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EVALUATION OF WATER DISTRIBUTION PIPELINE PERFORMANCE AGAINST EARTHQUAKES

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ABSTRACT

In the last century several moderate to strong earthquakes caused substantial damage to buried pipeline systems in urban areas. The damage data were very valuable and useful to develop pipeline damage relationships which can be used for estimating potential pipelines damage from future earthquakes in seismic hazard studies. However, characteristics and limits of the pipeline damage relationships should be identified clearly before applying them in different countries. Material composition and joint characteristics of water supply networks in various countries differ significantly. Some examples from Turkey, Japan, USA, and Taiwan water distribution systems are provided in this study. Regarding pipeline damage relationships, there is a certain need for a shift from the use of the general "ductile or brittle" pipe concept to the use of "real" pipe type and joint. This study also presents the results of physical loss estimations for drinking water distribution system in Denizli, Turkey (a mid-size city) during future **M**6.5 earthquakes caused by two different fault ruptures (Pamukkale and Karakova-Akhan Faults). Both transient ground deformations (TGD) and permanent ground deformations (PGD) from liquefaction induced lateral spreads were used to predict pipeline damage. Physical loss estimation analyses were performed by using Geographical Information Systems (GIS).

Keywords: GIS, lifelines, loss estimations, pipeline damage, risk assessment, seismic hazards

INTRODUCTION

Many cities around the world were caught by destructive earthquakes without any seismic planning and preparation. For example, the devastating 1999 **M**7.4 Kocaeli and **M**7.2 Duzce, Turkey earthquakes, caused substantial water supply damage in many cities and the water service could not be restored until many months after the earthquake. Table 1 summarizes pipeline performance at some locations during the 1999 Kocaeli and Duzce earthquakes. It took almost 3 to 6 months to restore water to its original levels at these locations. Asbestos cement (AC) pipelines, which are considered as brittle pipe, were the dominant pipe type in the water distribution systems in the earthquake hit areas. The level of seismic damage in urban areas around the world proved once more the importance of risk reduction and mitigation studies for the pipeline systems. The physical loss estimation analyses are important part of risk reduction and mitigation studies. Pipeline damage relationships are used for estimating potential pipelines damage from future earthquakes in seismic hazard studies. As a result of substantial damage data obtained from recent moderate to strong earthquakes in various countries, significant progress has been made on the improvement of pipeline damage relationships in the last decade. Dealing with data coming from different water distribution networks in various countries, however one should exercise great care for understanding the characteristics and source of the damage

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relationships in use. The comparisons of water distribution networks in various countries herein show that pipe compositions (including joint types) in the water distribution networks differ significantly from country to country. The history and development of water supply systems in urban areas of Turkey was investigated and compared with water supply systems of cities in other countries.

This study represents also the first time that such a comprehensive loss estimation study is performed for a water supply system in Turkey. Both transient ground deformation (TGD) and permanent ground deformation (PGD) damage on water pipelines were considered. Pipeline damage estimations for Denizli City were calculated by using various damage relationships and earthquake scenarios. The post-earthquake performance of the water pipeline system was evaluated and various mitigation strategies were suggested. In the process, maps of liquefiable areas and zones of predicted lateral displacements in Denizli were prepared.

Table 1. Pipeline performance at some locations during the 1999 Kocaeli and Duzce earthquakes

Location	Earthquake	Water Distribution Network Information	Damage	Source
Adapazari (population was about 184,000)	1999 Kocaeli	Over 500 km of trunk and distribution lines (primarily AC with relatively small lengths of steel pipeline)	70 % of the pipeline were damaged with some leakage detected in the remaining 30 % [Entire pipeline system was replaced with primarily HDPE (high density poly ethylene) piping, and some welded steel and AC pipes]	O'Rourke et al. (2000)
Gölcük (population was about 76,500)	1999 Kocaeli	120 km of polyvinyl chloride (PVC), steel, High Density Polyethylene (HDPE) and AC	45 % of the system was destroyed with other another 25 % damaged	O'Rourke et al. (2000)
Sapanca (population was about 17,000)	1999 Kocaeli	About 90 km of almost entirely AC pipes	400 damages have been recorded after the earthquake (replaced damages with PVC pipes)	Sarıkaya and Koyuncu (1999)
Duzce (population was about 76,000)	1999 Kocaeli and Duzce	About 780 km of PVC, Cast iron (CI), and AC pipes	About 500 to 800 repairs (Time-line analysis of pipeline repair data following the Kocaeli and Duzce earthquakes was used to earthquake-related pipe repairs. Interpretation of pipeline damage caused by the Duzce earthquake is obscured by the effects of the earlier Kocaeli Earthquake)	Tromans, et al. (2004)

COMPOSITION CHARACTERISTICS OF THE WATER DISTRIBUTION NETWORKS IN DIFFERENT COUNTRIES

Development history of water distribution systems in Turkey

In Turkey, primarily municipalities are owners of the water distribution networks in urban areas and they control and sell water to the consumers. However, the Bank of Provinces (Iller Bankasi) in Turkey had historically great influence in establishment of water distribution networks in urban areas. The Bank of Provinces is an affiliated institution of the Turkish Ministry of Public Works and Settlement. The Bank of Provinces was first established under the name of "Municipalities Bank" in 1933 and later in 1945 it was renamed with its current name (Iller Bankasi, 2006). With the restructuring, its authority and responsibility expanded from municipalities to villages and provincial administrations. Its major function was to provide financial and technical assistance to local authorities for settlement development besides banking operations. Among others its main duties included to carry out technical works, to develop projects for urban developments such as water distribution networks, and to implement the projects for the infrastructural investments on behalf of the local governments. A new law in 1968 limited the water related services of the Bank of Provinces to urban areas with populations between 3,000 and 100,000. However, regulations changed later in 1983 which allowed the Bank of Provinces to cover Municipalities having a population less than 3,000 and cities with a population higher than 100,000 if their Municipality Committees give the authorization. According to the Bank of Provinces statistics, the total amount of pipelines placed in Turkey by its support between the years 1969 and 2005 was about 175,000 km.

