

Seismic damage probabilities for segmented buried pipelines

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ABSTRACT: Having aging buried pipeline systems, many lifeline utility (e.g., water) companies worried about the performance of their systems against various hazards. For example, water distribution engineers of water utility companies need methodology that would assist in estimating the optimum time to replace water mains. Risk assessment of these systems provides a valuable tool for the mitigation studies. In seismic areas, pipelines are affected by earthquake loading and get some damage. The damage state is controlled by several parameters related to pipeline properties, geological and geotechnical characteristics of the locations where pipelines exist and seismic intensity. Because these parameters show substantial change for a pipeline system, which generally spreads over large areas, geographical information systems (GIS) are used for evaluations. In this study, the fragility relations relating the probability of buried pipeline damage within the pipeline system to the seismic intensity levels were presented. The seismic intensity is represented by peak ground velocity (PGV). The 1994 Northridge Earthquake and Los Angeles water supply system damage database were used to develop the fragility relations. By using the GIS, a grid of different sizes were superimposed on the pipeline damage and PGV maps. Effects of grid size on the damage probability curves were discussed.

1 INTRODUCTION

Having aging buried pipeline systems, many lifeline utility (e.g., water) companies worried about the performance of their systems against various hazards. Risk assessment of these systems provides a valuable tool for the mitigation studies. The basic equation for the risk calculation under extreme events is (e.g., Vrouwenvelder, 2009):

$$\text{RISK} = \sum P(H) P(D|H) P(S|D) C(S) \quad (1)$$

where H represents the hazard and $P(H)$ is the probability of exceedance of a given intensity over a given time period, D is the damage, $P(D|H)$ is the probability that the given facility get damage when subjected to the given hazard intensity, S is failure scenario, $P(S|D)$ is the probability that the given system fail when subjected to the given damage and C is the cost for the given failure scenario. The summation is over all relevant hazards, damage types and scenarios. The calculated risks can be used to calculate robustness index as proposed by Baker et al. (2008).

The objective of this study is to develop fragility relation relating the probability of pipe failure to the seismic ground motion parameter, namely peak ground velocity. In essence, a relationship to determine $P(D|H)$ for earthquake hazard is presented. The 1994 Northridge, USA earthquake pipeline damage was used to develop the relationships.

A similar approach was used by O'Rourke et al. (1999) to develop fragility relations relating the probability of pipe failure at a specified fault crossing location to the amount of fault offset.

2 PIPELINE DAMAGE IN PAST EARTHQUAKES

The earthquakes that occurred close to large urban areas caused significant damage. This was partly because of the relative size of buried pipeline systems that was exposed to earthquake and partly weaknesses in the systems. Some examples for weaknesses are aging of the pipelines, corrosion and inflexible joints. Selected cases for buried pipeline damage caused by earthquakes in the last two decades are given below.

During the 2008 Wenchuan, China, earthquake ($M_s = 8$) substantial damage to water pipelines occurred. For example, in Anxian County, there were 100 damages of which 70% and 30% are on iron and steel pipelines, respectively at 39.6 km of pipelines with diameters ranging from 63 to 300 mm (Yifan et al., 2008). There were also damages to steel gas pipelines.

The two largest municipalities whose water systems were significantly affected by 23 October 2004 Niigata Ken Chuetsu, Japan, $M_w = 6.6$ earthquake were Nagaoka and Ojiya. As reported by Scawthorn et al. (2006), Nagaoka's water

supply system has approximately 1,084 km of service main and distribution pipelines. The system's total length consists of about 66% ductile iron pipe, 21% unplasticized polyvinyl chloride (PVC) pipe, 7% steel pipe, 6% cast iron pipe, and 0.5% asbestos cement pipe. The larger main pipelines were generally undamaged; smaller-diameter pipes were significantly damaged. Nagaoka sustained 287 failures in its system of water transmission and distribution pipes.

Ojiya's water supply system has approximately 328 km of service main and distribution pipelines. The system's total length consists of about 71% ductile cast iron pipe, 16% steel pipe, 9% unplasticized PVC pipe, and 4% polyethylene pipe. The city sustained 102 failures in its system of water transmission and distribution pipelines. Many failures occurred in pipes of relatively small diameter.

