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SEISMIC VULNERABILITY ASSESSMENT OF DENIZLI CITY, TURKEY WATER SUPPLY SYSTEM

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SUMMARY

Immediate post-earthquake water supply system function is important for domestic use and fire suppression. In this study, the vulnerability of water supply system in Denizli city, Turkey was evaluated against future earthquakes. Denizli is an important industrial and tourism center and also one of the largest cities in the west part of Anatolia. Recent studies show that this region is expected to have an earthquake of about **M**6.3. Damage to the water supply system during such an earthquake both from the transient ground deformations (wave propagation effects) and permanent ground deformations such as soil liquefaction were assessed using HAZUS methodology. Recent research results and damage correlations obtained from the Los Angeles water supply performance during the 1994 Northridge, USA earthquake were also incorporated into the assessment. Geographic Information Systems (GIS) were used in the analyses. The post-earthquake performance of the water supply system was evaluated and various mitigation strategies were suggested.

INTRODUCTION

During the devastating 1999 **M**7.4 Kocaeli, Turkey earthquake, substantial water supply damage occurred in many cities. For example, the entire water distribution system in Adapazari was damaged. The brittle asbestos cement (AC) pipelines that were deployed throughout the city, combined with ground deformation from liquefaction and softening of alluvial sediments, resulted in widespread damage O'Rourke [1]. The water service could not be restored until many months after the earthquake. One of the most critical lessons of the earthquake is the need for seismic planning, with appropriate supplies and back up systems for emergency repair and restoration.

This paper provides a description and seismic evaluation of Denizli city water supply system. Denizli is an important industrial, tourism, and export center in the Aegean region of Turkey which extends from the

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Aegean Sea coast to the inner parts of western Anatolia. According to 2000 Census data, Denizli city has a population of 275,480 which makes it the second largest city in the Aegean region. Because Denizli is located in a seismically active region, earthquake disaster prevention and mitigation studies are very important to reduce risk from earthquakes and to prepare for emergency response and recovery from an earthquake. In recent years, liquefaction and seismic shaking maps were prepared for Denizli PAU [2]. However, no earthquake risk assessment study has been performed for infrastructures. This work is part of a larger effort to evaluate the seismic performance of structures in Denizli.

Figure 1 shows general Denizli area which is under the jurisdiction of eleven municipalities. The boundaries of municipalities are also shown in the figure. Municipalities manage the water distribution