Municipalities have Water Works departments who deal with daily operations of their water distribution systems. Some of these departments, especially in metropolitan municipalities (populations greater than 750,000) have relatively big independent budget, hence they can plan and organize large investments to their systems (e.g., ISKI for Istanbul). Others mostly depend on the technical and financial support of the Bank of Provinces. Hence, the policies of the Bank of Provinces have direct impact on the composition of water distribution networks in small and mid-size cities. One such policy was the use of primarily AC pipes in water supply systems until about mid 1990s. Hence, many water supply systems including the systems at the earthquake regions were built using primarily AC pipe material. In recent years, however use of polyvinyl chloride (PVC) pipes (especially for diameters between 100-200 mm) was increased in the distribution systems.

Composition characteristics of the water distribution pipelines

Figure 1 shows the distribution of pipe materials in the water supply system of 5 cities in Turkey. Except for Denizli water supply system information which is described in this paper, information about the composition of water distribution systems in the cities was obtained directly from respective municipalities through written communications. The statistics represent the current situation of the networks in the respective cities. Istanbul water distribution system is remarkably different than others as ductile iron (DI) is the principal pipe material used in the system. Also high proportion of PVC pipes in other distribution systems is clearly noticeable. Discussions with experts from the Bank of Provinces indicated that composition of Denizli water distribution system is more representative of other mid-size cities in Turkey.

Figures 2, 3 and 4 show typical installations for PVC pipelines in Turkey. Figure 2 shows the materials and process used in repair of a PVC water distribution pipe. Figure 3 shows the installation of a new PVC pipe branch to an existing pipeline by using cast iron T-fitting. Figure 4 shows a new service connection to the existing PVC pipeline. These joints and connections represent the weak localities in the pipeline network.

Figures 5a and 5b show the composition of water distribution pipelines with respect to pipe materials in the water supply system of some cities in Japan (data from Scawthorn, 2006 and Eidinger, 1998), USA (data from Toprak, 1998), and Taiwan (data from Shih and Chang, 2006). Majority of the pipelines in Japan were ductile iron whereas the majority in Los Angeles, USA were cast iron. PVC pipe material were dominant in Taiwan water distribution system. The second prominent pipe type is ductile iron. It should be noted that the data from all three countries were obtained for water distribution systems at localities which experienced strong ground motion by a large earthquake.

Figure 6 shows some typical joint types in Japan water distribution systems. These joints were primarily used in pipelines greater than 300 mm in diameter (Eidinger, 1998). Types “S” and “S-II” joints are special earthquake resistant joints whereas type K is a mechanical joint. Type “S” joints have 2-4 cm of flexibility (500-2600 mm diameter) and type “S-II” joints have 5-7 cm of flexibility (100-450 mm diameter). Type “S” were used until 1980 and type “S-II” were used since 1980. During the 1995 Kobe earthquake, the performance of type “S” joints was average whereas performance of type “S-II” joints was very well. Type K joints didn’t performed well.

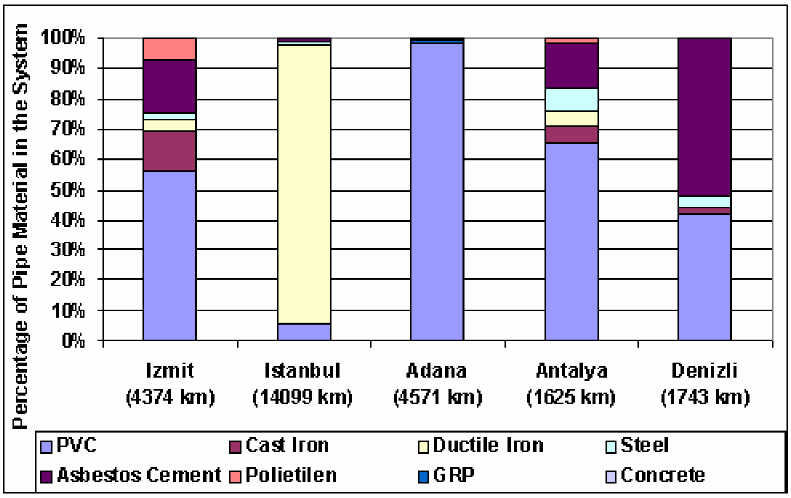
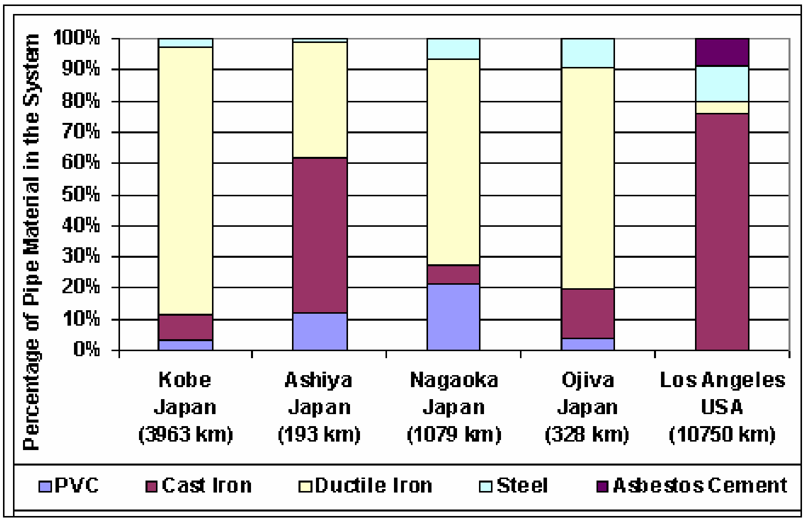


Figure 1. Composition of water distribution systems in selected cities of Turkey (modified from Toprak, et al., 2006)

