DOWNTIME ESTIMATION AND ANALYSIS OF LIFELINES AFTER AN EARTHQUAKE

DOWNTIME ESTIMATION AND ANALYSIS OF LIFELINES AFTER AN EARTHQUAKE

Omar Kammouh [1] Gian Paolo Cimellaro [2] Stephen A. Mahin[3]

ABSTRACT

This paper provides an empirical probabilistic model for estimating the downtime of lifelines following earthquakes. Generally, the downtime of infrastructure varies according to several factors, including the characteristics of the exposed structure, the earthquake intensity, and the amount of available human resources. Having so many variables makes the process of estimating the downtime even harder. Therefore, it is necessary to have a simple and practical model to estimate the downtime of infrastructure systems. To do so, a large database has been collected from literature, which includes damage data for many earthquakes that took place in the last century. The database has been used to create restoration curves for four types lifelines: Water distribution network, Gas network, Power system, and Telecommunication network. Different restoration curves have been developed based on several criteria, such as the earthquake magnitude, development level of the affected country, and countries with enough data. The restoration curves have been presented in terms of probability of recovery and time; the longer is the time after the disaster, the higher is the probability of the infrastructure to recover its functions.

Keywords: Lifelines, Downtime, Restoration curves, Infrastructures, Seismic resilience, Recovery.

1. INTRODUCTION

Estimating the infrastructure downtime following an earthquake is a subject on which scientists and policy makers have recently focused their attention. The downtime can be defined as the time required to achieve a recovery state after a disastrous event; therefore, it is strictly linked to the indirect losses of the

[1]Visiting Scholar at Univ. of Illinois at Urbana Champaign UIUC, Dept. of Civil Engineering, 205 N Mathews Ave., Urbana, IL 61801. E-mail: omar.kammouh@polito.it.
[2]Visiting Professor, Dept. of Structural & Environmental Engineering, University of California, Berkeley, Berkeley, USA (Corresponding author) E-mail: gianpaolo.cimellaro@polito.it.
[3]Member, ASCE; Prof. of Civil Engineering., Univ. of California, Berkeley, CA 94720 E-mail: mahin@berkeley.edu

damaged infrastructure [1]. Downtime is usually caused by the construction repair of the damaged structure and the arrangements needed to mobilize resources. Comerio (2005) defined downtime as the sum of rational and irrational components [2]. The rational components include construction costs and repair time, while the irrational components consider the time needed to mobilize resources and make decisions.

The downtime is an essential parameter to estimate resilience. Several attempts have been made recently to quantify the disaster resilience considering the downtime. Some of these studies tackled the engineering resilience on the country level [3, 4] and some on the local level [5-7]. In engineering, resilience is defined as "the ability of social units (e.g. organizations, communities) to mitigate hazards, contain the effects of disasters when they occur, and carry out recovery activities in ways to minimize social disruption and mitigate the effects of further earthquakes" [8-11]. Under this context, downtime is the time span between the moment the earthquake occurs (t_0), when the functionality *Q(0)* drops to *Q(1)*, and the time when the functionality of the utility is completely restored (t_1) [8, 12, 13] (Figure 1). Some of the factors that can possibly affect the downtime include: the structural inspection, the assessment of damage, the finance planning, the bidding process, the repair effort, and the engineering consultation [14, 15].

One of the first attempts to evaluate the disruption time following a disaster event was done by Basöz and Mander (1999) [16]. In their work, they developed downtime fragility curves for the transportation lifeline. The fragility curves were later integrated in the highway transportation lifeline module of HAZUS. Another downtime estimation methodology was developed based on a modified repair-time model [17]. This methodology estimates the downtime of only the rational structural components of a system, due to the uncertainty involved in the process. In addition, the Federal Emergency Management Agency (FEMA) has introduced the *Performance Assessment Calculation Tool* (PACT). PACT is an electronic calculation tool, and repository of fragility and consequence data, that calculates and accumulates losses. It includes a series of utilities used to specify building properties and update or modify fragility and consequence information in the referenced databases. PACT is considered the companion to FEMA P-58, a significant 10-year project funded by FEMA to develop a framework for performance-based seismic design and risk assessment of buildings [18]. Almufti and Willford (2013) have proposed the *Resilience-based Earthquake Design Initiative* (REDi™) based on the results coming from PACT [19]. The goal was to provide owners and other stakeholders a framework for implementing resilience-based earthquake design and achieving higher performances.