The 1999 Ji-Ji, Taiwan earthquake (or called Chi-Chi earthquake) caused widespread damage at vital lifelines including water distribution systems and natural gas supply systems. Chen, et al. (2002) presented the gas pipeline performance of Taichung City which is the largest city in the disaster area of the Ji-Ji earthquake. The length of pipelines installed exceeded 979 km (not including the pipes leading to the customers' residences from the distribution lines). Pipeline network was mainly composed of three types of material—polyethylene (PE pipes), steel (steel pipes), and cast iron (CI pipes). The steel pipes included polyethylene covered steel pipes, galvanized steel pipes, and ordinary steel pipes. The cast iron pipes were used for pipelines with larger diameters, but rarely used recently. In terms of pipeline lengths, the steel pipes were the longest with 800 km, while the PE pipes accounted for 152 km. The cast iron pipes had only 27 km. Various sizes of pipelines ranging from 25 to 250 mm were used in constructing Taichung City's gas supply network. Pipe diameters with more than 100 km of pipeline are 50, 80, 100 and 150 mm. Chen, et al. identified damage locations according to data gathered immediately after the Ji-Ji Earthquake, re-evaluated them for accuracy and finally concluded with 795 damages.

In order to study the damage patterns of natural gas and water pipelines in the Ji-Ji earthquake, Chen, et al. established a GIS database and analysis procedures. They also conducted statistical analysis to understand the correlation between repair rate (RR) and seismic parameters such as the peak ground acceleration, peak ground velocity, and spectrum intensity by attempting different grid sizes and calculating the size parameters as suggested by Toprak (1998). Hwang et al. (2004) evaluated particularly the performance of the steel pipelines of Taichung City's gas supply network. Both Chen, et al. (2002) and Hwang et al.

(2004) used damage ratio (or repair rate) in their correlations.

The 1994 Northridge, U.S.A. earthquake provided a unique opportunity to develop and improve correlations between pipeline damage and seismic parameters. The research described in Toprak (1998), O'Rourke et al. (1998), O'Rourke and Toprak (1997) represented the first time that comprehensive GIS analyses were performed for a large US water supply with extensive Earthquake damage and strong motion data. There was widespread pipeline damage and deployment of strong motion instruments throughout the City of Los Angeles at the time of the earthquake. The earthquake damage included 15 transmission line, 74 trunk line (nominal pipe diameter ≥ 600 mm), and 1,013 distribution lines (diameter < 600 mm) repairs. Furthermore, reliable information about pipeline characteristics, repair, and strong motion measurements has been collected. As part of the research, all of approximately 10,750 km of distribution lines and 1,000 km trunk lines were digitized and incorporated in a GIS database that also includes repair records and the corrected strong motion records of 165 seismograph stations.

3 FRAGILITY RELATIONSHIPS

3.1 Characterization of seismic hazard

Among the various seismic parameters, the most statistically significant correlations were found for PGV (O'Rourke et al., 1998; Toprak, 1998; ALA, 2001). PGV has a more direct physical interpretation in terms of its effects on buried pipelines. PGV is correlated with axial strains experienced in the soil due to seismic wave propagation as expressed in the following general equation (Committee on Gas and Liquid Fuel Lifelines, 1984):

$$\epsilon_g = V_{\max}/C \quad (2)$$

where ϵ_g is the maximum seismic ground strain, V_{\max} is the maximum ground velocity, and C is the seismic wave-propagation velocity. Depending on the slippage developed between a pipeline and the surrounding soil, a certain percentage of the soil strain is transferred to the pipeline. Because of this relationship, a good correlation between PGV and pipeline damage would be expected.

Toprak (1998) and O'Rourke et al. (1998), Toprak, et al. (2008) relationships were developed primarily from CI pipeline damage although they made limited comparisons with damage for other pipe types. Also they considered effect of pipe size on damage correlations by dividing the data into two groups as distribution (nominal pipe

diameter < 600 mm) and trunk lines (nominal pipe diameter \geq 600 mm).

3.2 The methodology

In order to develop fragility relation relating the probability of pipe failure to the seismic ground motion parameter, namely peak ground velocity, the study area is divided into 2 km \times 2 km, 1 km \times 1 km, 0.5 km \times 0.5 km, and 0.25 km \times 0.25 km grids. Different grid sizes are used to evaluate the effect of grid size on the probabilities of pipe failure. Toprak et al. (1999) discussed the visualization of spatially distributed pipeline damage using GIS and emphasized the effect of grid size on pipeline repair rate values. Figure 1 show the 2 \times 2 km grid superimposed on the map of Los Angeles water supply system affected by the 1994 Northridge earthquake. The lines in the figure show the pipelines whereas the full circles show the pipeline repairs.

The focus in this study is on distribution pipelines and particularly cast iron pipelines. The total length of the distribution lines is 10,750 km. About 76%, 11%, 9%, and 4% of the distribution lines are composed of cast iron (CI), steel, asbestos cement (AC) and ductile iron (DI), respectively. Out of 944 distribution line repairs, about 78%, 17%, 3%, 1%, and 1% are cast iron, steel, asbestos cement, ductile iron and other pipe type repairs, respectively (Toprak et al. 2008). Since 76% of the water distribution system consists of CI pipelines with widespread distribution throughout the city, this type of pipeline can be used most effectively to evaluate the distribution and characteristics of damage over the entire area (O'Rourke & Toprak 1997).