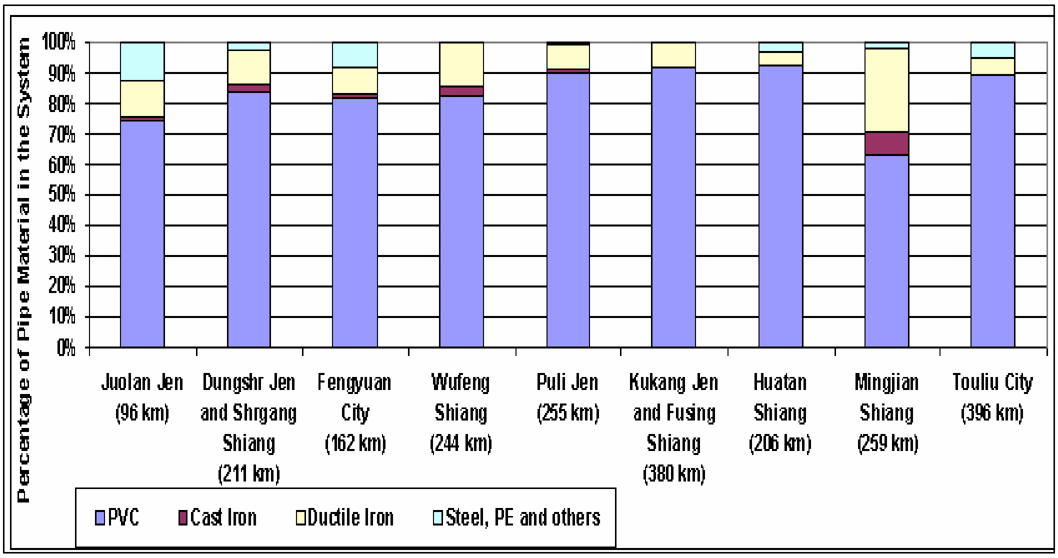
Figure 2. Repair of a PVC water distribution pipe with a PVC fitting

Figure 3. PVC pipe branch installation with a cast iron T-fitting

Figure 4. A new service connection to an existing PVC distribution pipe

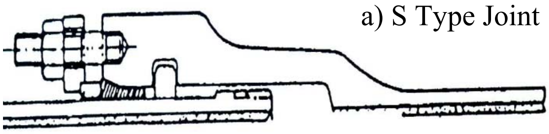


(a) Japan and USA

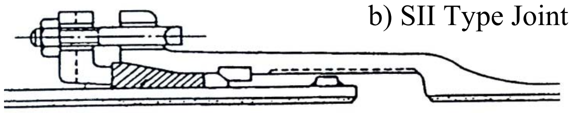


(b) Taiwan

Figure 5. Composition of water distribution systems in different countries



a) S Type Joint



b) SII Type Joint

c) SII and K Type Joints

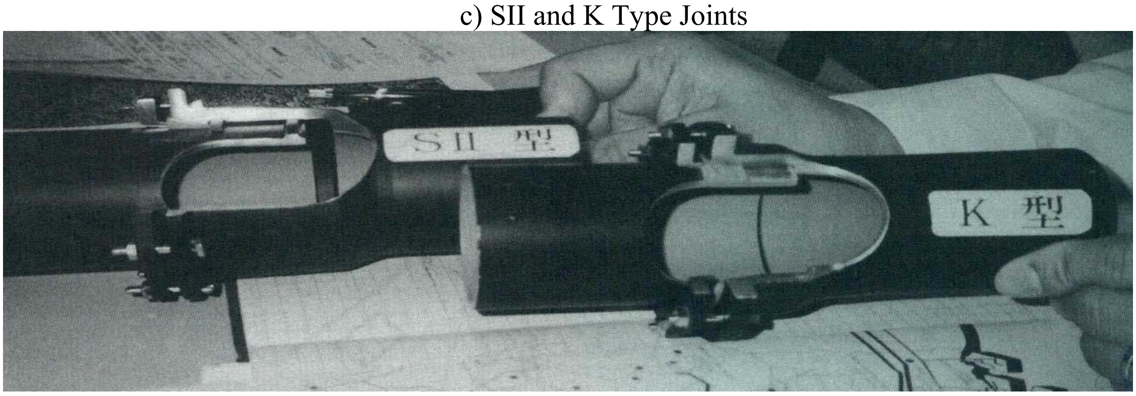


Figure 6. Typical joint types in Japan water distribution systems (from Eidinger, 1998)