Moreover, a performance-based earthquake engineering method to estimate the downtime of infrastructures using fault trees was introduced in [20]. This method is applicable only when the downtime is mostly controlled by the non-structural systems damage. It assumes that the restoration starts immediately after the event and the damaged components are repaired in parallel.

Another concern regarding the downtime evaluation is the infrastructure interdependencies. This is a subject on which most of current research effort is placed, mainly because of its complexity and uncertainty. Critical infrastructure systems are highly interconnected and mutually interdependent where damage to one infrastructure can produce cascading failures on other systems [21]. For instance, telecommunication and water systems require continuous supply of energy to maintain their normal functions, while the power infrastructure needs the water and various telecommunication services to generate and deliver electricity. Although the presence of interdependencies can significantly improve the operational efficiency of infrastructure, recent worldwide events have shown that interdependencies can increase systems vulnerability. The level of interdependencies between systems can determine how long a dependent system can stay inoperable. The Lifelines Council of San Francisco completed a study on the interdependencies of the city's infrastructure systems [22]. They evaluated the infrastructures' performance following a hypothetical major earthquake with a magnitude of 7.9. The study suggests that some of the lifelines were closely coupled and interdependent with the performance and restoration of the other lifelines. The interdependency was responsible for a significant recovery delay when the infrastructures have only experienced a moderate damage.

Generally, several factors are involved in the downtime estimation, such as the characteristics of the exposed structure, the earthquake intensity, and the amount of human force that is assigned to recover the damaged structure. With these factors, the process of estimating the downtime becomes harder. Therefore, it is crucial to have a simple model for estimating the downtime of infrastructures [15]. The aim of this study is to develop a probabilistic model to evaluate the downtime of lifelines following a seismic event. Four different types of lifelines are analyzed in this work, namely power, water, gas, and telecommunication. First, a large database has been collected from a wide range of literature. The database contains real restoration data for many seismic events that occurred in the last century. Probabilistic restoration functions have been constructed using the gamma distribution, which has been selected because of its good fit to the empirical data. For each of the four lifelines, a group of fragility curves has been developed based on several factors, such as the earthquake magnitude, development level of the affected country, and countries with enough data. The restoration curves have been presented in terms of probability of recovery and time; the longer is the time after the disaster, the higher is the probability of the infrastructure to recover its functionality.

2. DOWNTIME DATA ANALYSIS AND INTERPRETATION

Figure 2 shows the location of all 32 earthquakes considered in this study. Approximately, 90% of the earthquakes analyzed in this research took place along the Ring of Fire of the Pacific Ocean, a string of volcanoes and seismic activity sites. The other 10% of the earthquakes took place along the Alpide belt, a line that passes through the Mediterranean region, Turkey, Iran, and northern India. The database was gathered from renowned authors and official institutions, and belongs to earthquakes that have occurred after the 60's, because there was little or no reliable information about the damage caused by earlier earthquakes.

Table 1 lists all the earthquakes considered in this work along with the year in which they occurred, the country they hit, and their intensity in terms of Richter magnitude. Several other damaging earthquakes that occurred around the same period have also been collected but not included in this study because no engineering damage reports could be obtained for those events. Nevertheless, the events included in this study are sufficient to provide useful illustrations for the recovery behavior of the examined lifelines.

Figure 3 shows the distribution of the analyzed earthquake in terms of location. Most of the collected data belong to earthquakes that took place in the USA, Japan, and South America. This is because damage data are continuously collected and reported by the competent authorities in these regions, mainly to allow this data to be used by scholars to improve community resilience.