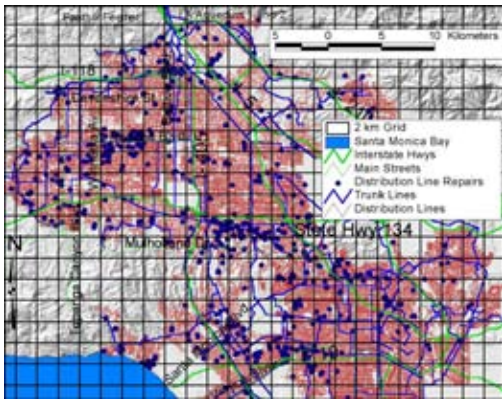


Figure 1. A 2 \times 2 km grid superimposed on map of Los Angeles water supply system affected by the 1994 Northridge Earthquake (Modified after Toprak, et al., 1999).

A complete discussion of the City of Los Angeles water supply system and the 1994 Northridge earthquake damage in that system can be found in Toprak (1998) and O'Rourke & Toprak (1997).

In the current study, PGV values from ShakeMap for the 1994 Northridge earthquake were used (Toprak et al. 2008). ShakeMap (<http://earthquake.usgs.gov/eqcenter/shakemap/>)—rapidly, automatically generated shaking and intensity maps—combines instrumental measurements of shaking with information about local geology and earthquake location and magnitude to estimate shaking variations throughout a geographic area (Wald et al., 2005). The results are rapidly available via the Web through a variety of map formats, including Geographic Information System (GIS) coverages. The fundamental output product of the ShakeMap processing system is a finely sampled grid of latitude and longitude pairs with associated amplitude values of shaking parameters at each point. These amplitude values are derived by interpolation of a combination of the recorded ground shaking observation and estimated amplitudes at locations that fill in gaps, with consideration of site amplification at all interpolated points. The resulting grid of amplitude values provides the basis for generating color-coded intensity contour maps, for further interpolation to infer shaking at selected locations, and for generating GIS-formatted files for further analyses. ShakeMap utilizes the larger of the two horizontal components at strong motion recording stations.

The strong motion database of 1994 Northridge earthquake had provided the most extensive data of its type up to 1994 for pipeline damage correlations. Yet, the spacing between stations was tens of kilometers in most of the cases. The ShakeMap processing system however produces a finely sampled grid of latitude and longitude pairs (about 1.5 km spacing) with associated amplitude values of shaking parameters at each point. These amplitude values are derived by interpolation of a combination of the recorded ground shaking observation and estimated amplitudes at locations that fill in gaps, with consideration of site amplification at all interpolated points. Hence, the PGV values should be more close to the reality as opposed to just statistically interpolating PGVs using sparsely distributed stations. The PGV values as a grid system and as a map of PGV contours for the 1994 Northridge earthquake were obtained from the following web site: http://earthquake.usgs.gov/eqcenter/shakemap/sc/shake/Northridge/#Peak_Ground_Velocity.

With GIS, the number of particular pipeline repairs and the length of pipelines are determined in each grid cell. The resulting pipe repair numbers and lengths are then grouped in such a way to

