Seismic Reliability Analysis of Lifeline Systems

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SUMMARY:
Lifelines are essential to urban life as they include all kinds of facilities and systems as water, gas, fuel, power, communication and transportation. The scope of this paper is to evaluate the influence of the uncertainties of seismic load and damage state definition in system's reliability. At first, a rapid pre-estimation of the reliability of the system just after the earthquake is conducted. Then probabilistic seismic risk analysis by using mesh is done, and damage probability of pipelines derived. The final estimation of the seismic performance of the system is achieved by combining a probabilistic vulnerability curve and a Monte-Carlo simulation. As a case study the water network of Padang-Indonesia is selected. The methodology is general and it can be used for all lifelines in order to increase the reliability of the lifeline systems and to enhance the national or local mitigation plans.

Keywords: lifeline, reliability, Monte-Carlo simulation, probabilistic, seismic risk analysis

1. INTRODUCTION

Events such as the 1994 Northridge, 1995 Kobe, 1999 Izmit, 2003 Bam, 2009 Padang, 2010 Santiago, and the 2011 Tohoku earthquakes have exposed the seismic vulnerability of various lifelines and caused business interruption losses. Lifeline systems such as water-supply, power, telecom, gas-supply, sewage, and transportation are critical civil infrastructures. These systems are essential elements for the functioning of all economic and social activity of an industrialized nation. The functional loss of these systems due to an external perturbation can cause severe impact on a community in numerous ways. This loss has the potential to cut water supplies, reduce or eliminate electrical system capacity, and sever gas links. Specifically, seismic hazards cause significant damage to these systems. Therefore, it is important to proactively assess and mitigate the seismic risk of lifelines.

In the case of a water distribution system, the availability of water in highly populated areas is essential for fighting fires that may break out following a major earthquake which can be destructive and costly in terms of human life and damage to environment. Since the severity of such consequences increases with the number of people exposed, higher design standards are stipulated for areas having greater population density.

The first step in acquiring a safe distribution system is the realistic assessment of the potential environmental hazards like the hazard posed by earthquakes on such systems. This can only be achieved by employing probabilistic methodologies due to the underlying uncertainties, variability and randomness in both earthquakes and the capacity of the pipeline system. The probabilistic model used in this study for the assessment of the seismic reliability of lifelines is composed of the following three main parts: Seismic hazard analysis, Damage analysis and Network reliability analysis.

The basic aim of this study is to use a probabilistic model for the assessment of the reliability of lifeline systems with multiple sources under seismic hazard. Particular attention is given to water distribution systems having and an illustrative case study is presented.

2. SEISMIC HAZARD ANALYSIS

Seismic hazard analysis provides quantitative information useful for designing and checking the safety of structures subject to seismic activity. In order to assess risk to a structure from earthquake shaking, It must first determined the annual probability or rate of exceeding some level of earthquake ground shaking at a site, for a range of intensity levels. Therefore it is necessary to analyze the available data on past earthquakes. For this purpose, earthquake catalogs of instrumental records and of historical earthquakes are to be utilized.

The classical seismic hazard analysis model, (Cornell, 1968), adopted in this study considers the randomness in three dimensions. The magnitude of a future earthquake, its location in time and its location in space constitute the random components in this model. These random characteristics can be reflected into the Probabilistic Seismic Hazard Analysis model by assessing the statistical distributions associated with them. At its most basic level, PSHA is composed of; Identify all earthquake sources capable of producing damaging ground motions, Characterize the distribution of earthquake magnitudes, Characterize the distribution of source-to-site distances associated with potential earthquakes, Predict the resulting distribution of ground motion intensity as a function of earthquake magnitude, distance, etc, and finally Combine uncertainties in earthquake size, location and ground motion intensity, using a calculation known as the total probability theorem, Eqn. 2.1 (Baker, 2008).

$$\lambda(IM > x) = \lambda(M > m_{\min}) \int_{m_{\min}}^{m_{\max}} \int_{0}^{r_{\max}} P(IM > x | m, r).f_M(m).f_R(r) dr.dm \tag{2.1}$$

where $\lambda(IM > x)$ is the rate of $IM > x$, $\lambda(M > m_{\min})$ is the rate of occurrence of earthquakes greater than $m_{\min}$ from the source and $f_M(m)$ and $f_R(r)$ are probability density functions for magnitude and distance, and it is integrated over all considered magnitudes and distances.