Data related to infrastructure damage caused by earthquakes is reported in the literature in both qualitative and quantitative forms. The challenge faced during the data collection process was to have a normalized database that can be combined and used in the downtime analysis. It has been decided that only scholarly publications reporting numerical data were to be considered. Reports with exclusively qualitative data have not been considered in the analysis, which mainly improved the quality of the developed curves. Another reason why qualitative data has been excluded is because such data reflects only the degree of damage of the infrastructures, and not the restoration function or the recovery speed. For instance, countries that already have a restoration plan and allocate enough resources to the recovery process would bounce back to a functional state in a short time regardless of how severely their infrastructures were damaged. Moreover, transforming the infrastructures damage into restoration time would require several assumptions that cannot be verified and could make the results biased. Since the objective of this research is to have a tool to estimate the downtime of infrastructures for a given location and a given earthquake magnitude, only documents reporting the actual time needed to restore the infrastructure service have been examined. The restoration time and the restoration speed of the infrastructures depend on several factors, such as the size of the infrastructure, the interdependency with other systems, the allocated financial and human resource for restoration, the level of initial damage suffered by the infrastructure, etc. Although these factors can vary among countries and even regions, the authors decided not to extrapolate restoration curves related to these parameters due to the paucity of data. Splitting the available data based on these factors would result in unreliable outputs as the data sets would be very small to carry out a probabilistic study. Instead, other parameters are considered in the study, such as the earthquake magnitude, development level of the affected country, and countries with enough data. The normalization of the raw data was not necessary as it is expressed in the same scale and can be combined (i.e., number of days required to restore the service). The normalization of data would be necessary if the qualitative damage data was considered because qualitative and linguistic terms vary between reports and include intrinsic subjectivity.

Recovery in the context of this work means returning full service to the population (i.e. the number of users served before and after the disaster event is the same, regardless of the state of the infrastructure). Table 2 lists the complete database used to create the restoration curves of the lifelines. The different earthquakes are listed in a random order. It is notable that each earthquake has caused damage to multiple infrastructure systems at the same time. For instance, in the city of Loma Prieta, the earthquake caused damage to two power plants, ten water systems, five gas stations, and six telecommunication systems. The affected infrastructures needed different times to recover even when the infrastructures are of similar types. For example, the two power plants that were affected by the Loma Prieta earthquake needed 2 and 0.5 days respectively to recover. There were some cases where either the damage information was not available or no damage was recorded. Such cases are marked with a dash (-) inside the table. In total, the number of affected infrastructure units analyzed in this paper are: 63 power systems; 84 water systems; 47 gas systems; and 34

Telecommunication systems. In the following, the raw data of three selected earthquakes is presented to show how the restoration times of the damaged infrastructures were extracted from the source text. The raw data of the rest of the earthquake events can be found in the references reported in Table 2.

2.1 Valdivia 1960, Chile [23]

The Valdivia earthquake was the strongest shaking ever recorded, with a magnitude of 9.5 on the Richter scale and an intensity of XI to XII on the Mercalli scale. This earthquake shocked all South America and destroyed the Chilean city of Valdivia. More than 5.000 people died and more than 2 million people were forced to leave their homes. The shock was so strong that new lakes were formed and some rivers shifted their course. After the big shake, a huge tsunami devastated all the coastline of Valdivia city, destroying houses, bridges, boats and ports. Despite the power of the earthquake, the Chilean utilities of the region performed quite well, mainly due to the preparation of the country to this kind of hazards. One electrical system was affected by the earthquake, and it took five days to recover its function. The water system was also affected and it fully recovered after exactly 50 days. As for the gas and telecommunication infrastructures, no damage was reported as the two systems functioned normally after the earthquake.

2.2 El-Asnam 1980, Algeria [24]

An earthquake of magnitude 7.1 and a focal depth of 15 km struck the city of El-Asnam in northern Algeria on the 10th of October 1980. 23.5% of the buildings of the city collapsed during the 1980 quake. More than 6.500 people died after the shock and 9.000 were injured. This event was an example of a poor post-earthquake study. Only information regarding the downtime of the water system was reported. The water system remained inoperative for two weeks following the deadly earthquake.

2.3 Niigata 1964, Japan [25]

On June 16, 1964, Japan was jarred by the strongest earthquake to hit the country since the Kanto Earthquake in 1923. The shake, which measured 7.7 on the Richter scale, was felt in over two-third of the main Japanese island of Honshu, but the most affected region was the Niigata prefecture. The earthquake destroyed more than 8.000 houses, disrupted all public utilities, severely interrupted all the communication systems, and put out of commission almost all the land, sea, and air transport facilities. The region of Niigata stayed with partial power supply for 24 days until the power system was recovered. The earthquake affected three water systems in the city, and they took 15, 4, and 10 days to recover, respectively. Two gas systems were damaged by the quake; the first was heavily affected, and it remained inoperative for 6 full months, while the second was slightly damaged, and it took only 2 days to recover. No major damage in the telecommunication infrastructure was recorded as no drop in service was experienced by the users.