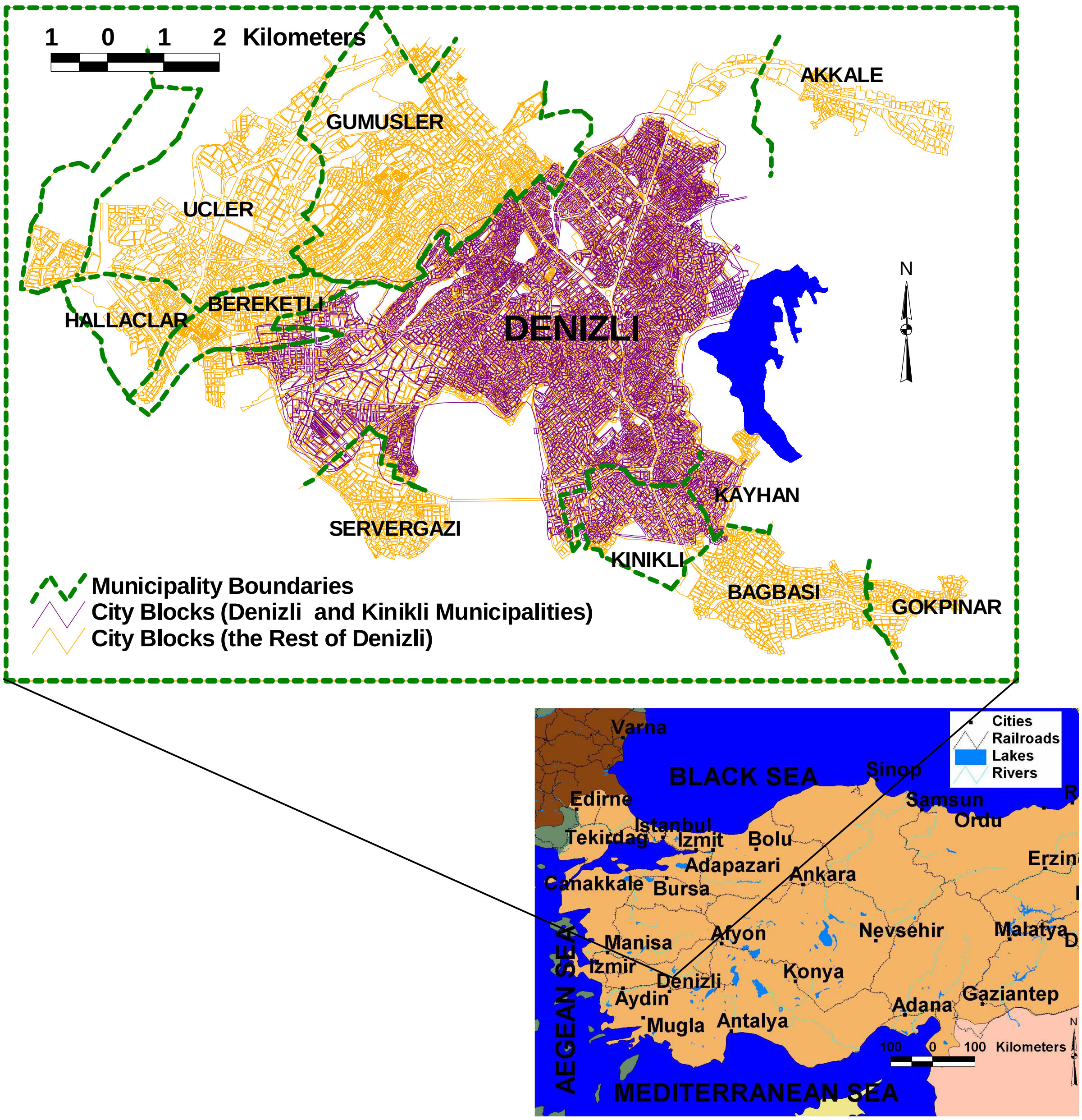


Figure 1. Denizli City and the Study Region

system within their boundaries and sell water to residential and business customers. In this paper, we concentrated primarily on the water distribution system of Denizli, which is the largest municipality in Denizli city, and of Kinikli.

SEISMICITY OF DENIZLI REGION

Denizli is located in the east of Aegean extensional province of Turkey. This North-South extensional regime has formed primarily NW-SE and E-W extending graben and horst systems bounded by normal faults. The most active grabens in the province are NW-SE extending Gediz graben and E-W extending Menderes graben (Figure 2a). The figure shows the active faults in the province. Denizli basin is situated close to the confluence of the Gediz and Menderes grabens.

Figure 2b shows historic earthquakes that occurred in the region before 1900 with their maximum intensity values and earthquakes between 1900-2004 with a magnitude greater than 5. The data are obtained from Kandilli Observatory and Earthquake Research Institute KOERI [3]. As shown in the figure, the Aegean extensional province had many historic earthquakes with intensities of IX and X. Some of these earthquakes was around Denizli and caused heavy damage and casualties. Altunel [4] summarized the historical earthquakes and their damage to Denizli and its proximity. The historical development of the ancient cities in this area was affected significantly by earthquakes. The ancient cities around Denizli, e.g. the former Roman City of Hierapolis (modern Pamukkale), and faulted archeological relics are the subject of many earthquake related research activities Hancock [5]. The most recent earthquake that caused major damage around Denizli was in Menderes graben in 1899 (Intensity IX).

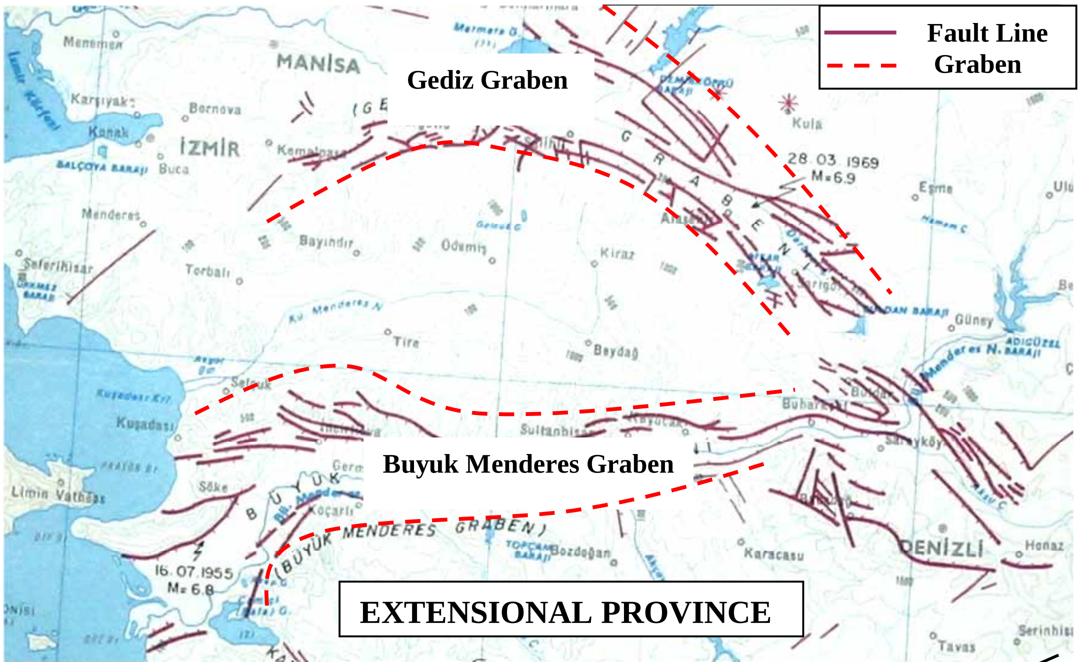
The recent earthquakes that occurred around Denizli was smaller than M6 (Figure 2b). However, many damaging earthquakes occurred in the region. During the 1965 Denizli-Honaz earthquake (**M**5.7), 14 people were killed, 217 people were injured and 488 structures were damaged. During the 1976 Denizli earthquake (**M**4.9), 4 people were killed, 28 people were injured, and 3200 structures were damaged KOERI [3], MTA [6]. The 1976 earthquake affected particularly the central part of Denizli.