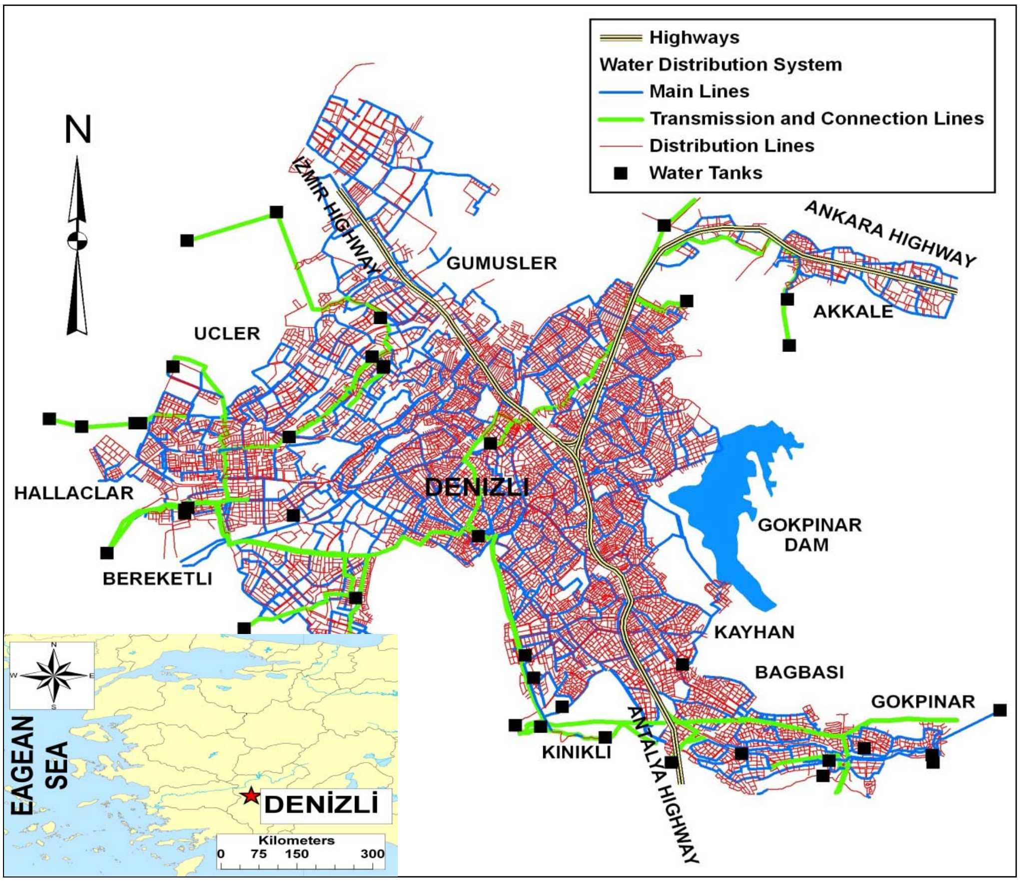


Figure 7. Map of Denizli City water supply system (modified from Toprak, et al., 2006)

PREDICTION OF PIPELINE DAMAGES IN THE CITY OF DENIZLI

Water supply system of Denizli

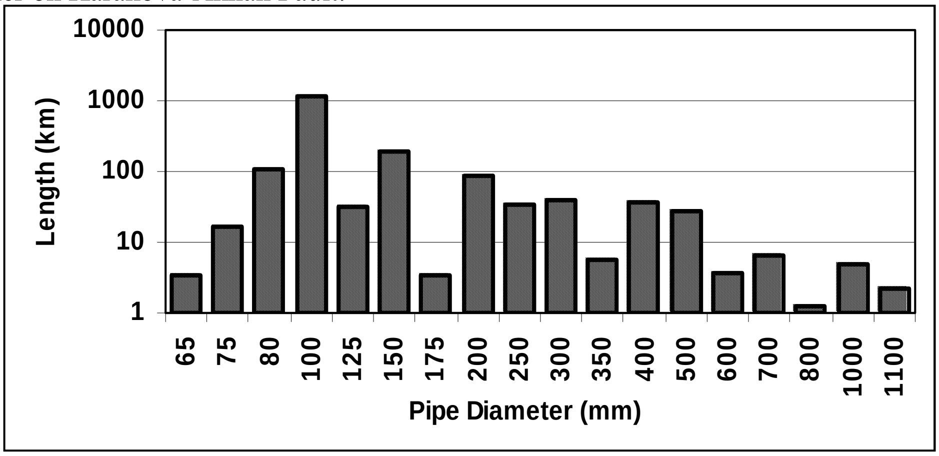
Water is supplied to Denizli from 5 main sources (approximate capacities are given in parenthesis): Derindere spring (250 litre/sec), Gokpinar spring (700 litre/sec), Kozlupinar spring (70 litre/sec), Benlipinar spring (20 litre/sec), and many wells (400 litre/sec). The high capacity springs are located outside to the southeast of the water service area whereas the low capacity springs are located within the water service area in Denizli. The wells are distributed within and outside of the water service area. Water from these sources is collected at water storage tanks, treated and released to the distribution system. General Denizli area is under the jurisdiction of eleven municipalities, some of which share the water brought from the same source. Municipalities manage the water distribution system within their boundaries and sell water to residential and business customers. Denizli Municipality is the largest municipality in Denizli city in terms of population and service area. Because of suitable topography of the area, the water distribution system relies on gravity flow. There are seven main pressure zones in the system which is divided into 28 subzones. Following the topography of the area, these zones generally coincides with the service areas of water tanks. The distribution system is designed so that the zones are independent of each other. As a result, the damage can be contained in a particular zone.

Fig. 7 shows the map of the water distribution pipelines of all municipalities in Denizli City. Also shown in the figure are transmission pipelines which bring water from the sources to the city, connection lines which connect one water storage tank to another, main lines which transfer water from tanks to distribution lines and the locations of water storage tanks. The GIS database of the water supply system and its details is provided in Toprak and Taskin (2006), only the salient features of the system will be provided herein.

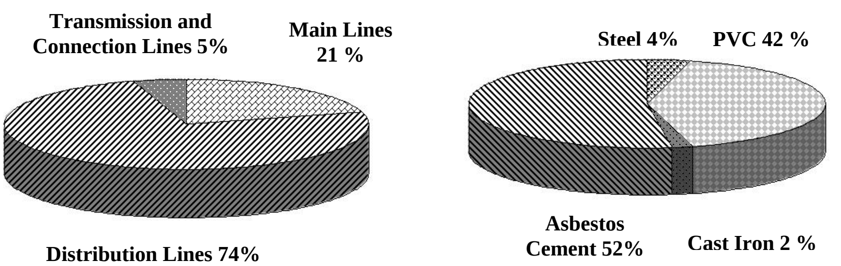
Fig. 8 presents charts that show the relative lengths of pipelines in the water supply system with respect to pipe diameter and composition. It should be noted that the vertical scale in Fig. 8a is logarithmic scale. The figures were developed using the GIS database. The total length of pipelines about 1745 km about 95% of the transmission and connection lines are made of steel pipelines. The main and distribution lines are made of AC, CI, and polyvinyl chloride (PVC). About 54 and 44 % of them are made of AC and PVC, respectively. The distribution lines consist of pipelines with diameters between 65-200 mm whereas the main lines consist of pipelines with diameters between 100-600 mm. The CI pipelines are the oldest pipelines in the system. They primarily serve to the old parts of Denizli which include important local business districts with high population density. In recent years, Water Works of municipalities adopted a policy of switching from AC pipes to PVC pipes in new placements as well as replacements. Therefore, PVC pipelines are the newest pipelines in the system.