3. METHODOLOGY

The main challenge faced in this work is to illustrate the gathered data in the form of restoration curves. Typically, real data is complex to handle because they are exposed to a series of errors that vary in nature and magnitude. In this paper, the collected restoration raw data are fitted with a statistical distribution. Choosing the right distribution can be a difficult task due to the relevant number of distributions available in literature. To characterize new raw data with a distribution, four questions need to be asked. The first question is whether the data is discrete or continuous. The second is whether the data is symmetric or if there is asymmetry in the distribution. The third question relates to the presence of upper or lower limits on the data. The last question deals with the possibility of observing extreme values in the distribution. Answering these questions can be fundamental in fitting the right distribution.

Different distribution families that satisfy the characteristics of the infrastructure restoration process have been selected. The parameters of the distributions have been estimated using the maximum likelihood estimation method. The distribution with the optimal fit has been identified (1) visually using the probability paper visual test, and (2) statistically using the Kolmogorov-Smirnov (K-S) and Chi-Square tests for Goodness-of-fit. In the following, the statistical distribution selection procedure is discussed in detail.

3.1 Parameters estimation

Different methods for estimating the parameters of a distribution can be used; among these are the *method of moments* and the method of *maximum likelihood* [26, 27]. In this work, the method of maximum likelihood is used to estimate the parameters of the distributions. The likelihood of a set of data is the probability of obtaining that particular set of data given the chosen probability distribution model. This expression contains the unknown model parameters. The values of these parameters that maximize the sample likelihood are known as the Maximum Likelihood Estimator MLEs [28]. Unlike to the method of moments, the maximum likelihood method derives the point estimator of a parameter directly. The maximum likelihood estimate (MLE) of a parameter possesses many desirable properties. In particular, for a large sample size, the maximum likelihood estimator is often considered to provide the best estimate of a parameter [27].

3.2 Fitting analysis

Visual testing is the easiest and simplest way to test a distribution. This is done by comparing the histogram of the raw data to the distribution. To either accept or reject a distribution, the cumulative frequency of the empirical data is compared to the cumulative distribution function (CDF) of the theoretical distribution. Alternatively, one can use probability paper to check if a given distribution conforms to the empirical data [27]. A probability paper is usually constructed using a transformed probability scale in such a way to obtain a linear graph between the cumulative probabilities of the underlying distribution and the values of the random variable. The probability paper procedure has minimized our choices to only three distributions: The *exponential*, *lognormal*, and *gamma* distributions.

When a particular distribution is determined to model a phenomenon using a given probability paper by simply visual inspection, the validity of the theoretical distribution can be verified statistically using *goodness-of-fit* tests. There are multiple tests to verify the goodness-of-fit in the literature, such as the Kolomogorov-Smirnov (or K-S), the chi-square, and the Anderson-Darling (or A-D). The latter, in particular, is useful when the tails of a distribution is important. Therefore, only the K-S and chi-square goodness-of-fit tests are performed in this paper and the results are presented in the following section.

3.3 The distribution with optimal fit

Dating back to 1967, The Kolmogorov-Smirnov test (K-S) is considered one of the oldest and most useful tests of fit for distributions [29]. The basic idea of the *Kolmogorov-Smirnov* test is to compare the experimental cumulative frequency with the CDF of an assumed theoretical distribution. If the maximum difference between the experimental and theoretical frequencies is larger than a certain value for a given sample size n, the theoretical distribution is not acceptable for modeling the underlying population; conversely, if the difference is less than a critical value, the theoretical distribution is acceptable at the defined significance level α [27]. Mathematically, it is represented as follows:

$$D_n = \max_x |F_X(x) - S_n(x)| \quad (1)$$

where D_n is a random variable, $F_X(x)$ is the CDF of the theoretical distribution, $S_n(x)$ is the stepwise empirical cumulative frequency function. For a significance level *α*, the K-S test compares the observed maximum difference D_n with the critical value D_n^α, which is defined for a significance level *α*, as follows:

$$P(D_n \leq D_n^\alpha) = 1 - \alpha \quad (2)$$

In this paper, the K-S test analysis for only two data sets is presented. Table 3 shows the data sets considered in the analysis, extracted from Table 2. Both sets correspond to the events with an earthquake magnitude within the range EM 6-6.9.

