large that destructive shivers have been witnessed in the past recent years. In addition, although the expansion of old towns and creation of new towns status post destruction using modern technologies have improved the level of living, it has also propagated the number of earthquakes with the same old power to mass loss of human lives, urban services, and facilities of the cities. As a result, using methods such as those of retrofitting by human experiences can assist and reduce the damages and mortalities to the least and secure the lifelines.
In general, water and water waste systems consist of two major segments including transmission system and water treatment plant. Transmission systems are known for being the most important segment of all sewage systems, but simultaneously it is the most vulnerable segment of sewage systems in seismic zones. Transmission systems are mainly comprised of three components including pipelines, pumping stations, and manholes; which according to the results and experiences from the earthquakes of 1999 in Turkey (Izmir), 1994 Northridge-Los Angeles (compressing rupture and dehiscence of the pipes junction in network distribution), 1995 in Kobe(Japan), and 1999 in Taiwan can conclude that earthquake causes major damage to pumping stations, and its other main foundation, the power outage for pumping stations, as witnessed in previous earthquakes to be power outage for pumping stations. As a result, retrofitting the pipelines systems can greatly reduce the damages on water and water-waste systems in case of earthquakes. In this article, with regard to the status of water treatment plant and drinking water facilities and general classification of the factors affecting sewage damages, vulnerability level and seismic immunizing strategies of them during an earthquake will be studied and introduced using results of proposed method by Shakib-Bayat (2000).

2. TEHRAN WATER NETWORK

2.1. Water Resources, Water Treatment Plants, Raw Water Transfer

According to data released by the Information center of Tehran province water and sewage organization, important segments of Tehran water and sewage network are water resources (Table2.1), water treatment plants (Table2.2), and raw water transfer (Table2.3) are listed as:

Table 2.1. Water resources of Tehran Metropolis:

Water resources	Taleghan Dam	Latyan Dam	Lar Dam	Karaj Dam	Deep Well
Supply ration	%70				% 30 - 1172 ring
Design acceleration	%15g	%15g	%25g	%12g	____________

Table 2.2. Water Treatment Plants in Tehran and their Vulnerability:

Treatment plant name	Year of operation	Source of water supply	Diameter of water transmission pipe	Type of water transmission pipe	Length	Earthquake risk
Jalalieh	1955	Karaj river	1000 mm	Steel	40Km	Hazardous
Kan	1963-1970	Taleghan Dam	2000 mm	Concrete	33Km	
Tehran pars	1967	Latian Dam	2700 mm	Concrete	10Km	
Tehran pars	1984	Latian Dam	2700 mm	Concrete	10Km	
Sohanak	2004	Lar Dam	3600 mm	Concrete	40Km	

Table 2.3. Raw Water transfer Pipelines in Tehran:

Type of facility	Length (Km)	Dimension (m)
Channel	8	2.1 × 64.1
Tunnel	28	D=2.7
Steel pipe	73	D=1
Concrete pipe	67	D=2

2.2. Water Distribution Network

The water distribution network of cities in Tehran Metropolis has length of 14983 Km and diameter range of 80-800 Mm which the pipes of this network are made of steel, concrete, ductile iron, asbestos and polyethylene.

2.3. Connections

Generally, flexible mechanical connector bolts such as Johnson Couplings (in case of steel pipes), and Tyton joints(in case of ductile iron pipes) are used in transmission lines and water distribution networks in order to joint pipes together or install the valves and accessories.

2.4. Wastewater Treatment

Table 2.4. Wastewater Treatment Plants in Tehran

Treatment plant's name	Year of operation	Pipe material	Diameter(mm)	Length(km)
Sahebgheranieh	1955	Asbestos cement	200~150	5.3
Mahallati	1999	Asbestos	400 ~ 200	76.17
Zargandeh	1987	Asbestos cement	400 ~ 200	23
Gheitarieh	1986	Asbestos cement - Cement	400 ~ 200	2.18
Shahre ghods	1995	Asbestos-P.V.C-Concrete	1200 ~ 150	198
Ekbatan	1984	Asbestos	1000 ~ 250	29
Dolat Abad	2002	Asbestos-Concrete	500 ~ 150	32
Shoosh	1982	Concrete-P.V.C	400 ~ 160	42

2.5. The Origin of Earthquake Faults

Generally, Tehran metropolis is mostly developed by accumulated alluvial layers on the hard rock. Study range is composed of 22 regions (Figure 2.1) and Tehran major faults (Figure 2.2).