Aydan [7] evaluated past earthquake data of Turkey and the crustal deformation measurements by GPS. They calculated the mean stress distribution in the western Turkey and concluded that the highest concentrations occurred in Denizli region. They estimated the magnitude of a possible earthquake in Denizli basin as **M**6.3. A recent liquefaction and shaking hazard mapping work done for the Denizli municipality used this magnitude earthquake for the scenario earthquakes PAU [2]. To be consistent and to use the results from the mentioned study, a **M**6.3 earthquake is used in the current work.

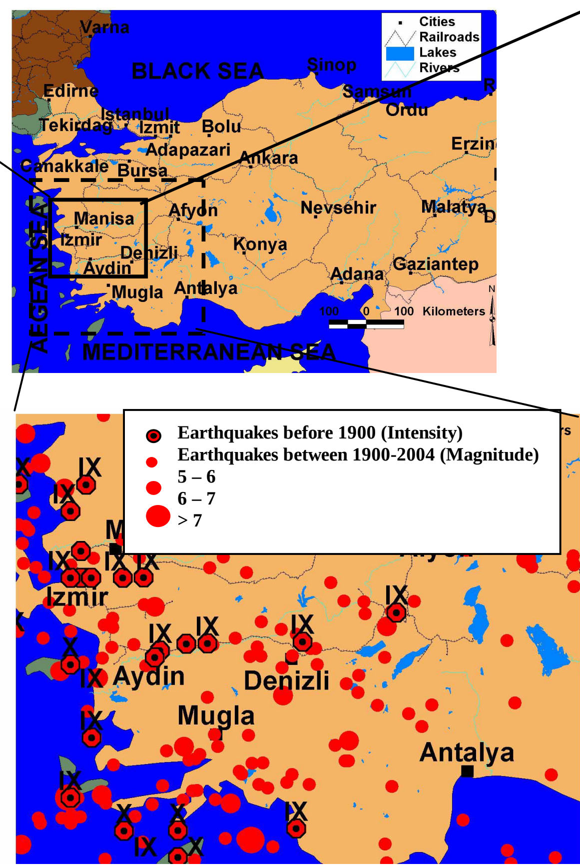
WATER SUPPLY SYSTEM

Water distribution system in Denizli was commissioned in 1953. The water supply system has been enlarged since then in proportion to the population increase from 48,925 in 1960s to 275,480 in 2000s. In order to meet the existing and future demand increase, multi million US dollars projects started in 1990s. In addition, Gokpinar Dam just next to Denizli was completed (Figure 3). Because of these investments, no water shortages are expected in near future.

Water is supplied to Denizli from 4 different sources (approximate capacities are given in parenthesis): Derindere spring (250 litre per second), Gokpinar spring (1100 litre/sec), Benlipinar spring (20 litre/sec), and many wells (400 litre/sec). The springs are located outside the service area whereas the wells are



(a) Fault Lines Around Denizli (MTA [6])



(b) Seismic Activity Around Denizli

Figure 2. Fault Lines and Past Earthquakes Around Denizli

located within and outside of the service area. Water from these sources are collected at water storage tanks, treated and released to the distribution system. Some municipalities share the water brought from the same source.

Because of suitable topography of the area, the water distribution system relies on gravity flow except for a few high elevation localities like Camlik and Yenisehir. There are seven main pressure zones in the system (Figure 3). These pressure zones are also divided into subzones, totaling 28. The subzones are shown with their identifying numbers in the figure. 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.

The water distribution system maps of overall Denizli were provided by Denizli municipality. These maps included the 1993 maps and some older maps. The 1993 maps were prepared as part of the water supply system development project for overall Denizli. The older maps show the cast iron pipelines. We also obtained many drawings and documents from Denizli Municipality Water Works which showed the placement and replacement of pipelines in Denizli up to 2003. All these data were used to prepare digital maps and database of Denizli city water distribution system. The Geographical Information System (GIS) program Arcview ESRI [8] was used primarily during the data input and analysis phases.

Figure 3 shows the map of the water distribution pipelines of Denizli and Kinikli municipalities. Also shown in the figure are transmission pipelines which bring water from the sources to the city, connection