Figure 4 shows the cumulative step function of (a) the water distribution infrastructure, and (b) the power network infrastructure for the data corresponding to EM 6-6.9. The Gamma, exponential, and lognormal cumulative distributions functions are plotted against the stepwise function for each data set to visualize the distribution fit. As we can see in the figure, it is very hard to rely on visual interpretation to choose the distribution with the best fit; therefore, the goodness-of-fit testing is necessary,

Table 4 shows the goodness-of-fit tests for the two data sets. For both infrastructures, all theoretical distributions are acceptable as the value of D_n is always lower that the critical value D_n^α for a significance level $\alpha = 0.05$. From the table. the gamma distribution yields the best results (i.e. lowest D_n).

Similarly, the Chi-square goodness of fit test has been performed to consolidate our distribution choice. The Chi-square goodness-of-fit test compares the observed frequencies n_1, n_2, …, n_k of *k* values (or in *k* intervals) of the variate with the corresponding theoretical frequencies e_1, e_1,…, e_k calculated from the assumed theoretical distribution model. The assumed theoretical distribution is an acceptable model if the following equation is satisfied:

$$\sum_{i=1}^{k} \frac{(n_i - e_i)^2}{e_i} < c_{1-\alpha, f} \quad (3)$$

where $c_{1-\alpha,f}$ is the critical value of the chi-square distribution at the cumulative probability of $1-\alpha$, $f = k - 1$ is the number of degrees-of-freedom (d.o.f.), where f must be reduced by one for every unknown parameter that must be estimated.

Figure 5 shows the frequency histogram plot of the downtime data corresponding to (a) the water distribution infrastructure, and (b) the power network infrastructure for earthquake magnitudes EM 6-6.9. The probability density function (PDF) of the Gamma, exponential, and lognormal theoretical distributions are displayed and compared against the empirical data points. Table 5 shows the goodness-of-fit tests for the two downtime data sets. For the water distribution system, the chi-square test results (χ_f^2) for the three theoretical distributions are below the maximum threshold ($C_{1-\alpha,f}$). This signifies that all three distributions can be used to model the downtime data. For the power network, however, only the gamma distribution is acceptable because the chi-square tests for the exponential and lognormal distributions exceed the given threshold for a 5% significance level *α*.

In conclusion, among the three, the gamma distribution was found to be the optimal fit, having passed the goodness-of-fit tests for the remaining data sets. Hence, it is hereafter used to build the restoration curves. The restoration curves for each lifeline have been created using the distribution fitter toolbox in MATLAB® [30], which uses the maximum likelihood estimation method to estimate the parameters of the theoretical distribution.

4. RESULTS: THE RESTORATION CURVES

Restoration curves were developed for the power, water, gas, and telecommunications systems using the collected downtime data. The variables considered to plot the curves are: (i) the number of days required to restore full service to customers (horizontal axis) and (ii) the probability that the utility is completely restored to the customers (vertical axis). To provide a better understanding of the restoration process, the collected data has been divided based on different categories, as follows:

1) *Earthquake magnitude (EM)*: Although it is not the only parameter, the earthquake intensity plays a primary role in defining the infrastructure damage and the downtime. This classification assumes that the

earthquake magnitude is fully correlated with the induced damage. The collected data has been classified into four groups of Richter magnitude scale (strong 6-6.9; Major 7-7.9; Severe 8-8.9; and Violent 9-9.9). For each lifeline, a group of restoration curves considering the four EM ranges have been developed.

2) *First world countries vs developing countries*: developing restoration curves for each single country is not feasible due to the relatively small amount of available data. As an alternative, the data was divided based on the level of development of countries. Countries were classified as either first world countries or developing countries. For each group, lifelines restoration curves have been created.

3) *Countries with large database*: it is interesting to see how specific countries are performing in terms of disaster recovery. Restoration curves for the US, Japan, and countries in South America have been developed since a large portion of the collected data belong to these three regions.

4.1 Category 1: Earthquake magnitude

Figure 6 shows the restoration curves for the four lifelines based on the earthquake magnitude. The intensity of the earthquake is a key parameter in defining the downtime, and this is shown in Figure 6 where most of the times the lifeline restoration rate follows the earthquake magnitude.