3. LIFELINE DAMAGE ANALYSIS

The reliability of a lifeline system under earthquake excitation depends on the seismic reliability of its components that consist of two types, node and link. The seismic reliability of a component requires the determination of its seismic capacity, which is defined as the resistance to earthquake loads. Considering various uncertainties and the random factors involved, the seismic capacity should be described based on a probabilistic model. The uncertainties stem from the uncertainties in the material properties, dimensions and the models used for the evaluation of the capacity.

3.1. Node Damage Analysis

If the capacity (strength) of an element is described by a random variable C and the demand (loading) on the element by a random variable *D*, failure will occur when *C*≤ *D*. If *C* and *D* are taken as the basic variables for any element, then the failure probability, P_f , can obtain by Eqn. 3.1.

$$P_f = P(C \le D) = P(C - D \le 0) = \iint_{c-d \le 0} f_D(d).f_C(c) dd.dc \tag{3.1}$$

where $P(\circ)$ denotes probability and f_D and f_C are the probability density functions for *D* and *C*, respectively. Here, C and D are assumed to be statistically independent from each other. In contrast, the probability of being in a survival state, P_s, is calculated by Eqn. 3.2.

$$P_s = P(C > D) = (1 - P_f) = R \tag{3.2}$$

Generally, in this context, the survival probability, R, is referred to as reliability. In the case of dependence, the probability of failure is given by Eqn. 3.3.

$$P_f = \iint_{wf} f_{CD}(c,d)dd.dc \tag{3.3}$$

where $f_{CD}(c,d)$ is the joint density function of C and D; wf is the failure domain defined in two-dimensional space. The implementation of the reliability model described earlier requires information on the probability distribution of seismic demand and capacity.

3.2. Link Damage Analysis

Previous research analyzing the seismic vulnerability of line components has led to relations between seismic ground motion intensity and line break density (Katayama et al., 1975; O'Rourke and Ayala, 1993; Eguchi, 1991a). The guidelines prepared by the Federal Emergency Management Agency (FEMA, HAZUS 2003) suggest that damage to water pipe caused by strong ground motion can be expressed as a function of *PGV* as Eqn. 3.4.

$$RR = K \times (0.0001) \times PGV^{2.25} \tag{3.4}$$

where RR is the repair ratio, which is the number of pipe breaks per kilometer of pipe length, K is a coefficient determined by the pipe material, pipe joint type, pipe diameter and soil condition, and PGV expressed in cm/sec. The coefficient K for ductile pipelines is equal *0.3*. That is, ductile pipelines have *30%* of the vulnerability of brittle pipelines.

If the water main connecting two facilities is short, it may be assumed that the seismic demand on that water main connecting two facilities is essentially uniform. Thus, the failure probability of a water line can be computed by generalizing the above formulation by modeling the number of breaks by a non-homogeneous Poisson process, Rausand et al. (2004) as Eqn. 3.5.

$$P_f = 1 - \exp\left(- \int_L RR(PGV(s))ds \right) \tag{3.5}$$

where $RR(\circ)$ is the repair ratio expressed as a function of $PGV(s)$, which is a function of site S, and L is the length of the water main.

4. LIFELINE RELIABILITY ANALYSIS

Every element of a network experiences different seismic demand depending on its geographical location and its dynamical characteristics. The main interest is how the seismic damage of each of the vulnerable network's elements affects the overall network performance. One of the most important parameter for network reliability assessment is connectivity analysis. Two different levels of network connectivity analysis exist, rough and general. The first level has the main purpose to evaluate the state of the system as a whole, while the second is more advance level.

4.1. Rough Reliability Analysis

The rough reliability analysis is based on the calculation of two coefficients; α and γ that characterize the network connectivity as Minimum, Intermediate and Maximum connected network, according to Table 4.1 (Taafee, 1973).

