Seismic Risk Assessments of Water Pipelines - A Case Study for the City of Los Angeles Water System Pipeline Network

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ABSTRACT

Understanding the system-level risks of an infrastructure network is a critical step in developing a seismically-resilient network. In a complex seismic environment, numerous future earthquakes that have a broad range of magnitude, rupture location, and probability can affect a spatially distributed network and cause drastically different damage severity and service interruption time. Characterizing system-level risks involves the assessments of system damage potentials from all possible future earthquakes probabilistically. This paper shows a case study where system-level damage potentials for the City of Los Angeles water pipeline network were assessed using a stochastic method. The study considers both the distribution of earthquake-induced shaking and ground deformations, and the locations of the pipe network within the areas of varying shaking and ground deformation. System-level damages, including repair costs and repair time, were established at various target probability levels.

CCS CONCEPTS

• Applied Computing → Physical science and engineering → Engineering.

KEYWORDS

Seismic Resilience, Infrastructure seismic risk, Seismic risk for water pipelines, Probabilistic seismic risk assessments

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1. Description of the Los Angeles' Water Pipeline System

The water pipelines for the City of Los Angeles consist of more than 7,000 miles of underground pipes and cover an area of 1,214 km^2, supporting a population of about 4 million people. This study includes both the transmission lines (pipelines with 24-inch or larger diameters) and distribution lines (pipelines less than 24-inch diameter) of the water pipeline system. The map in Figure 1 shows the transmission (trunk lines) highlighted in red. As measured by length, approximately 93.1% of the pipes are associated with the distribution system and only about 5.2% of the pipes are transmission lines. Although the transmission system is expected to have the least exposure to seismic hazards, damage and disruption to it may have more significant impacts (i.e., damage to transmission lines will disrupt larger quantities of water from reaching customers, and the repair of transmission pipelines will take significantly longer).

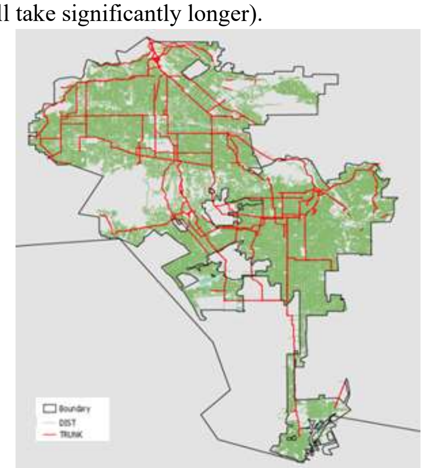


Figure 1: The water transmission and distribution pipeline systems for the City of Los Angeles.

2. Probabilistic Pipeline System-Level Risk Assessments

To model the seismic hazard exposed to a network, a stochastic catalog of simulated earthquakes is constructed, where the statistical distributions of magnitudes, locations, and occurrence probabilities of future earthquakes in a region are characterized and conform to geological or geodetic observations. Given a simulated event in the catalog, stochastic event footprints, including wave passage and seismic-induced ground failure, such as soil liquefaction, rupture surface displacement, and landslide, are established. Responses of the network within the areas of varying shaking intensity and ground failure are then estimated. The synthetic catalog of earthquake events, commonly referred to as an "event set," together with the predicted stochastic event footprints, are crucial in probabilistically assessing system-level seismic risks of a spatially distributed network system.

To assess the seismic response of a pipeline network, pipeline fragility models are typically used. Pipeline fragility models depict the number of repairs (including leaks and breaks) per unit length as a function of the intensity from wave passage or the amount of displacement from ground deformation, and are often distinguished by pipe material, joint type, pipe size (diameter), age and other characteristics of the pipelines. System damage, characterized by the total number of expected repairs, can then be estimated by aggregating the expected number of repairs throughout the network for each earthquake simulation. With all earthquake simulations in the event set, the probability of exceeding a specified level of system-level damage is then established. The relationship of system damage as a function of annual frequency of exceedance, or inversely, return period, often referred to as "risk curve," fully describes the damage potentials of a network exposed in future earthquakes. Figure 2 illustrates the analytical procedure used for assessing the seismic performance of the City of Los Angeles' water pipelines.