The restoration curves of the lifelines are characterized by a similar behavior. The only difference lies in the restoration rate. The power system has a very high probability to recover within 60 days, unlike the other infrastructures that need at least 100 days to reach the same probability. This outcome is expected because all lifelines need power to function, and thus the power system is always the first to recover. The telecommunication system, on the other hand, is heavily dependent on the power network, and this delays its restoration until the power system is recovered. Similarly, the water system reaches a restoration probability close to 1 after approximately 100 days. Table 6 shows the distributional parameters used in the statistical analysis of each lifeline derived using the maximum likelihood estimation method.

In standard fragility analysis, the fragility functions for the different damage states within the same data sample should not intersect. Intersection of fragility curves may occur when each curve corresponding to a specific damage state is fitted independently of one another [31]. In order to avoid the intersection of fragility curves corresponding to different damage states, the same standard deviation is usually assumed [31], where the parameters of the distribution functions representing different states of damage are simultaneously estimated by means of the maximum likelihood method. In that method, the parameters to be estimated are the median of each fragility curve and one value of the standard deviation that is assumed the same for all fragility curves. In the loss analysis, however, the intersection of the functions could happen. Losses do not necessarily follow a specific pattern (i.e. it may cost more to repair a lower damage state). Restoration times are even more dependent on the invested resources (i.e. sever damage may be recovered quickly due to engagement of overwhelming resources, for example, using military resources to construct temporary bridges). This Justifies the intersection of the curves in Figure 6.

4.2 Category 2: First world countries vs developing countries

Table 7 classifies the countries according to their level of development. USA, Japan, and New Zealand have been considered as “first world countries” while the remaining countries have been grouped under “developing countries”. Figure 7 shows the restoration curves of the database grouped according to the level of development of the affected countries. For all infrastructures, the developed countries tend to have a higher recovery probability at a given downtime. This means that the developed counties are more likely to recover the lifelines in a shorter period. For both groups, the restoration curve of the power system reaches a high probability of recovery quicker than the other lifelines, usually because the functionality of the different lifelines is greatly dependent on the power network. Table 8 presents the statistical parameters of the theoretical distributions derived using the maximum likelihood estimation.

4.3 Category 3: countries with large database (USA, Japan, and countries in South America)

A large portion of the collected downtime data belongs to the three regions USA, Japan, and South America. Data related to these countries was large enough to develop independent recovery curves, except for telecommunication infrastructure in the region of South America. Table 9 presents the parameters of the gamma distribution CDFs used for building the restoration curves. Figure 8 compares the restoration rate of the lifelines in the three regions, regardless of the earthquake intensity. The USA takes the lead in the recovery of all lifelines, while Japan comes second. Finally, countries in South America are the last to recover the infrastructure. South America generally experienced earthquakes of larger magnitudes in the history than the other countries, and this can be a possible factor for this result.

5. DISCUSSION

The results presented above show some interdependencies and coupling behaviors among the lifelines. The power system was always the first infrastructure to recover its normal functions following the disaster, usually because all lifelines depend on the power system, and so right after the event it should restore as soon as possible. For the telecommunication system, the restoration process starts fast, but then the probability of restoration in the following days after the earthquake becomes less than that of the power system. This is probably due to the interdependency of the two systems; that is, if the power system is not fully restored, the telecommunication service will not be restored as well. The water and gas networks show a lower recovery rate, where both infrastructures are dependent on the power system for service transmission. In most cases, the gas distribution system is the utility that takes longer to be completely restored. One reason can be the mandatory tests and investigations required after a hazardous event, which force the utility to be closed for extra days.

Generally, estimating the recovery delay caused by infrastructures interdependencies can be a challenging task due to the complexity involved in the process. In this work, the lack of information regarding systems interdependencies have prevented such an analysis.

The downtime depends on several factors, such as the size of the infrastructure and the development level of the country (i.e. developed countries have higher degree of infrastructure interdependency). Identifying all variables that affect the downtime can be an approach for normalizing and estimating the dependent downtime. In our work, the interdependency of the analyzed infrastructures are embedded in the results and they are behind the introduced restoration curves. In addition, the work presented here is an empirical study based on a probabilistic analysis; therefore, parameters such as the interdependency can be considered as an intrinsic characteristic of the data.

The main challenge faced while creating the database was to deal with different studies, with different analysis, and different formats. There is not yet an international standard to collect the performance of the utilities after hazardous events, and this led to exclude several studies because the damage data reported was not scaled and cannot be combined. That is, some data points were qualitative and biased, and consequently they did not qualify to be included in the study. A standard procedure to analyze the performance of lifelines following natural disaster remains a need to improve community resilience.