Table 4.1. Network Characterization

Network categorization	**Gamma coefficient (γ)**	**Alpha coefficient (α)**
Minimum connected	$1/3 \le \gamma \le 1/2$ where $k \ge 4$	$\alpha = 0$ where $k = \sigma + 1$
Intermediate connected	$1/2 < \gamma < 2/3$ where $k \ge 4$	$0 < \alpha < 1/2$ where $k \ge 3$
Maximum connected	$2/3 \le \gamma \le 1.0$ where $k \ge 3$	$1/2 \le \alpha \le 1.0$ where $k \ge 3$

The calculations of the gamma and alpha coefficients according to the theory of graphs are provided by Eqn. 4.1 and Eqn. 4.2.

$$\gamma = \frac{\sigma}{3(k-2)} \tag{4.1}$$

$$\alpha = \frac{\sigma - k + 1}{2k - 5} \tag{4.2}$$

where σ is the number of links and k is number of nodes. The numerical value of gamma coefficient expresses the percentage of connectivity of the network while the physical meaning of alpha coefficient is the percentage of the existence of circular connections in the network.

4.1. General Reliability Analysis

The advanced network reliability analysis calculates the direct and indirect connections between different points of the network. The network reliability model considered in this study is based on the model proposed by Yoo and Deo, (1988) in which path enumeration method is implemented, (Alexoudi, 2005).

Earlier it is introduced the probability of failure for each element, so now it should be propagate all these singular probabilities of failure through the network and present the result as the probability of failure or probability of exceeding any other defined damage state of the whole network. This transformation from element level to the network level was performed using Monte Carlo simulations. Monte Carlo simulation is one of the most widely used techniques in simulating the behavior of physical systems. Its advantage lies in the simplicity of modeling systems with a large number of uncertain parameters and imprecisely known characteristics of their probability distributions.

Certain events are categorized as success and some others as failure events. An event is a success event if the graph realization corresponding to every elementary event constituting that event has at least one path. An event is a failure event if the graph realization contains no paths. Generally, nodes are assumed to be failure free and here it is also assumed that link failures are statistically independent of each other. Evaluation of reliability requires computing the probability of events.

5. CASE STUDY

In view of the previous sections, it is to be noted that the probabilistic assessment of seismic hazard requires information on the seismicity parameters, attenuation relationship, geographical locations of seismic sources and locations of the components of the lifeline. The links constitute the main consideration in evaluating the reliability of a lifeline network. The reason for this is the fact that links are highly vulnerable since they extend spatially over a region.

Geological structure and soil conditions on which the components of a lifeline are constructed and properties and quality of the material used in constructing the lifeline are the main factors that have to be considered in evaluating the seismic resistance of the links. Incorporation of these effects is attained by considering links having random resistances. In order to show the implementation of the proposed model a water distribution system is considered.
Water distribution systems aim at transporting water from reservoirs to the users without any

interruption. In this case the resulting network involves multiple sources. In a well organized water distribution system, water is expected to flow to the destination point properly with desired level of pressure and quality.

Especially, after a hazardous earthquake, it is vital to attain the connectivity of the water distribution system for some urgent circumstances such as fires and hospital services. A water distribution system is composed of feeding pipes, service pipes, main and redundant pipes, buster pumps, valves, fire taps, pressure reducing systems, service connections and reservoirs. In network idealization, links are represented by pipes, the reservoirs form the sources and the rest can be taken as nodes. For a water distribution system, the network reliability is defined as the probability of reaching from any one of the multiple sources to the specified destination successfully. Computation of this probability forms the multiple-source lifeline reliability problem.

5.1. Padang-Indonesia Water Network

The system considered here is the water distribution system of the Padang city where is the capital of the west Sumatra in Indonesia. It has been located in high potential seismicity region and affected by strong earthquake in 2009. The network has three main reservoirs and associated trunk mains and a number of boreholes. The Padang city water network includes 1800 km of Steel, ACP, Galvanized steel pipe, ductile pipe and PVC in total trunk and distribution pipeline. Model of the network is consists of 274 nodes and 339 links, as shown in Fig. 5.1.