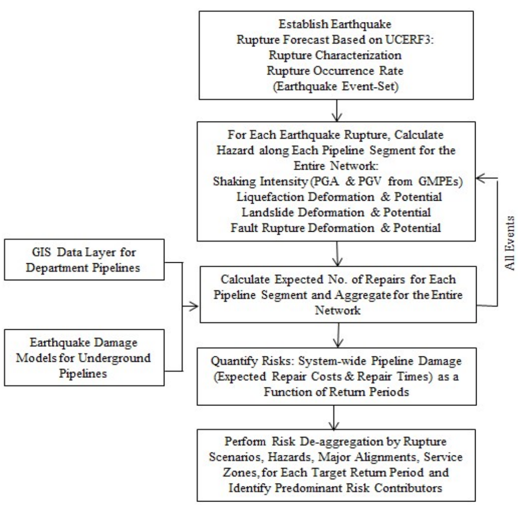


Figure 2: System-level risk calculation procedure for a pipeline network system

3. Seismic Hazard Modeling

The event set developed by ImageCat was used in this study. The event set adapts the United States Geological Survey (USGS)'s 2014 National Seismic Hazard Mapping Project model [1], using the Robust Simulation approach [2]. The approach comprehensively captures the epistemic and aleatory uncertainty in seismic hazard models through simulations of an ensemble of hazard solutions through random-walk simulations within a time-window equivalent to 500,000-years.

Shaking The NGA West2 empirical ground motion models (GMMs) [3] were used to model stochastic intensity footprints, taking into account both the between- and within-event uncertainty, as well as the spatial correlation of ground motion within an event [4]. Two ground motion parameters are calculated: peak ground acceleration (PGA) and peak ground velocity (PGV). PGA is used for soil liquefaction and landslide triggering and ground displacement estimates, and PGV is used for assessing wave passage related damage to pipelines. To account for the soil effect on ground motion, the Vs30 map published by the California Geological Survey (CGS) [5] was used to infer the site conditions throughout the pipeline locations.

Liquefaction Zoned portions of southern California were evaluated where there is overlap of the pipelines and liquefaction hazard zones mapped by the California Geological Survey (CGS). Liquefaction susceptibility and displacement were estimated based on available borehole and Standard Penetration Test (SPT) or Cone Penetration Test (CPT) data to provide a conservative estimate of liquefaction and lateral spreading using current groundwater conditions [6, 7, 8, 9].

Surface Rupture Fault zones were selected using mapped fault traces from both the CGS Alquist-Priolo (AP) maps and the USGS Quaternary Fault and Fold Database [10]. The probability of surface rupture occurrence given the magnitude and the expected surface displacements are estimated using published empirical models [11, 12].

Landslide The CGS mapped potential landslide zone was used for earthquake-induced landslides. Displacement based on earthquake magnitude and PGA was calculated using the equation presented in Rathje and Saygili [13].

4. Pipeline Fragility Models

The pipeline fragility models used in this study were developed by Honegger and Eguchi [14], where pipeline fragilities were characterized by age, pipe material, type of joint, and type of seismic hazard. In general, brittle pipes (which may be more prone to breakage during an earthquake) include pipes made of asbestos cement, cast iron, vitrified clay, and old polyvinyl chloride. Flexible pipes refer to pipes made of steel, high-density polyethylene, and new polyvinyl chloride. Robust pipes include ductile iron, reinforced concrete cylinder or box, welded steel with arc-welded joints, and steel or ductile iron pipe with mechanical seismic joints.

5. Repair Costs and Repair Times

Estimating the cost and time to repair a damaged pipe can be difficult. It depends on the magnitude of the earthquake, and the level of preparation practiced by the controlling agency. For trunk lines, the model relied essentially on data from past earthquakes where repairs to large diameter pipelines were made [15, 16, 17]. For the repair of distribution pipelines, the model used repair data provided by the Los Angeles Department of Water and Power (LADWP), which LADWP used to assess how well its Asset Life

Cycle Management Program was contributing to mainline pipeline performance. Within the distribution line system, the repair times for pipes are significantly shorter than that of the repair times for trunk lines, which is consistent with experience from past earthquakes.