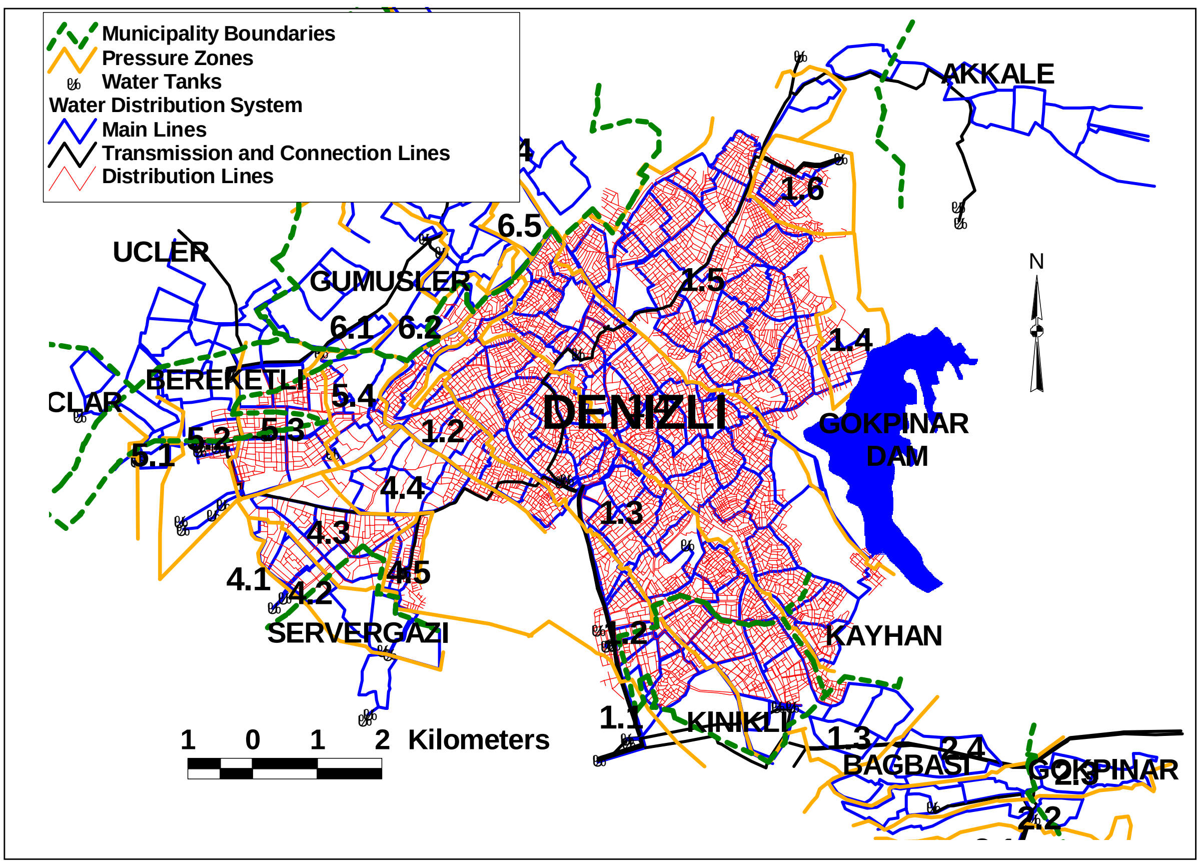
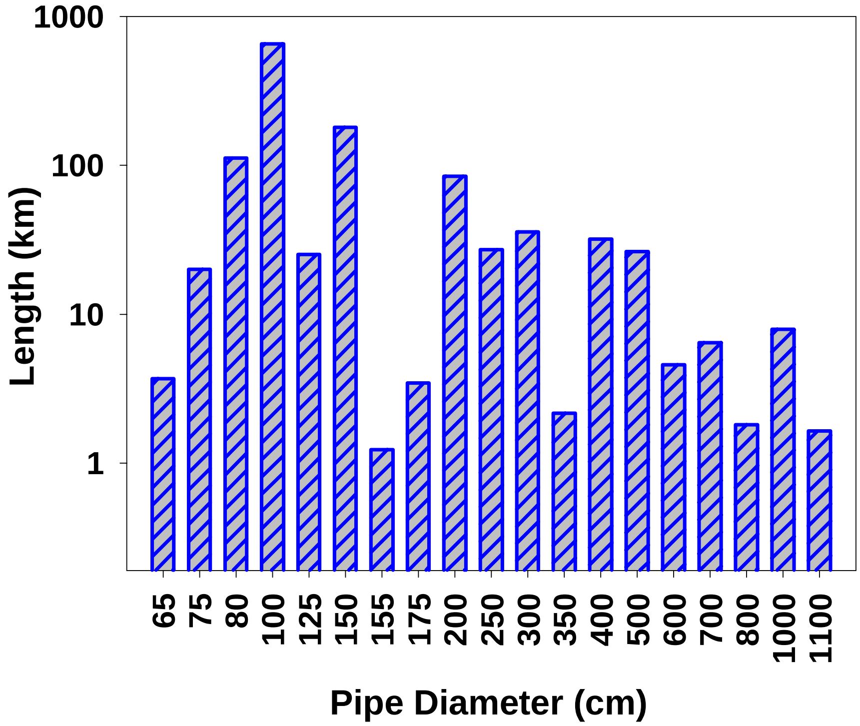


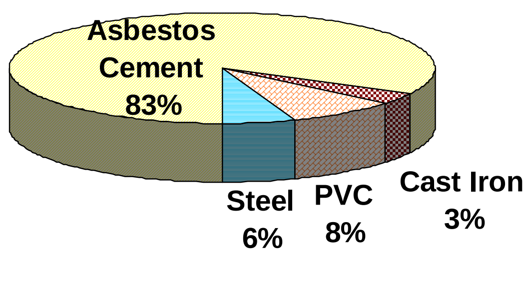
Figure. 3. Map of Denizli City Water Supply System

lines which connect one water storage tank to another, and main lines which transfer water from tanks to distribution lines. The latter lines are shown for almost all Denizli city. Also shown in the figure are the locations of water storage tanks.