Prediction of pipeline damages from TGD and PGD effects

Pipeline damage commonly expressed as repair rate, which is the number of pipeline repairs in an area divided by the length of the pipelines in the same area. Following the current practice, this study uses the damage relationship between pipeline damage and peak horizontal ground velocity (PGV) for TGD effects (Toprak, 1998; O'Rourke et al., 1998) and the relationship between pipeline damage and amount of ground movement or deformation for PGD effects. Comprehensive treatment of TGD effects on Denizli water supply system can be found in Toprak and Taskin (2006) whereas comparison of relative effects of TGD and PGD on Denizli water supply system can be found in Toprak et al. (2006). The study herein presents only the salient features of damage predictions from two different **M**6.5 magnitude scenario earthquakes caused by two different fault ruptures, one on Pamukkale Fault and the other on Karakova-Akhan Fault.



a) Length of Pipelines with Respect to Pipe Diameter



b) Relative Lengths of Pipelines with Respect to Pipe Composition

c) Relative Lengths of Pipelines with Respect to Type

Figure 8. Composition statistics of pipelines in Denizli City water supply system (from Toprak and Taskin, 2006)

Prediction of pipeline damage due to ground shaking from scenario earthquakes requires first, determination of the distribution of PGV in the study area. Fig. 9 shows the water supply system superimposed on PGV zones for Karakova-Akhan fault scenario earthquake. The analyses were performed by using GIS and Campbell attenuation relationship (e.g., Campbell, 1997). Because the faults are located to the northeast of Denizli, there is a repeated pattern of peak ground velocity oriented from the northeast to the southwest of Denizli. The repair rates corresponding to each PGV zone was determined using various pipeline damage correlations such as Toprak (1998), O'Rourke and Jeon (1999, 2000), ALA (2001), and O'Rourke and Deyoe (2004). The number of repairs then was calculated for each PGV zone by multiplying the corresponding repair rates and length of pipelines. The repairs for each PGV zone were determined for brittle (AC and CI) and ductile pipelines (steel and PVC) separately. By summing the repairs for each PGV, the total number of repairs for a particular earthquake scenario was obtained.

Regarding PGD effects, this study focused primarily on pipeline damages resulting from liquefaction induced lateral spreads. Major fault lines are located either at the border or outside the city boundaries. Furthermore, the state of current knowledge about some minor faults (activity or displacement capacity) in the city is not sufficient to include damages from surface faulting in the analyses herein. Data from various sources were evaluated and used in the liquefaction analyses in this study (e.g., PAU, 2001; 2002; 2003). Data include primarily observation digs (127 locations), standart penetration tests (SPT) (120 locations), borings without SPT (61 locations), and laboratory index tests. Ground water level information were also available at many soundings. The area consists of primarily Neogene aged sedimentary rocks and Quaternary deposits.

Liquefaction analysis were performed using the "simplified procedure" described in Youd and others (2001). The method require SPT data along with the laboratory index tests results. Only 77 of SPT soundings in Denizli could be used directly in the methodology, because of some missing information such as fines content. Peak ground acceleration at each SPT hole location were calculated using Campbell and Bozorgnia (2003) attenuation relationships. Two **M**6.5 magnitude scenario earthquakes caused by ruptures on Pamukkale and Karakova-Akhan Faults were used. Soil class of the area was reflected in the PGAs using soil amplification factors of FEMA-368 (2000). Local soil class in the selected region was considered to be between Soil Class C and D of FEMA-368 (2000). Then, factors of safety against liquefaction were computed at each hole and contours of factor of safety were drawn for Denizli area using geographical information systems (GIS). In the simplified procedure, the factor of safety is computed by dividing the liquefaction cyclic resistance ratio, which is determined from the penetration resistance, by the cyclic shear ratio produced by the earthquake. The lowest SPT value at each sounding were used to calculate factors of safety. Figures 10a and b, respectively show contours of factor safety against liquefaction for the two scenario earthquakes caused by ruptures on Pamukkale and Karakova-Akhan faults. Assuming that the areas enclosed by the contours of factor safety equal to one in Figures 10a and b correspond to the liquefiable areas, Figures 11a and b show the areas which are predicted to liquefy in Denizli as a result of the scenario earthquakes.

Liquefaction-induced lateral ground displacements cause significant disruption to pipeline systems. Several equations has been introduced in the past for the prediction of lateral spread displacements at liquefiable sites (e.g., Hamada et al., 1986; Bartlett and Youd (1995). Recently, Youd et al. (2002) revised and improved Bartlett and Youd (1995) empirical equations. They derived the equations by using the multilinear regression (MLR) of a large case history database. They introduced two equations; one for gently sloping ground conditions and the other for relatively level ground conditions with a "free face" towards which lateral displacements may occur. Because pipelines are located far away from the "free faces" and most of the sources of "free faces" such as channels are covered in the city, only the equation for gently sloping ground conditions were used to predict lateral spread displacements in this study. Lateral displacements were calculated at each SPT sounding location where liquefaction was predicted. The geotechnical parameters at each hole were determined using SPT test results and sieve analysis results on the samples taken from respective holes. The procedures described in Youd et al. (2002) were followed in the calculations. Source distance to each