6. Results

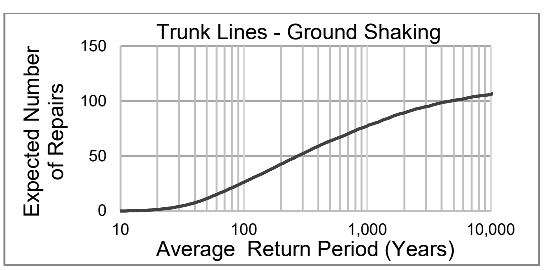
The pipeline system-level risks analyses have been conducted for truck lines and distribution lines, respectively, for ground shaking and ground failure (including liquefaction, rupture surface displacement and landslide). The system risk curves, where the expected number of repairs, repair costs or repair times are expressed as a function of return period, are plotted in Figures 3 to 5. The expected system risks at return periods of 100-, 500-, 2,500- and 10,000-years are also tabulated in Tables 1 through 3.

Some general observations are discussed below:

1) As measured by the number of pipeline repairs, the overall risk to the LADWP pipeline system is dominated by the performance of the distribution system. Because of the greater geographic extent, more distribution pipelines will be subjected to the effects of moderate to large seismic events. In contrast, the transmission system (trunk lines) is expected to have the least exposure to seismic hazards. System damage to trunk lines, although much less compared to distribution lines, is nevertheless important because of their implication for system repair costs and restoration times after an earthquake (i.e., damage to transmission lines will disrupt larger quantities of water from reaching customers, and the repair of transmission pipelines will take significantly longer).

2) Overall system risks are dominated by ground shaking effects. The reason for this is simply that the system is subjected to larger areas of strong ground shaking than to ground failure. However, damage caused by ground failure (e.g., surface fault rupture, liquefaction, or landslide) will be more concentrated and may be more difficult to repair. For example, the repair of pipelines in areas experiencing ground displacement may include not only the repair of pipelines but also the repair of the ground or soil surrounding the pipeline as well.

3) System repair costs and repair times provide direct indicators of earthquake impacts. Although pipeline repair times are not directly related to the service restoration time (largely owing to the redundancy of the system), it nevertheless provides a basis for assessing the scale of impact of the future earthquakes on network performance.



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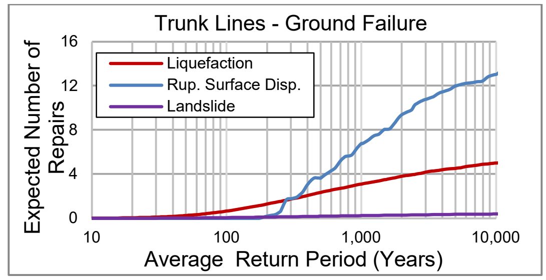

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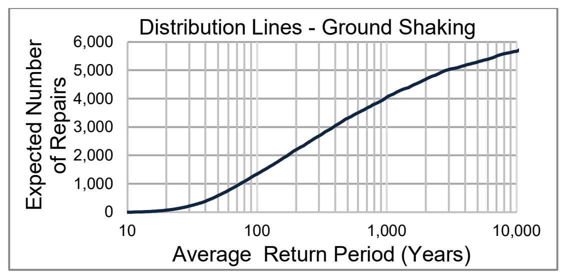
Figure 3. System-level risk curves for trunk lines due to a) ground shaking and b) ground failure

Table 1. Expected number of repairs for trunk lines

Return Period (Years)	Expected Number of Repairs			
	Shaking	Liquefaction	Rup Surface Displacement	Landslide
100	27	1	0	0
500	63	3	4	0
2,500	92	4	11	0
10,000	106	5	13	0