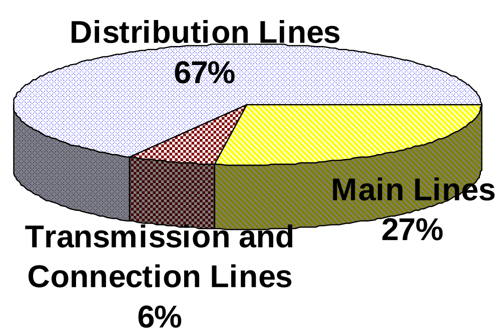
Figure 4 presents charts that show the relative lengths of pipelines in the water supply system with respect to pipe diameter and composition. It should be noted that the vertical scale in Figure 4a is logarithmic scale. The figures were developed from above mentioned maps, documents, and construction bids up to 2003. The total length of pipelines about 1232 km. The transmission and connection lines are made of steel pipelines. The main and distribution lines are made of asbestos cement (AC), cast iron (CI), and polyvinyl chloride (PVC). About 90% of them are made of asbestos cement. The cast iron (CI) pipelines



(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. 4. Composition Statistics of Pipelines in the Water Supply System

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.

PHYSICAL LOSS ESTIMATION FOR PIPELINES

Background

Earthquake damage to buried pipelines can be attributed to transient ground deformation (TGD) or to permanent ground deformation (PGD) or both. TGD occurs as a result of seismic waves. PGD occurs as a result of surface faulting, liquefaction, landslides, and differential settlement from consolidation of cohesionless soil. The relative magnitudes of TGD and PGD determine which one will have predominant influence on pipeline response. TGD generally induces much smaller levels of pipeline strain and deformation than PGD. Nevertheless, TGD covers a broader area than PGD.

Existing pipeline damage correlations with seismic parameters such as peak ground acceleration (PGA) and peak ground velocity (PGV) are primarily empirical and obtained from past earthquakes. An overview of damage correlations can be found in Toprak [9]. The recent correlations obtained from the 1994 Northridge earthquake improved the state of damage correlations significantly because of the largest databases ever assembled in U.S. of spatially distributed transient and permanent ground displacements in conjunction with damage to water supply and transportation lifelines O'Rourke [10]. The 1994 Northridge earthquake caused the most extensive damage to a US water supply system since the 1906 San Francisco earthquake. Three major transmission systems, which provide over three-quarters of the water for the City of Los Angeles, were disrupted. Los Angeles Department of Water and Power (LADWP) and Metropolitan Water District (MWD) trunk lines (nominal pipe diameter ≥ 600 mm) were damaged at 74 locations, and the LADWP distribution pipeline (nominal pipe diameter < 600 mm) system was repaired at 1013 locations. The earthquake-induced damage to water pipelines and the database developed to characterize this damage have been described by O'Rourke [11], and only the resulting damage correlations of this work are summarized herein.

The records from 241 Northridge earthquake strong motion instruments at free field rock and soil stations were examined and the data from 164 corrected records were used to evaluate the patterns of pipeline damage with the spatial distribution of various seismic parameters. Figure 5 shows the cast iron (CI) pipeline repair rate (number of repairs divided by the length of the pipelines in the same area) contours superimposed on peak ground velocity (PGV) zones, which were developed by interpolating the larger of the two horizontal components associated with each of 164 corrected motion sites. Using the GIS database, a pipeline repair rate was calculated for each PGV zone, and correlations were made between the repair rate and average PGV for each zone. As explained by Toprak [9], similar correlations were investigated for pipeline damage relative to spatially distributed peak ground acceleration, spectral acceleration and velocity, Arias Intensity, Modified Mercalli Intensity (MMI), and other indices of between repair rate and measures of seismic intensity. The most statistically significant correlations were found for PGV. By correlating damage with various seismic parameters, regressions were developed both distribution and trunk line repair rates. Such correlations are important for loss estimation analyses that are employed to assess the potential damage during future earthquake and develop corrective measures and emergency response procedures to reduce the projected losses (e.g., Whitman [12]).

Figure 6a presents the linear regression that was developed between CI pipeline repair rates and maximum PGV on the basis of data from the Northridge and other U.S. earthquakes. The PGV parameter, however,