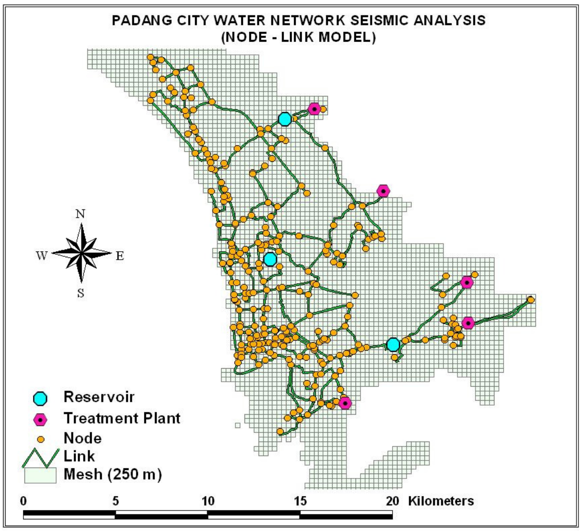

Figure 5.1. Node-Link model of Padang water network

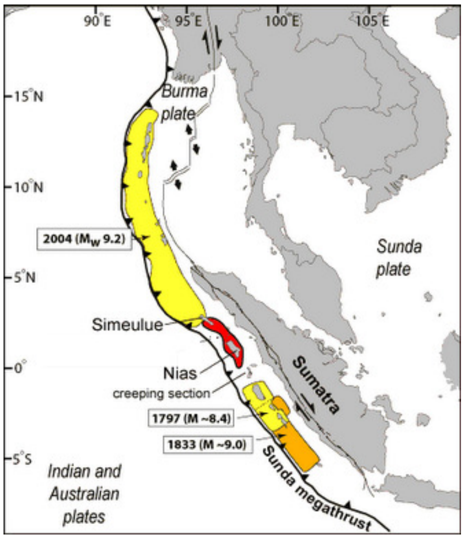

Figure 5.2. Sumatra Seismic zones

5.2. Padang Water Network Seismic Performance

On the 30th September 2009, a moment magnitude Mw7.6 earthquake occurred off the island of Sumatra, Indonesia, near the city of Padang. This earthquake had a devastating effect on many of the buildings and affected infrastructure and communities there. Directly after the earthquake, residents went one month without the complete restoration of the main water supply.

Immediately after the event, the main trunk for the central Padang region was severed in two places. The distribution network of the water was also disrupted due to the pipe damages. As the pumps for the boreholes were powered by electricity, this supply was also terminated. This caused the loss of 85% of the borehole service and effectively left the central region with no water. The largest water treatment facility demonstrated the benefits of redundancy in the production process. In this plant, water was supplied by two pipes, that older pipe broke but the newer pipe suffered no damage and enabled to continue functioning (Wilkinson et al. 2009).

5.3. Seismic Hazard Analysis of Padang

It is interested in all earthquake sources capable of producing damaging ground motions at the site. These sources could be faults, which are typically planar surfaces identified through various means such as observations of past earthquake locations and geological evidence. If individual faults are not identifiable, then earthquake sources may be described by area Regions in which earthquakes may occur anywhere. Once all possible sources are identified, it can identify the distribution of magnitudes and source-to site distances associated with earthquakes from each source. The west Sumatra Island seismic zones are shown in Fig. 5.2.

In this study it is used total probability theorem, Eqn. 2.1, to perform the PSHA calculation for *PGA* and *PGV*, using the Kanno et al. (2006) attenuation relation ground motion model. PSHA parameters, based upon topological properties taken from risk assessment, are computed. Lifeline systems are of large scale, complex and geographically distributed; use of GIS for the integration and manipulation of all available data has become more popular. Therefore, Padang district geology, seismicity, grid mesh 250 m dimension and water network are modelled in GIS, Faraji et al. (2011).

The description of the seismic hazard map is a monotonic function with the return period *T* and the exposure time *n*. The return period is the average time span between two events of a given magnitude at a particular site. The exposure time usually equals the expected life of the structure. In order to calculate the design life expectation of the structure, both these parameters must be employed when calculating the risk of the structure with respect to a given event, FEMA (2003). The risk assessment is thus the likelihood of at least one event that exceeds the design limits of the structure in its expected life. In this study, Padang *PGV* and *PGA* seismic hazard maps calculated for 475 return period and are shown in Fig. 5.3 and Fig. 5.4 respectively.