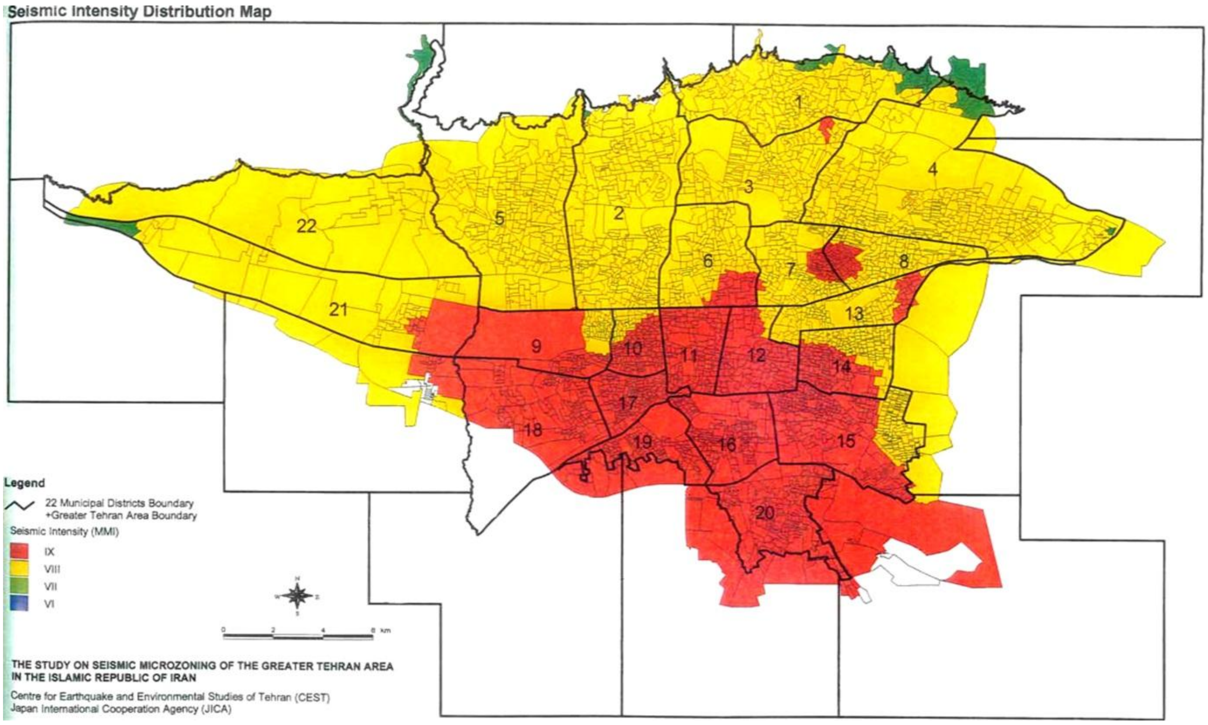

Figure 2.1. Seismic micro zonation map of 22 regions

2.5.1. North and south ray faults (length about 20km)
The last Seismic event related to these faults happened back in year 855 and it has not had any significant seismic activity in the last 1000 years. Seismic activity of these faults will cause major and serious damages and destructions.

2.5.2. North Tehran fault (length about 90km)
Damages caused by seismic activity of this fault would be lower than Ray fault.

2.5.3. Masha fault (length about 200km)
This fault has repeatedly activated number of times, and the largest historical earthquake due to this

Fault was occurred in 958 with magnitude of 7.7 Mw, and the last one is accrued in 1830.