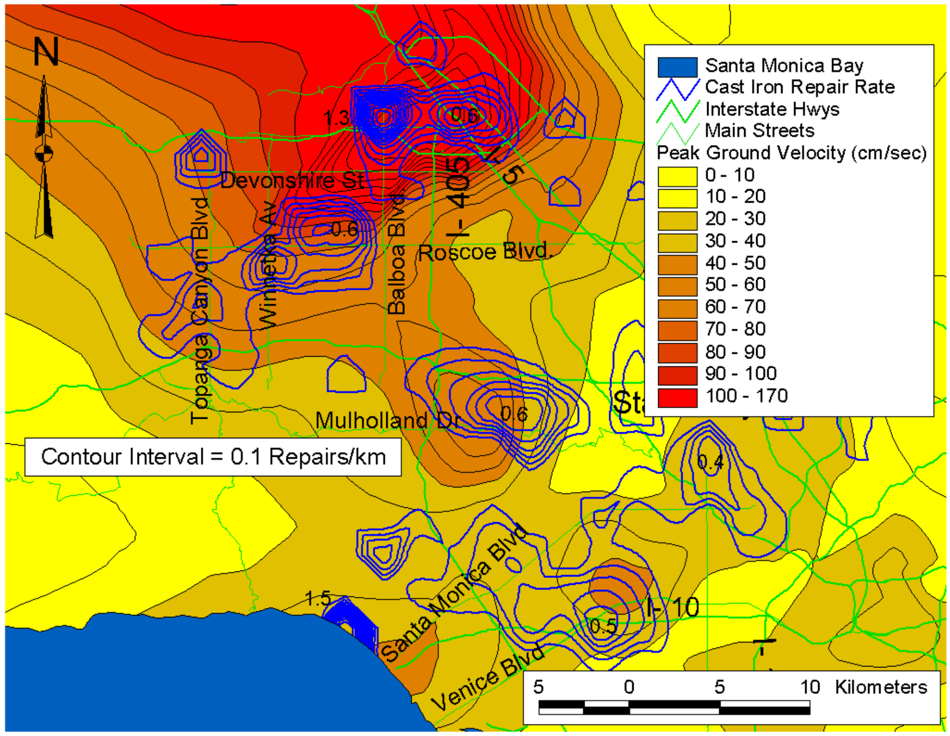
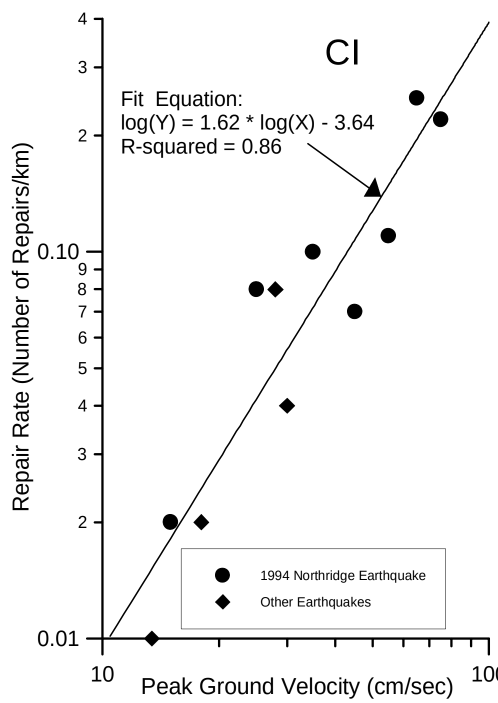
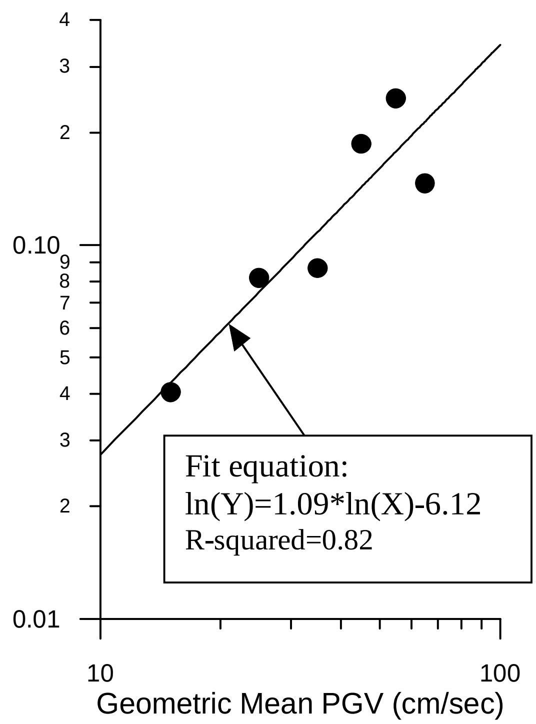


Figure 5. Pipeline Repair Rate Contours Relative to Northridge Earthquake Peak Ground Velocity O'Rourke [10]



(a) Maximum



(b) Geometric Mean

Figure 6. CI Repair Rate Regression with Maximum Toprak [9] and Geometric Mean of PGV O'Rourke [14]

can be defined in several different ways. For example, in attenuation relationships, PGV is commonly defined as the geometric mean of the two largest horizontal components (e.g., Campbell [13]). PGV is also defined as the larger of the two horizontal components, which is the value used in Figure 6a.

Figure 6b show the CI repair rates for the Northridge earthquake regressed against the geometric mean PGV O'Rourke [14]. Because of the filtering mechanism used during the analyses, the resulting regressions are relevant to TGD and applicable for PGV≤ 75 cm/sec.