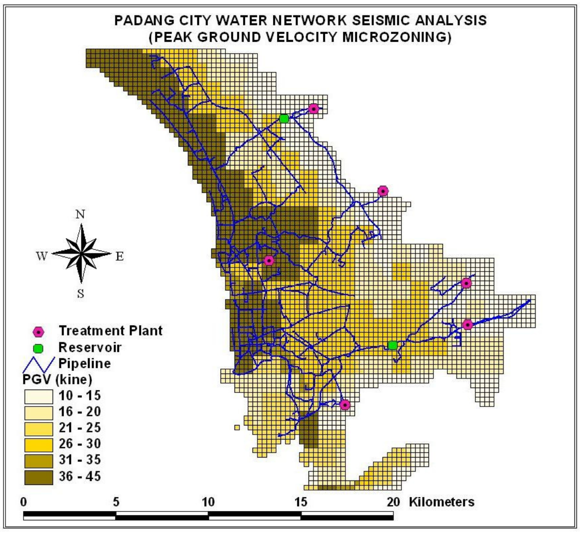

Figure 5.3. Padang PGV hazard map

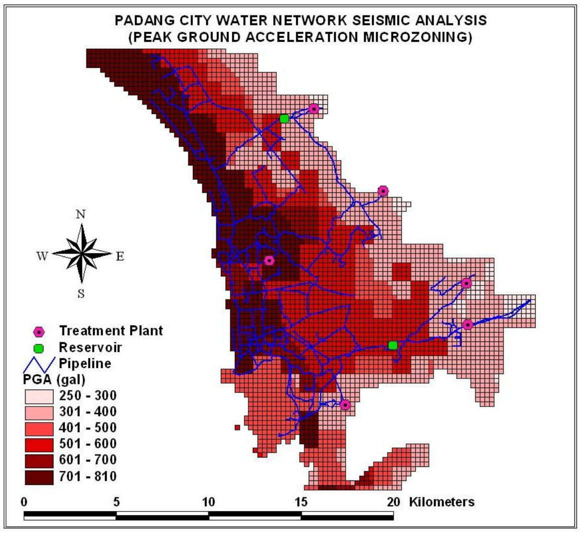

Figure 5.4. Padang PGA hazard map

In fact, there is 90% chance that these ground motions will not be exceeded (50 years of exposure time). This level of ground shaking has been used for designing ordinary lifelines and buildings in high seismic areas.

5.4. Padang Water Network Damage Analysis

Physical damage to facilities within the water network, such as tanks, pumps, and building enclosures, can be modeled by their seismic fragilities, which define the conditional damage state probability as a function of ground motion intensity. The joints, valves, tees, and measuring and pump stations are modeled as nodes and are assumed to be perfectly reliable. The pipes are idealized as links.

Generally water pipes installed in the Padang area were Cement-asbestos and some of them were PVC and polyethylene. Only large-diameter water mains, with diameters 300-800 mm, were concrete, cast and ductile iron. Considering the typical water pipes, pipe material, joint type, diameter and soil conditions in Padang, it is assumed various K in Eqn. 3.4 and calculated Padang water network pipelines damage ratio as shown in Fig. 3.5.

5.5. Padang Water Network Reliability Analysis

The overall damage of water network depends upon the number of the Monte-Carlo simulation runs. About 6% ranges differences obtained in breaks/km for the different Monte-Carlo runs. A minimum 10000 run simulation was used. The simulation results under scenario earthquake, reliability of network nodes are illustrated in Fig. 3.6.