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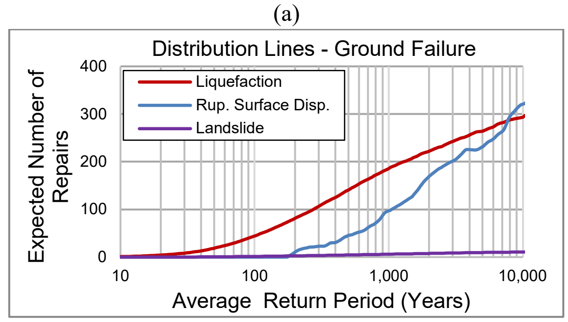

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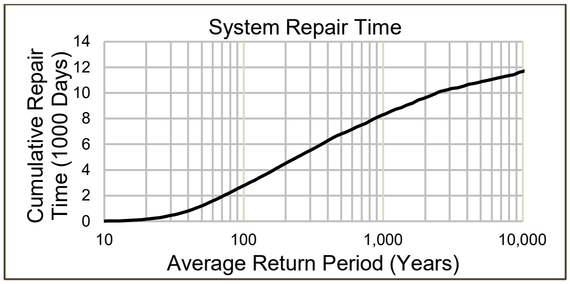
Figure 4. System-level risk curves for distribution lines due to a) ground shaking and b) ground failure

Table 2. Expected number of repairs for distribution lines

Return Period (Years)	Expected Number of Repairs			
	Shaking	Liquefaction	Rup Surface Displacement	Landslide
100	1,351	44	0	2
500	3,321	141	46	5
2,500	4,876	232	189	8
10,000	5,679	293	321	11



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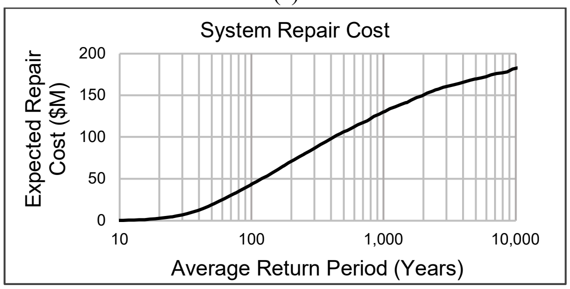

(b)

Figure 4. System-level risk curves for a) repair time and b) repair cost

Table 2. Expected repair costs and repair times

Return Period (Years)	Expected Repair Cost ($M)	Accumulative Repair Time (Days)
100	33.7	2,773
500	82.9	6,080
2,500	122.6	10,064
10,000	143.2	11,680

7. Conclusions

In a complex seismic environment, a water pipeline network may be damaged in moderate to large earthquakes, causing short to long service interruption times. To construct and maintain seismically resilient water lifeline networks, targeted system-level performance criteria were proposed by Davis et al. [15], as shown in table 5. These criteria are presented at four levels each associated with a different return period. The analytical framework presented in this study establishes a quantitative measure of the system performances at these target levels.

The results in this study show that the largest risks to the City of Los Angeles' water pipeline network are associated with the distribution system, mainly because it covers larger areas and is exposed to a broader set of seismic hazards. This is especially true when it comes to shaking effects. It must be noted, however, that the most serious impacts on overall water distribution may result from damage to the transmission or trunk line system. This is because damage to large pipelines that are responsible for bringing large quantities of water to the service region may take longer to repair and therefore, would dictate the need for alternative water supplies to maintain serviceability. Technical and financial resources can be planned and allocated to mitigate the known vulnerabilities and reduce the likelihood that the water pipeline network will be damaged in future earthquakes so that the target system performance criteria are met.

Table 5. Target system-level performance criteria

Level	Return Period	Target Water System Performance	Mw Range
1	100 years	Limited damage, no casualties, few to no water service losses. All customer services operational within about 3 days.	Less than 3.8 to 5
2	500 years	Life safety and property protection. All customer services operational within about 20 days, except water quantity; rationing may extend up to 30 days.	4.6 to 8.0
3	2,500 years	Life safety and property protection. All customer services operational within about 30 days, except water quantity; rationing may extend up to 60 days.	5.4 to 8.2
4	>2,500 up to 10,000 years	Life safety and property protection. All customer services operational within about 45 days, except water quantity; rationing may extend up to 12 months	6.2 to 8.3

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