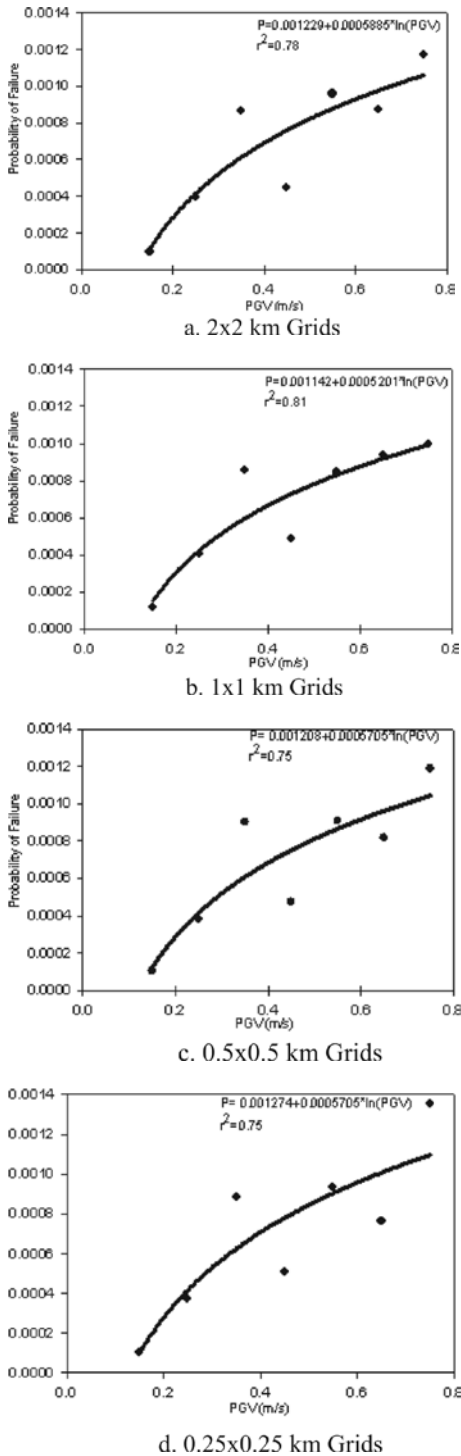


Figure 2. Probability of failures for pipelines obtained from 2×2 km, 1×1 km, 0.5×0.5 km, and 0.25×0.25 km grids.

correspond to 100 mm/s PGV intervals. In essence, corresponding values of the ground motion parameter based on the average ground motion to have occurred over the selected interval. The intervals are used in the following regression analysis. In order to obtain the probabilities of pipe failure, number of pipelines which failed and did not fail should be determined. For this purpose, it is assumed that the pipe length is about 6 m and the total number of pipes in each PGV category is calculated by dividing the length of pipelines by 6. The number of pipes in each PGV category that failed is determined by assuming that each repair corresponds to one damaged pipe. This assumption is substantiated by checking the distances between the repairs are greater than 6 m by using GIS. The probability of failure is taken simply as the ratio of the number of damaged pipes to the total number of pipes in the same PGV category zone.

3.3 The damage probability curves

Figures 2a, b, c and d show the probability of pipe failures with respect to PGV for 2×2 km, 1×1 km, 0.5×0.5 km, and 0.25×0.25 km grids. A simple regression analysis on the data is used to develop seismic vulnerability functions. Various regression models such as linear, logarithmic, and power were used in the regression analysis. As compared by r^2 values, the best results were obtained by the logarithmic model with the following expressions:

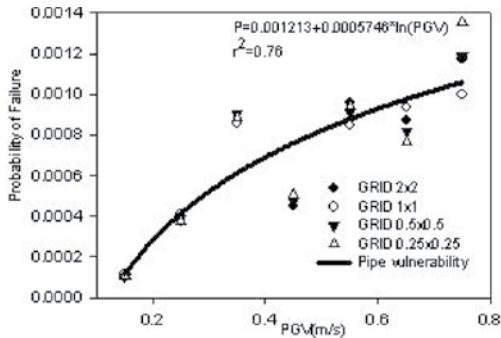
$$P = a + b \ln(PGV) \tag{3}$$

where P is the probability of pipe failure, PGV is the peak ground velocity, “a” and “b” are unknown regression coefficients. The coefficient of multiple determination r^2 is a measure of the fraction of total variation that can be explained by a regression model. If a regression model can explain all of the variation, r^2 is equal to 1. Conversely, an extremely poor model would result in r^2 value near zero.

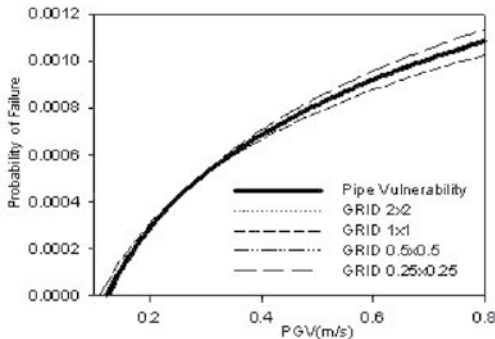
The damage probability curves are shown in Figures 2a, b, c and d for the respective grid sizes. The highest r^2 is obtained from 1×1 km grid. The equations for each case are also given on the figures.

4 COMPARISON OF THE CURVES AND CONCLUSIONS

Data from four different grid sizes are shown in Figure 3. Also shown in the figure are the probability of failure curve obtained from all data and the equation for the curve. The effect of grid size on the curves are not so significant compared the results reported by Toprak et al. (1999). This may



a. Data from various grid sizes



b. Comparison of probability of failure curves

Figure 3. Comparison of probability of failures for pipelines obtained from different grids.

be the result of evaluating the probability of pipe failures over the PGV intervals of 100 mm/s.

The seismic probability of failure curves for pipeline damage presented herein can be useful for risk studies of segmented water utility systems. For example, water distribution engineers of water utility companies may combine them with risks from other hazards in estimating the optimum time to replace water mains. Because of the screening of data (PGV values greater than 0.8 m/s are not included in the analysis) similar to Toprak (1998), the curves should be applicable primarily to ground shaking hazard.

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