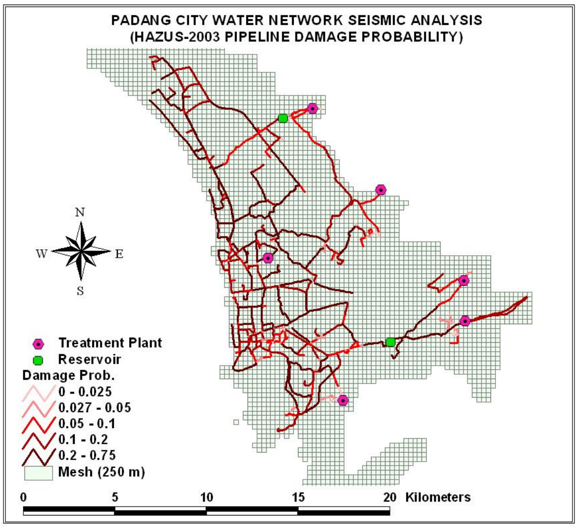

Figure 5.5. Damage probability of network links

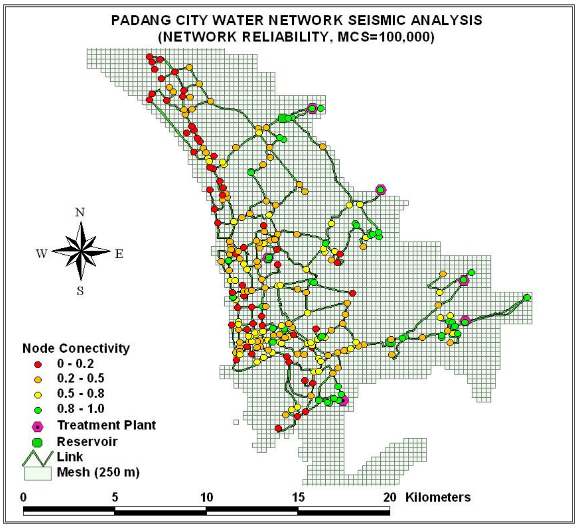

Figure 5.6. Reliability of network nodes

As a first level of reliability analysis, the connectivity of the system and the associated scattering of the results are evaluated by the coefficients gamma and alpha in Table. (1), initially for the undamaged, and then for damaged network. The calculated gamma and alpha values are 0.41544, 0.12155 for undamaged network and 0.20221, 0.00 for damaged network respectively.

According to the computed values of gamma and alpha, the water network of Padang can be considered, under normal conditions, as an intermediate to minimum connected network. Coefficients gamma and alpha alters in case of increased seismic loading. This proves that there is a degradation of the system to a minimum connectivity situation. The 66 available circular links in normal period are reduced up to zero for scenario earthquake of 475 years. This means that the redundancy of the system will be reduced by 100%. So, this level of scenario earthquake can affect seriously the system serviceability and may have serious impact to some critical facilities as hospitals, power supply stations etc.

Comparing to the devastating effect of recent earthquake on Padang water network and considering the fact that the level of this earthquake is lower than the scenario, it seems that the obtained results are acceptable.

6. CONCLUSION

The paper presented shortly a parametric analysis of the seismic loads based on a proposed seismic risk assessment methodology for the evaluation of the seismic performance of the water network of Padang city in Indonesia. Uncertainties regarding the seismic hazard estimation, the fragility curves and the evaluation of damage states were also discussed. The main conclusions of this rather introductory analysis mentioned that the connectivity is very sensitive to small alternations in alpha coefficient, especially in intermediate connected network. In the case of Padang water network, its redundancy can be minimized in a seismic scenario of 475 years. Several problems will be faced in the system connectivity even for a smaller earthquake scenario. Besides the damage state estimation and the evaluation of the connectivity of the system the paper present the vulnerability assessment of the water network of Padang in terms of damages for different level of PGVs. The results consistent with happened damages after the earthquake. Based on the results, most of high probable damaged pipelines are located in west part of Padang in coast area. Damaged pipelines density, especially in central west part of the city is more than another. Results of vulnerability analysis appropriately are consistent with reality and actual damages. Actual damages data is for Padang water network consist of total trunk and distribution pipelines. However in this study, only trunk lines are analyzed and also the exact material of pipelines and joint types were not clear. Therefore, some differences are due to those matters. The parametric analysis provided result to the prediction of the weak points of the system and an overall picture of water system performance during the studied seismic scenario in Padang city. Such analyses can provide a background for the design of pre-seismic upgrading measures, co-seismic emergency policy and enhance the post seismic actions.

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