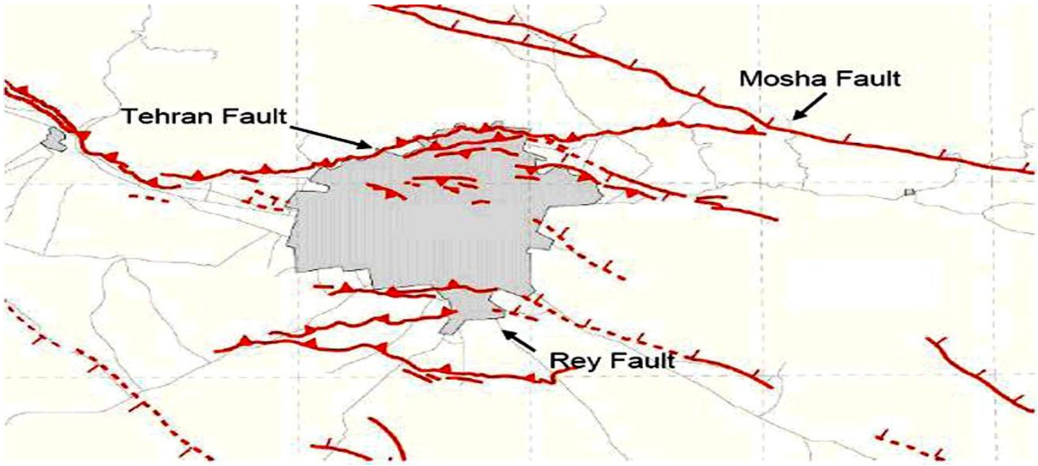

Figure 2.2. Tehran Major faults.

3. GENERAL CLASSIFICATION OF WATER NETWORK LOSSES CAUSED BY EARTHQUAKE

Since the buried pipes arrange as an extensive network of pipes in the ground, there are several factors that can threaten the safety of the pipelines, and the most damages to the sewage network have been caused by ground vibration and rupture which are divided into two categories:

3.1. Damages Due to Wave Propagation

When ground vibrates due to seismic wave propagation, the soil engages in various deformations leading pipes to start resisting creating a force which result an axial tension and in some regions appears as a deflection. Such damages caused by seismic wave propagation include but are not limited to volumetric surficial waves which can cause greater loss in wide range areas. Moreover, the rate of vibrations effective to the pipelines is expressible by peak ground velocity (PGV) and peak ground acceleration (PGA).

3.2. Damages Resulting From Permanent Deformation of the Earth

Deformations resulting from uneven movements of the earth are most important factors which threaten the pipelines and it appears after an earthquake. In addition to the vibration which is the simplest consequence of an earthquake, some factors arise due to heterogeneous deformation of earth that induces for essential deformation and destruction of pipelines and water and wastewater facilities. Such factors include:

3.2.1. Faulting

Nearly 25% of facilities failures, especially pipes, are due to dangers caused by faulting.

3.2.2. Landslide

Land-sliding causes deformations and lots of various damages to water and wastewater facilities. Landslide generally includes rock falling, creep, surficial slides, translational and rotational or deep movements. Rates of the slides are expressible in terms of permanent ground deformation (PGD).

3.2.3. Liquefaction

Liquefaction propagates for deformations on the grounds that encompass side deployments, fluid

Failures, reproduction decline, subsidence, and floating and condensation. In addition to the fact that liquefaction is one of the major effective consequences and damages to the manholes, it also causes to arising the buried objects such as pipelines.

4. PIPE FAILURES

Generally, source of damage or failures of pipes arise from the following: 1) Deformations, high axial, shear and bending stresses in the pipe due to a change in the waveform and phase difference in various parts of the pipe. 2) Displacements and high stresses in the pipes due to fault movement during an earthquake, or creating a surficial cut in an interrupted state of the fault by the pipeline. 3) Displacements and increased stresses due to soil slipping below the pipe caused by liquefaction during an earthquake. 4) Deformation and high stresses caused by dissimilar substrate of the pipes (mostly in sticky saturated substrates). 5) Appearing tensions and increased deformations at the junction of adjacent structures. 6) Corrosion and rusting of pipes in many past earthquakes such as 1999 in Taiwan (Chichi), 50% of broken pipes had been weakened by corrosion before the earthquake due to reduction of cross-section.