Data classification and categorization is another challenge faced in this paper. The collected data has been divided based on one criterion at a time. The considered criteria are: the earthquake magnitude, development level of the affected country, and countries with enough downtime data. For each of the three categories, a group of restorations curves has been developed for each infrastructure type. Distinguishing the data based on several criteria at once would lead to small data sets whose analysis would not be statistically defensible. Nevertheless, this will be considered in future research once enough data is gathered.

6. CONCLUSIONS

Downtime is one of the most difficult parameters to estimate in resilience engineering. Estimating the resilience of infrastructures due to earthquakes has been studied in the past; however, none of the studies highlighted a clear procedure to estimate the disruption time of damaged systems. This paper provides an empirical model for estimating the downtime of damaged infrastructures following an earthquake. The model uses a large database for earthquake events that occurred over the last few decades. Different types of statistical distributions have been tested and then the gamma distribution has been selected because of its good fit to the empirical data. Four main lifelines were considered in this work (power, water, gas, and telecommunication). For each of them, a group of restoration curves have been derived. The restoration curves were presented in terms of the number of days required to restore full service to customers (horizontal axis) and the probability that the utility will be completely restored to the customers (vertical axis). the longer is the time after the disaster, the higher is the probability of the infrastructure to recover its functions.

Given that such a model is still missing in literature, this work provides a useful tool to estimate the downtime of infrastructures hit by earthquakes. It allows evaluating the infrastructures' resilience, given that the downtime is a key parameter in the resilience estimation process. Future work will be oriented towards extending the database to include more earthquakes. In addition, special attention will be given to the infrastructure interdependency, which can increase the accuracy of the restoration curves. Other lifelines such as the transportation system will also be analyzed once satisfactory data is collected.

ACKNOWLEDGEMENTS

The research leading to these results has received funding from the European Research Council under the Grant Agreement n° ERC_IDEAL RESCUE_637842 of the project IDEAL RESCUE—Integrated Design and Control of Sustainable Communities during Emergencies.

REFERENCES

[1] Terzic V, Mahin S, Comerio M. Comparative life-cycle cost and performance analysis of structural systems. Proceedings of the 10th National Conference in Earthquake Engineering, Earthquake Engineering Research Institute, Anchorage, AK2014.
[2] Comerio M. Downtime modeling for risk management. In: Augusti G, Schuëller GI, Ciampoli M, editors. PROCEEDINGS OF THE NINTH INTERNATIONAL CONFERENCE ON STRUCTURAL SAFETY AND RELIABILITY (ICOSSAR). Rome, Italy: MILLPRESS ROTTERDAM NETHERLANDS; 2005.
[3] Kammouh O, Dervishaj G, Cimellaro GP. Quantitative Framework to Assess Resilience and Risk at the Country Level. ASCE-ASME Journal of Risk and Uncertainty in Engineering Systems, Part A: Civil Engineering. 2018;4:04017033.
[4] Kammouh O, Dervishaj G, Cimellaro GP. A New Resilience Rating System for Countries and States. Procedia Engineering. 2017;198:985-98.
[5] Kammouh O, Zamani-Noori A, Renschler C, Cimellaro GP. Resilience Quantification of Communities Based on Peoples Framework. 16th World Conference on Earthquake Engineering (16WCEE). Santiago, Chile: IAEE; 2017.
[6] Kammouh O, Noori AZ, Taurino V, Mahin SA, Cimellaro GP. Deterministic and fuzzy-based methods to evaluate community resilience. Earthquake Engineering and Engineering Vibration. 2018;17:261-75.
[7] Kammouh O, Cimellaro GP. PEOPLES: a tool to measure community resilience. In: Soules JG, editor. Proceedings of 2018 Structures Congress (SEI2018). Fort Worth, Texas. April 19–21, 2018: ASCE- American Society of Civil Engineering; 2018. p. 161 - 71, doi:10.1061/9780784481349.015.
[8] Bruneau M, Chang SE, Eguchi RT, Lee GC, O'Rourke TD, Reinhorn AM et al. A framework to quantitatively assess and enhance the seismic resilience of communities. Earthquake spectra. 2003;19:733-52.
[9] Cimellaro GP, Renschler, C., Reinhorn, A. M., and Arendt, L. PEOPLES: a framework for evaluating resilience. Journal of Structural Engineering, ASCE. 2016.
[10] Renschler CS, Frazier A, Arendt L, Cimellaro G-P, Reinhorn AM, Bruneau M. A framework for defining and measuring resilience at the community scale: the PEOPLES resilience framework. MCEER, Buffalo. 2010.
[11] Cimellaro GP, Zamani-Noori A, Kammouh O, Terzic V, Mahin SA. Resilience of Critical Structures, Infrastructure, and Communities. Berkeley, California: Pacific Earthquake Engineering Research Center (PEER); 2016. p. pp. 318.
[12] Cimellaro GP, Reinhorn A. Multidimensional performance limit state for hazard fragility functions. Journal of engineering mechanics. 2010;137:47-60.
[13] Kammouh O, Zamani-Noori A, Cimellaro GP, Mahin SA. Resilience Evaluation of Urban Communities Based on Peoples Framework. ASCE-ASME Journal of Risk and Uncertainty in Engineering Systems, Part A: Civil Engineering, under review. under review.
[14] Comerio MC. The economic benefits of a disaster resistant university: Earthquake loss estimation for UC Berkeley. Institute of Urban & Regional Development. 2000.