Pipeline Damage Prediction for Denizli Water Supply System

A **M**6.3 scenario earthquake caused by a normal fault was used in the evaluation of seismic performance of Denizli water supply system. The analyses were performed by using Geographical Information Systems (GIS). The mean PGV contours were developed by dividing Denizli map into 1x1 km grid system and determining the PGV at corners of each grid. Contours then were drawn from the spatial distribution of PGV values. The mean PGV values were calculated by using Campbell [13] attenuation relationship.

Figure 7 shows the water supply system superimposed on PGV zones. Also shown in the figure are the locations of fire hydrants. Length of pipelines in each zone was calculated using GIS. The number of repairs corresponding to each PGV zone was determined using pipeline damage correlations as explained in the previous section. Ductile pipelines (steel and PVC) are assumed to have 30% of the vulnerability of

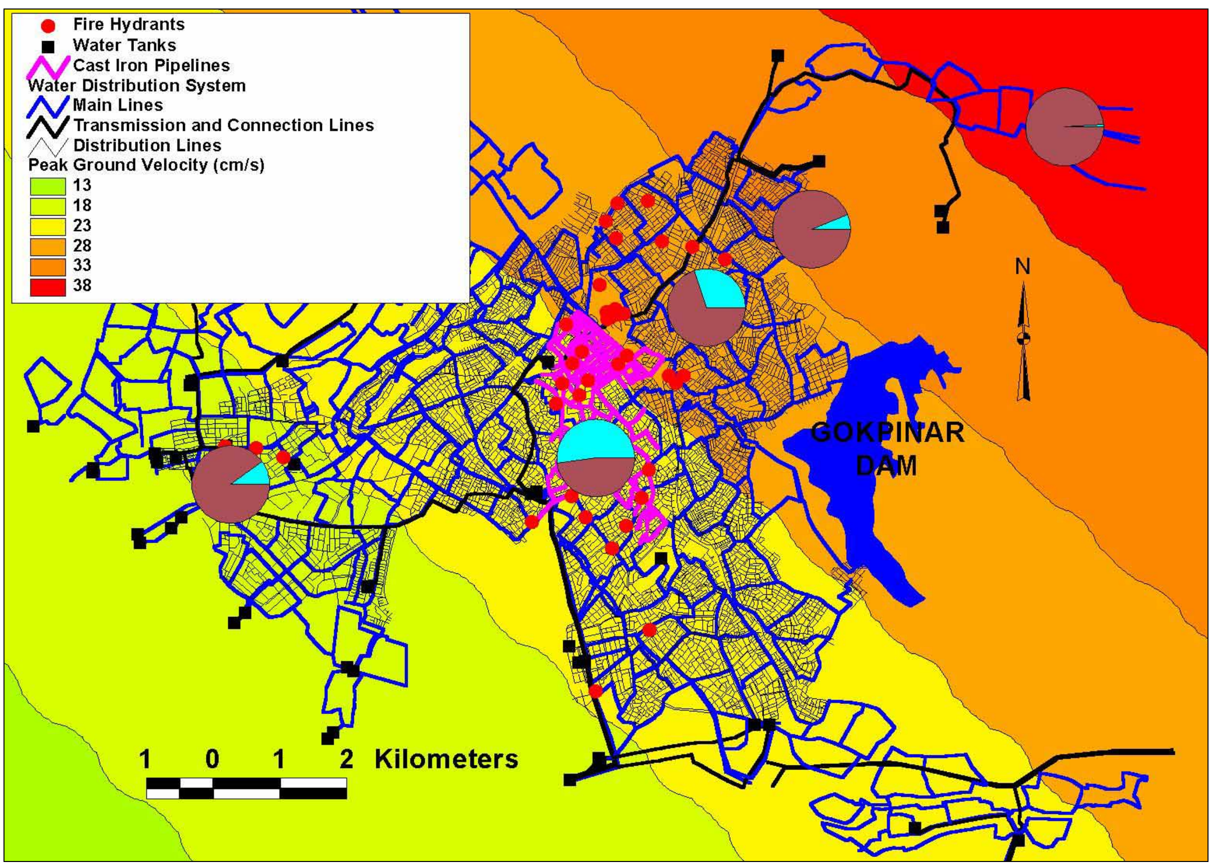


Figure 7. Water Supply System Relative to Denizli Scenario Earthquake Peak Ground Velocity