5. ESTIMATE THE VULNERABILITY OF TEHRAN WATER NETWORK

Based on historical earthquake data, Tehran has experienced several intensive earthquakes by returning periods of 150 years as explained above secondary to its logistic vulnerabilities. Therefore the probability of a strong earthquake in near future is very high in this city. Because Tehran hasn't experienced any disastrous earthquake since 1830, according to the Japanese International Cooperation Agency (JICA), the greatest amount of damage caused by an earthquake in Tehran is due to Ray fault activity. Moreover, Corrosion phenomenon is the most important factor that increases vulnerability of distribution networks against the vibrating waves, and dangers arising by an earthquake. Since all the main pipes in Tehran water and water-waste networks are mostly made of cast-iron and about 40 years of their lifetime is passed, an erosion rate is slightly about 24%, which nearly ¼ of entered water to Tehran is wasted through leaks. By repairing, retrofitting, in some cases replacing these pipelines, and by using flexible joints in water lines and distribution networks, the stresses and slight displacements caused by an earthquake can be depreciated and reduced. Tehran water and wastewater facilities were mostly investigated and calculated based on external and internal pressures and withstand static leads, and unfortunately seismic calculations have not been calculated yet. Also, there has not been any special consideration in order to ensure the quality of these facilities and their intersection zone with faults. Especially, by passing buried Karaj Dam water pipes through the Tehran Fault, the network is very vulnerable and there is high possibility of rupturing pipes Tehran water shortage. The first issue followed by water shortage is fire. Due to the cut in water pipes in 1972 earthquake in Managua (Nicaragua), rescuers were forced to pump the water from the nearby lake, but Tehran metropolis is not capable of using the same solution. In order to solve this issue, perhaps digging numerous deep-wells and creating large reservoirs to store the water in empty lands of the city adjacent to the highways can be helpful.

According to the proposed terms of Katayama and Kobo (1975), between the peak ground acceleration and (PGA) loss compared water distribution pipelines (Figure 5.1), Katayama and Kobo (1981) proposed the following terms (Eqn. 5.1.) and (Eqn. 5.2.) :

$$Rfm = Rf \times Cg \times Cp \times Cd \qquad (5.1)$$

$$Rf = 1.7 \times A^{6.1} \times 10\mathrm{e}-16 \quad \text{if} \quad Rf \geq 2 \qquad (5.2)$$

Rfm= damage ratio ($\frac{points}{km}$)

Cp = pipe formed factor & Cd = pipe diameter factor

Cg = Ground factor (0.1 for alluvial deposits and 0.5 for foothills areas)