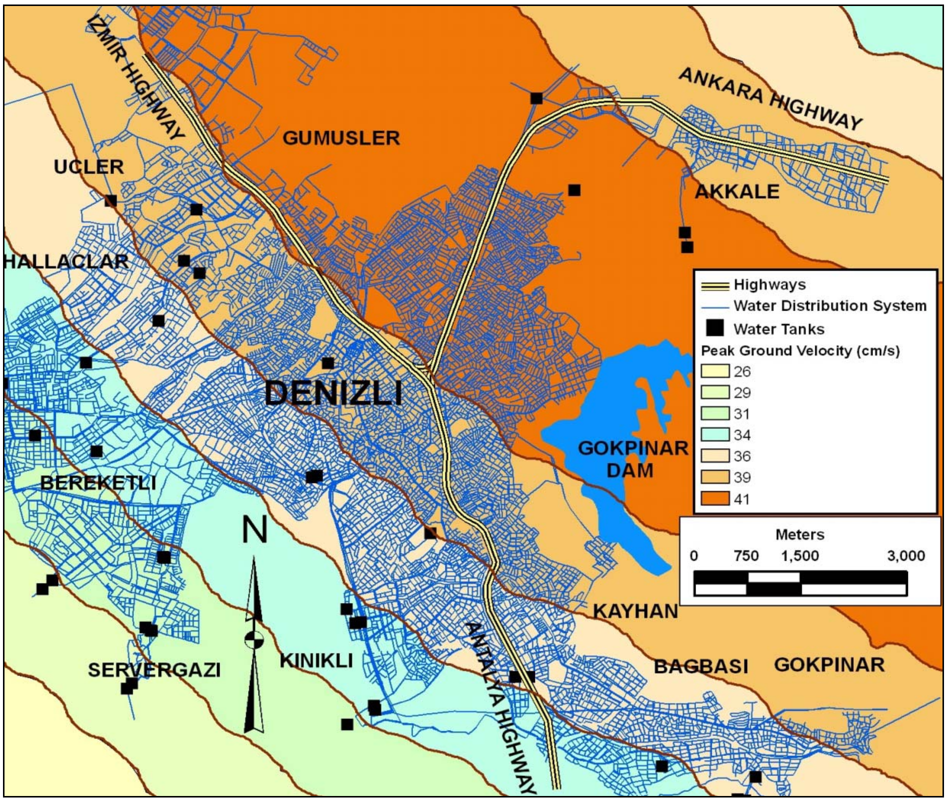
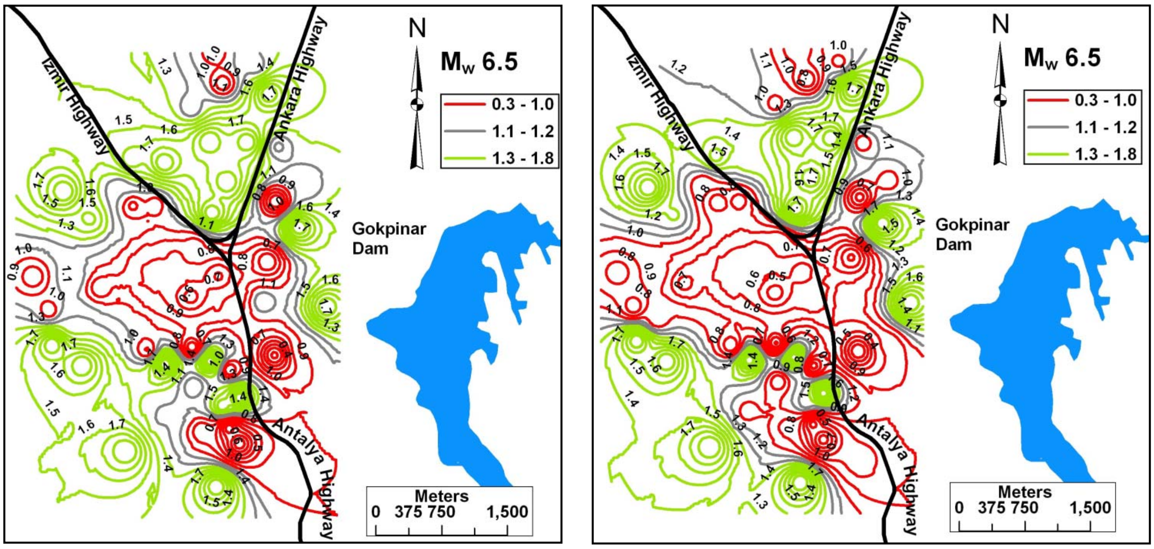


Figure 9. Water supply system superimposed on the peak ground velocity (PGV) zones from M6.5 Karakova-Akhan fault rupture scenario earthquake

SPT sounding location were determined using GIS and digital fault maps. Ground slope was determined using the digital elevation contour lines from 1/25,000 scale topographic maps which were digitized by Kumsar et al. (2004). Using the calculated lateral displacement, first contours of displacement, and after that zones of displacement were drawn in GIS as shown in Figure 12. Displacements as high as 84 cm was predicted in the study area. HAZUS (FEMA, 1999) and American Lifelines Alliance (ALA, 2001) damage relationships for PGD were used to predict the damage from lateral spread displacements in the study area.

RESULTS AND CONCLUSIONS

As a result of significant damage data obtained from recent moderate to strong earthquakes in various countries, substantial progress have been made on the improvement of pipeline damage relationships in the last decade. The developments had important ramifications for officials who work to reduce the risk from earthquakes and to prepare for emergency response and recovery from an earthquake. However, dealing with data coming from different water distribution networks in various countries, one should exercise great care for understanding the characteristics and source of the damage relationships in use. The comparisons of water distribution networks in various countries herein show that pipe compositions (including joint types) in the water distribution networks differ significantly from country to country. Combining data into two classes as “ductile or brittle” pipelines may lead to too much generalized damage relationships. Moreover, increasing awareness in reconnaissance efforts to obtain more specific information on water distribution systems and the damage may permit a shift from the use of the general “ductile or brittle” pipe concept to the use of “real” pipeline type. In order to go forward in this direction coordinated pre-earthquake and post-earthquake efforts are required. Pre-earthquake studies may involve gathering information about the existing water supply systems for the localities of interest. These studies can also be used to reduce the risk from future earthquakes. Post-earthquake studies may involve gathering reliable information for pipe diameter and