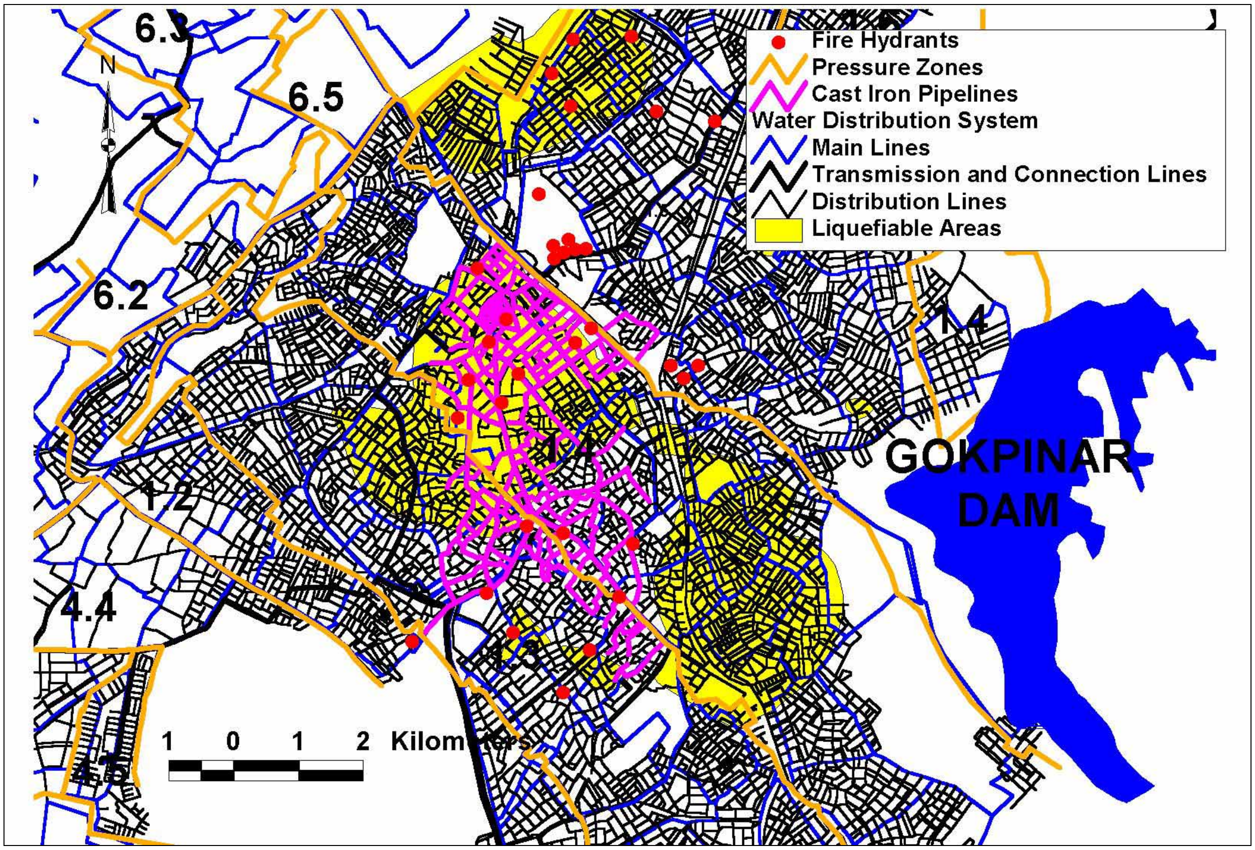


Figure 8. Water Supply System Relative to Liquefiable Areas

brittle materials FEMA [15]. The total number of repairs is predicted to be 86. The pie charts on the figure present the rate of pipeline repairs in each PGV zone (light color) to the rest of repairs (dark color). Slightly more than 50% of total repairs is predicted to occur in PGV equal to 23 cm/s zone. About 69 and 17 of all repairs are estimated to be leaks and breaks, respectively in the pipelines FEMA [15].

Figure 8 shows the water supply system superimposed on liquefiable areas. The liquefiable areas were taken from the liquefaction hazard map prepared for the Denizli municipality PAU [2]. Preliminary analyses according to the procedure outlined in FEMA [15] for permanent ground deformation (PGD) effects indicate that the number of repairs can be higher than 100.

RESULTS AND CONCLUSIONS

About 85% of Denizli water supply system was composed of brittle AC and CI pipelines. Both type of pipelines experienced widespread damage during the past earthquakes. It was reported that 70% of the AC pipelines were damaged, with some leakage detected in the remaining 30% in Adapazari during the 1999 Kocaeli earthquake O'Rourke [1]. Seventy one percent of the pipeline repairs were made to CI distribution pipelines after the 1994 Northridge earthquake Toprak [9]. Many CI pipelines in the central part of Denizli got damaged during the 1976 Denizli earthquake (**M**4.9) Kaygin [16]. AC pipelines are widespread in Denizli whereas CI pipelines, which are the oldest type in the system, serve old and busy central parts of Denizli. AC and CI 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 (Figure 8). A replacement program should start primarily with CI pipelines with extension to AC pipelines especially in and around high PGD zones as part of mitigation planning. This program can be integrated into regular maintenance efforts to combine resources. Various methods are available to minimize the impact of construction on residents, business and the environment at a reduced cost and time (e.g., Lund [17]).

In terms of impact upon the population served by the water supply system and the ability to fight post-earthquake fires, system functionality is an important measure Ballantyne [18]. The average repair rate calculated for **M**6.3 earthquake at Denizli results in serviceability index of about 30%. This shows significant reduction in the system performance right after the earthquake.

The analyses performed herein predict the number of repairs required after the earthquake. It is important for municipalities to have appropriate supplies and back up systems for emergency repair and restoration.

Although not considered in this study, failure of other structures during an earthquake can also have some effect on the water supply system performance. Building failure can damage the connections between the distribution line and the buildings, resulting in substantial water loss. Consequently, the system performance can be reduced significantly. Also water supply restoration can be affected by the extensive building damage as in the case of Adapazari after the 1999 earthquake.

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