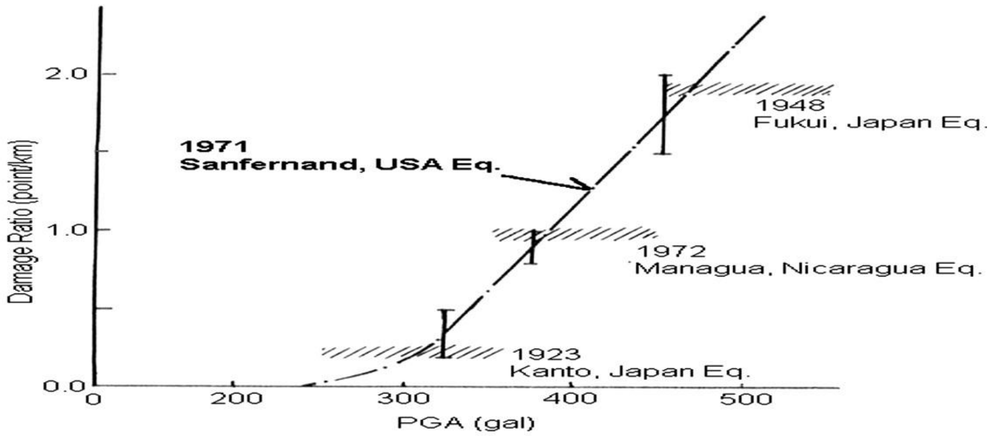

Figure 5.1. PGA-Damage ratio

The above formula was used for this study and the value for Cg equal to 0.5, Cp & Cd were assumed equal to 1. According to an earthquake resulting from seismic activities of Ray Fault, about 4100 points in 8520 Km of Tehran water network would get damaged, and dispersion of 86% of the points would be in southern areas.
Seismic profile and summary of parameters' results which are effective in water and sewage failure in Tehran after calculating is provided in the table below:

Table 5.1. Seismic profile and effective parameters in water and sewage pipes failure in 22 regions in Tehran

Municipal Region	PGA (g)	PGV($Cm/_s$)	PGD (in)	Probability of liquefaction (%)	Length of the initial lines (km)
1	0.05	4.55	0.00	0.00	373.20
2	0.05	4.55	0.00	0.00	635.60
3	0.35	31.85	2.70	0.21	335.70
4	0.05	4.55	0.00	0.00	800.80
5	0.05	4.55	0.00	0.00	516.40
6	0.35	31.85	2.70	0.21	299.00
7	0.35	31.85	2.70	0.21	436.70
8	0.35	31.85	2.70	0.21	494.20
9	0.35	31.85	2.70	0.21	199.60
10	0.50	45.50	7.20	0.55	392.30
11	0.50	45.50	7.20	0.85	320.90
12	0.50	45.50	12.26	2.13	279.10
13	0.35	31.85	2.70	0.21	343.70
14	0.40	36.40	4.20	0.50	531.50
15	0.50	45.50	12.26	2.92	721.40
16	0.50	45.50	12.26	2.92	348.70
17	0.50	45.50	12.26	1.81	331.50
18	0.50	45.50	12.26	1.38	344.40
19	0.50	45.50	12.26	2.13	239.10
20	0.50	45.50	12.26	2.92	362.80
21	0.35	31.85	5.20	1.06	145.20
22	0.05	45.50	0.00	0.00	65.00

Waste collection and disposal system was only constructed some in areas of Tehran and it has not had any larger extension yet, but it is on process of getting developed and extended. According to the final report, studies, and evaluations regarding seismic micro zoning, zone 17 has the highest seismic and

Vulnerable risk. Right after an earthquake, 57% of current water and water-waste facilities would be Operable which this percentage should get increased by improving and developing the network performance according to its main role in reducing the damages caused by an earthquake. The ground conditions in northern areas of the Tehran metropolis are better than its southern part, but Tehran is still vulnerable against an earthquake. The absence of standards and regulations for designing the critical arteries, not having enough specialists and technicians in field of seismic critical arteries engineering, lack of resources and scientific documents, lack of information on geological and tectonics, lack of information on soil status, and high defects in facility network maps are other factors that increase the issues of Tehran metropolis water and water-waste.

6. PROPOSED APPROACH ON SEISMIC DESIGN OF BURIED PIPES AND WATER, WASTEWATER IMPROVEMENTS AND RETROFIT FACILITIES (SHAKIB – BAYAT) APPROACH

Estimating maximum loads and stresses values created by the service load should be first consideration in designing underground utilities as it has been used in designing other structures. Next, a suitable type of pipe with standard stability will be provided. According to the proposed approach of Shakib-Bayat (2000), which can be a turning point towards the direction of obtaining seismic regulations of buried pipelines in the country of Iran, modified methods of strain and stresses over buried pipes caused by vibration of an earthquake are expressed. Estimated stresses (Axial, Flexural &Total) from the earthquake can be efficiently added to the stresses increased from other loads. In this article, important features of this approach will be discussed:

6.1. Upper Limit of the Axial Strain

Acknowledgement of total slip between the pipe and surrounding soil for the ground's large strains, the pipe's strain (Eqns. 5.1.1, 5.1.2, 5.1.3) will act independently to the adjacent soil strain, which in this phenomenon, high levels of strain such as slip are compared and limited.