a) Pamukkale Fault b) Karakova-Akhan Fault

Figure 10. Contours of factor safety against liquefaction for M6.5 earthquake

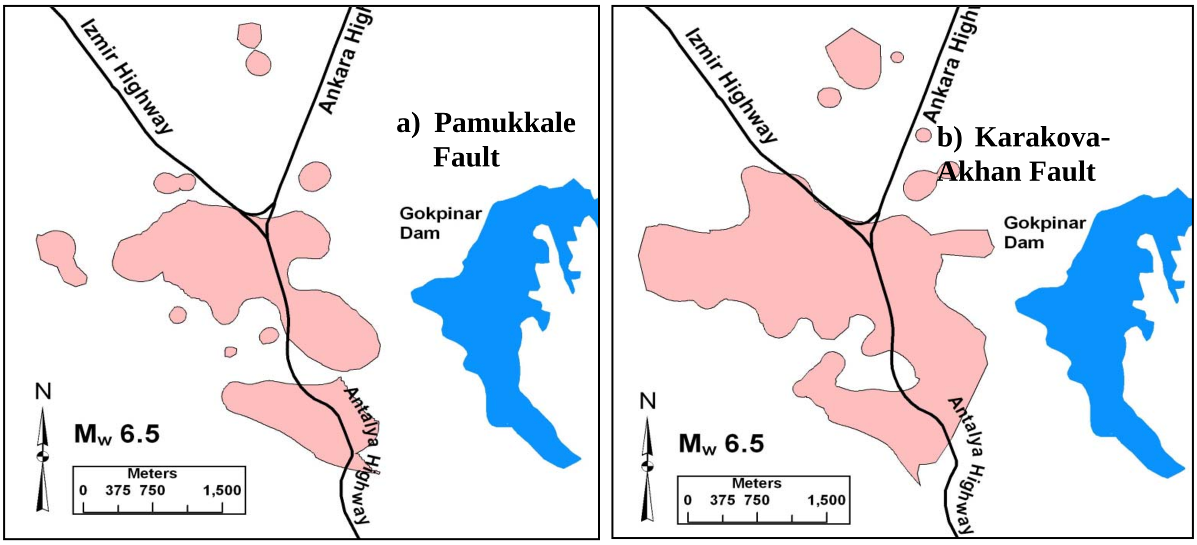


Figure 11. Predicted areas of liquefaction for M6.5 earthquake

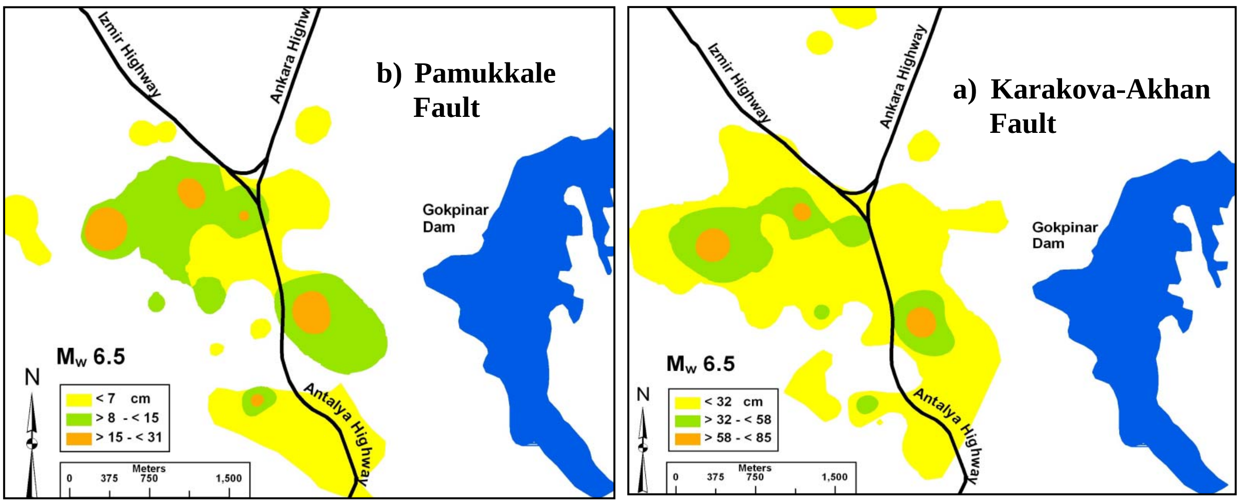


Figure 12. Predicted lateral displacements for M6.5 earthquake

composition, repair locations and type of repairs, soil conditions and strong motion. In this regard, it is important to speed up or encourage the efforts for development of databases for pipelines and strong ground motion. Local soil conditions along with seismic wave-propagation velocity should be part of the databases. Geographical information systems (GIS) are an important and useful tool to serve this purpose whether it is at input or analyses stage.

The physical loss estimation analyses results show that M6.5 earthquake may cause significant disruption to the Denizli water supply system. As a result of an earthquake on Pamukkale fault, the water system serviceability can be expected to be between 6 to 34 %. Furthermore, an earthquake on Karakova-Akhan fault can reduce the water system serviceability to a level between 3 to 6 %. To reduce this risk via mitigation and also as part of maintenance program, a replacement work has started with CI pipelines in the central part of Denizli. Different then CI pipelines, AC pipelines are widespread in Denizli. AC pipelines should be avoided especially in and around PGD zones. The high concentration of breaks and leaks in the pipelines caused by PGD can impair the functionality of fire hydrants in a wide area as well as delay the water service after the earthquake. The replacement program should be extended to AC pipelines especially in and around high PGD zones as part of mitigation planning.

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REFERENCES

American Lifelines Alliance (ALA). Seismic Fragility Formulations for Water Systems, Part 1-Guideline, www.americanlifelinesalliance.org. 2001.

Bartlett SF and Youd TL. "Empirical Prediction of Liquefaction-Induced Lateral Spread," *Geotechnical Engineering*, ASCE, 121, Issue 4, 316–329, 1995.

Campbell KW and Bozorgnia Y. "Updated Near-Source Ground-Motion (Attenuation) Relations for the Horizontal and Vertical Components of Peak Ground Acceleration and Acceleration Response Spectra," *Bulletin of Seismological Society of America*, 93, Issue 1, 314-331, 2003.