$$\boldsymbol{\varepsilon_a} = A.C_a \frac{S_v}{V_p} \cos\left(\frac{\pi H_d}{2H}\right) \leq \boldsymbol{\varepsilon_{max}} \quad (6.1)$$

ε_a =Pipe pivotal strain due to vibration, ε_{max} = Max pivotal strain of pipeline, H_d = Buried depth, A = Seismic factor, C_a = Coefficient of axial strain direction, S_v =Velocity spectrum of earthquake design, V_p = Velocity propagation in Axial wave, H = Hard bed layer depth.

$$\boldsymbol{\varepsilon_{max}} = \frac{T_u.L_e}{E_p.A_p} \quad (6.2)$$

T_u = Slip friction resistance, L_e = Effective length of pipeline, E_p = Modulus of elasticity of pipe material, A_p =Sectional area of pipe.

$$\boldsymbol{L_e} = L \leq \frac{L_p}{4} \quad (6.3)$$

L =Pipeline length, L_p =Pipeline length

6.2. Velocity of Axial Wave Propagation

According to what has been mentioned in this approach, due to the dilative characteristics of an axial wave (P), axial stresses mostly are created by effect of (P) waves, and flexural stresses get created because of lateral motion made by the shear wave (S). Therefore, in this approach characteristics of longitudinal flexural wave are used for flexural stresses (σ_b), and characteristics of shear wave of (S)

Are used for flexural stresses. These terms are also modified on applied reduction factors (Eqns. 6.4, 6.5, 6.6, 6.7):

$$\varepsilon_b = A.C_b \frac{D_a}{(2V_s)^2} \cos\left(\frac{\pi H_d}{2H}\right) \quad (6.4)$$

ε_b = Bending strain due to vibration, C_b = Coefficient of lateral direction strain, D_a = Pipe diameter(external) , V_s = Velocity propagation in shear wave.

$$\sigma_a = E_p \,.\, \varepsilon_a \quad (6.5)$$

σ_a = Axial stress due to vibration , E_p = Modulus of elasticity of pipe material , ε_a =Pipe pivotal strain due to vibration , σ_b = Bending stress due to vibration .

$$\sigma_b = E_p \,.\, \varepsilon_b \quad (6.6)$$

$$V_p = V_S \sqrt{\frac{2(1-\upsilon)}{(1-2\upsilon)}} \quad (6.7)$$

υ = Poisson ratio of soil

6.3. Pipe Ductility

In this method, in addition to reducing stresses with increasing ductility of pipelines phenomenon, ductility of the pipeline itself is also considered, so the stress (σ) value lowers by increasing the diameter (D) to thickness (t) ratio (Eqn. 6.8):

$$\downarrow \sigma = \frac{D}{t} \uparrow \quad (6.8)$$

6.4. Pipeline Length to Wave Length Ratio

Reducing the flexural stress (σ_b) with regard to reduction of pipe length (L) to wave length (L_p or L_s) ratio (Eqn. 6.9):

$$\downarrow \sigma_b = \downarrow \frac{L}{Lp \text{ or } Ls} \quad (6.9)$$

6.5. Flexibility of Connections

In this approach, in addition to the properties such as pipe's relative stiffness (K_p), surrounding stiffness (K_s) , wavelength effluent and pipe Length between continuous connectors, the connection stiffness (K_j) is also considered to reduce the flexural stresses (σ_b) and axial stresses (σ_a) because of having flexible connections.