Campbell KW. "Empirical Near-Source Attenuation Relationships for Horizontal and Vertical Components of Peak Ground Acceleration, Peak Ground Velocity and Pseudo-Absolute Acceleration Response Spectra," *Seismological Research Letters*, 68, Issue 1, 154-179, 1997.

Eidinger J., "Water System", Hyogoken-Nanbu (Kobe) Earthquake of January 17, 1995, Lifeline Performance, Ed. Schiff, A. J., Technical Council on Lifeline Earthquake Engineering, Monograph No: 14, 121-181, 1998.

Federal Emergency Management Agency (FEMA), National Institute of Building Sciences. *Earthquake Loss Estimation Methodology, HAZUS 99: Technical Manual*, 1999

FEMA-368 NEHRP, *Recommended Provisions for Seismic Regulations of New Buildings and Other Structures, Part 1: Provisions*, 2000

Hamada, M., Yasuda, S., Isoyama, R., and Emoto, K., *Study on Liquefaction-Induced Permanent Ground Displacements*, Association for the Development of Earthquake Prediction, Japan, 1986

Iller Bankasi (Bank of Provinces), <http://www.ilbank.gov.tr>; 2006

Kumsar, H., Çelik, S., B. and Kaya, M., "Geological and Geotechnical Urban Infomation System for Denizli City," *JEO-KBS Conference on InformationTechnologies* , Denizli, 25-31, 2004.

O'Rourke M and Deyoe E. "Seismic Damage to Segmented Buried Pipe," *Earthquake Spectra*, 20, 1167-1183, 2004.

O'Rourke, T. D. and Jeon, S. S., "Factors Affecting The Earthquake Damage of Water Distribution Systems," Optimizing Post-Earthquake Lifeline System Reliability, Proceedings, Fifth U.S. Conference on Lifeline Earthquake Engineering, W. M. Elliott and P. McDonough, Eds., Seattle, WA, ASCE, 379-388, 1999.

O'Rourke, T. D. and Jeon, S. S., "Seismic Zonation for Lifelines and Utilities, Invited Keynote Paper on Lifelines," *Proceedings Sixth International Conference on Seismic Zonation*, Palm Springs, CA, EERI CD ROM 2000.

O'Rourke, T. D., Toprak, S. and Sano, Y., "Factors Affecting Water Supply Damage Caused by the Northridge Earthquake," *Proceedings of the 6th US National Conference on Earthquake Engineering*, Seattle, WA, USA, 1-12, 1998.

O'Rourke TD, Erdogan FH, Savage WU, Lund LV and Tang A. "Section 5 (Lifelines)," in Supplement A to Volume 16, 1999 Kocaeli, Turkey, Earthquake Reconnaissance Report, *Earthquake Spectra*, December, 375-402, 2000.

Pamukkale University (PAU), Geology Department, Engineering Faculty, Pamukkale University, Denizli, "Geological and geotechnical properties of Gümüşler (Denizli) Municipality lands," 247p., 2003 (in Turkish).

Pamukkale University (PAU), Geology Department, Engineering Faculty, Pamukkale University, Denizli, "Geological, geotechnical, and hydrogeological properties of Denizli Municipality lands," 763p., 2002, (in Turkish).

Pamukkale University (PAU), Geology Department, Engineering Faculty, Pamukkale University, Denizli, "Geological, geotechnical, and hydrogeological properties of Bagbasi (Denizli) Municipality lands," 57p., 2001, (in Turkish).

Sarıkaya, H. Z. and Koyuncu, I., "Evalution of the Effects of Kocaeli Earthquake on Water and Wastewater Systems", Proceedings, *Proceedings of ITU-IAHS International Conference on the Kocaeli Earthquake, 17 August 1999*, A Scientific Assessment and Recommendation for Re-Building, 183-191, 1999.

Scawthorn C, Miyajima M, Ono Y, Kiyono J and Hamada M, "Lifeline Aspects of the 2004 Niigata Ken Chuetsu, Japan, Earthquake," *Earthquake Spectra*, EERI, 22, Issue S1, S89-S110, 2006.

Shih BJ and Chang CH, "Damage Survey of Water Supply Systems and Fragility Curve of PVC Water Pipelines in the Chi-Chi Taiwan Earthquake," *Natural Hazards*, 37, 71-85, 2006.

Toprak, S., "Earthquake Effects on Buried Lifeline Systems," Cornell University, Ithaca, NY, PhD Thesis,1998.

Toprak S and Taskin F. "Estimation of Earthquake Damage to Buried Pipelines Caused by Ground Shaking," *Natural Hazards*, Springer, Netherlands, 2006 (DOI 10.1007/s11069-006-0002-1)

Toprak S, Taskın F and Koc AC. "Prediction of Earthquake Damage To Water Supply System in Denizli City, Turkey," *Journal of Water Supply: Research and Technology - AQUA*, IWA Publishing, 2006 (in Review).

Tromans, I., Marlow, D. and Bommer, J., "Spatial Distribution of Pipeline Damage in Düzce Caused By the 1999 Kocaeli and Düzce Earthquakes," Paper No. 2916, 13th World Conference on Earthquake Engineering, Vancouver, Canada, August 1-6, 2004.

Youd TL, Hansen CM and Bartlett SF. "Revised Multilinear Regression Equations for Prediction of Lateral Spread Displacement," *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE, 128, 1007-1017, 2002.

Youd TL, Idriss IM, Andrus RD, Arango I, Castro G, Christian JT, Dobry R, Liam Finn WD, Harder LFJr, Hynes ME, Ishihara K, Koester JP, Liao SSC, Marcuson WFIII, Martin GR, Mitchell JK, Moriwaki Y, Power MS, Robertson PK, Seed RB and Stokoe KHII. "Liquefaction Resistance of Soils: Summary Report from the 1996 NCEER and 1998 NCEER/NSF Workshops on Evaluation of Liquefaction Resistance of Soils," *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE, 127, Issue 10, 817–833, 2001.