6.6. Seismicity Conditions of Iran

In this method, the factor used for various seismic hazard zones for Iran is as follows:

Table 6.6. Seismic Factor Defined in the Proposed Approach Shakib-Bayat

Seismicity risk	Low	Medium	High	Too high
Seismic factor (A)	0.08	0.10	0.13	0.16

7. SUGGESTIONS FOR REDUCING VULNERABILITY AND SEISMIC RETROFITTING OF WATER AND SEWAGE PIPELINES

7.1. Using New Types of Pipes

In that few years, the usage of new types of pipes such as mild steel, various types of thermoplastic, manufacturing a variety from GRP pipes and other new types of products is common. More recently, different ways are being utilized for reinforcement. For example, wire grids (mesh), non-uniform distribution of filaments wired with glass fibers, or plastic fibers are reinforced in an attempt to produce and use at different types of pipes. Using this type of methodology and non-traditional material has expanded the need to perform various tests and practical experience. Although preliminary experiments indicate good appearance, high strength and other physical properties, it still is not a substantial and quick way to respond to their performance or durability after a long time and under the practical operation, hence one should not quickly offer reliable judgment with doing a few simple tests. New products that have been used in parts of water and wastewater project in Tehran have become outstandingly reliable over time and achieved positive and hopeful results.

Moreover, another effective method for raising the strength of the pipes is increasing pipe wall thickness. For instance, if the pipe entails more plasticity, it will be less in risk of vulnerability for damage. In addition, using flexible connections is one of the most effective methods to increase the seismic resistance of pipelines. Since pipeline diameter (D) changes due to stress concentration, increases the vulnerability of pipe, in such instances pipe strain (ε_C) shouldn't exceed (2~5) %. In addition, to prevent localized wall loss due to pressing form the surrounding soil, pipe strain (ε_C) should be limited to the following (Eqn. 7.1):

$$\varepsilon_C = \frac{t}{2D} \tag{7.1}$$

D = Pipe diameter, t = Pipe wall thickness

Stresses caused by the earthquake in the pipelines can be reduced by the following: increasing the damping of soil-pipe system, using suitable filler material for trench, perfect platform selection and increased use of damping coatings such as bituminous or plastic.

In addition, using shorter pipeline segments, along with bends and longitudinally in terms of design are all important factors for decreasing the vulnerability of these pipes to damage in the setting of earthquakes. For this case desire length (Lc) can be calculated equal (Eqn.7.2):

$$L_c = \frac{3R}{4\lambda} \quad \rightarrow \quad \lambda = \left(\frac{K_0}{4EI}\right)^{0.25} \tag{7.2}$$

EI = Pipe stiffness, K_0 = Bed reaction ratio, L_c = Desired length

Furthermore, the specific weight of pipe and its contents should not be less than the specific weight of soil to prevent the risk of tuck. It is essential to note that the risk of pipe failure in pipelines junction to structure and other side facilities is high, and to reduce vulnerability it is necessary the connection segment used has a high handling capacity. For example, pipeline placement on a dike that made of

Resistance soil (fine grained, low viscosity, low density).

Moreover, angle through the facilities from the fault location should be chosen against the possible movement of the fault such that the type of arising stress will bear tension its greatest minimum. Pipe diameter at fault location that does not exceed from 50cm up to pipeline should be able to follow easily from substrate moving.

Therefore, as described above, it is better that at fault location the pipeline is directly and away from curvature and limit the use of joints, flanges and similar constraints as much as possible, and finally the distance at two sides of the fault should be at least 60(m) to 200 (m).

Finally, to prevent local yielding body of pipe at fault location, burial depth (Hd) to pipe diameter (D) ratio $\left(\frac{Hd}{D}\right)$ should equal to (1.5~3.5) and pipe diameter (D) to wall thickness (t) ratio should be $75<\left(\frac{D}{t}\right)<130$.

ACKNOWLEDGMENT

Today, Tehran metropolis has been developing quickly and without a proper system to prevent disasters caused by possible earthquakes. It is significant to acknowledge that industrialized countries such as Europe and America have utilized the above mentioned systematic planning’s as part of their major water and wastewater facilities and networks, hence leading to absence of serious earthquake after math damages in these countries. By using such upmost equipment in accordance with the appropriate seismic standards mentioned they have worked towards excellence in terms of preventing negative complications and improved their systematic ways. Although, this does not indicate that these facilities are complete weakness, control and accuracy of its performance, overcome partial or total weak points. From this we can conclude that by using the important modalities such as retrofitting, upgrading, seismic proper design of facilities that can reduce the possible severe damages caused by the earthquake in Tehran.

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