[15] Kammouh O, Cimellaro GP. Restoration Time of Infrastructures Following Earthquakes. 12th International Conference on Structural Safety & Reliability (ICOSSAR 2017). Vienna, Austria: IASSAR; 2017.
[16] Basöz N, Mander J. Enhancement of the highway transportation lifeline module in HAZUS. National Institute of Building Sciences. 1999;16:31-40.
[17] Beck J, Kiremidjian A, Wilkie S, King S, Achkire Y, Olson R et al. Decision support tools for earthquake recovery of businesses. Interim report for CUREe-Kajima phase III project1999.
[18] Hamburger R, Rojahn C, Heintz J, Mahoney M. FEMA P58: Next-generation building seismic performance assessment methodology. 15th World Conf on Earthquake Engineering2012.
[19] Almufti I, Willford M. REDi™ Rating System: Resilience-based Earthquake Design Initiative for the Next Generation of Buildings, Version 1.0. October, ARUP, San Francisco, CA. 2013.
[20] Porter K, Ramer K. Estimating earthquake-induced failure probability and downtime of critical facilities. Journal of business continuity & emergency planning. 2012;5:352-64.
[21] Pfefferbaum R, Pfefferbaum B, Van Horn R. Communities Advancing Resilience Toolkit (CART): The CART Integrated System. Oklahoma City: Terrorism and Disaster Center at the University of Oklahoma Health Sciences Center; 2011.
[22] CCSF Lifelines Council. Lifelines Interdependency Study. Report. San Francisco, CA: City and County of San Francisco Lifelines Council; 2014.
[23] Edwards C, Eidinger J, Schiff A. Lifelines. Earthquake Spectra. 2003;19:73-96.
[24] Nakamura S, Aoshima N, Kawamura M. A review of earthquake disaster preventive measures for lifelines. Proceedings of japan earthquake engineering symposium1983.
[25] Scawthorn C, Miyajima M, Ono Y, Kiyono J, Hamada M. Lifeline aspects of the 2004 Niigata ken Chuetsu, Japan, earthquake. Earthquake Spectra. 2006;22:89-110.
[26] ANG H-S A, TANG HW. PROBABILITY CONCEPTS IN ENGINEERING PLANNING AND DESIGN. Vol. 1, Basic Principles1975.
[27] Tang WH, Ang A. Probability concepts in engineering: Emphasis on applications to civil & environmental engineering: Wiley Hoboken, NJ; 2007.
[28] Sematech/NIST. e-Handbook of Statistical Methods, http://www.itl.nist.gov/div898/handbook/, April, 2018.
[29] Chakravarti IM, Laha RG, Roy J. Handbook of Methods of Applied Statistics: Techniques of Computation, Descriptive Methods and Statistical Inference/by IM Chakravarti, RG Laha, J. Roy: Wiley.; 1967.
[30] Guide MUs. The mathworks. Inc, Natick, MA. 1998;5:333.
[31] Shinozuka M, Feng MQ, Lee J, Naganuma T. Statistical analysis of fragility curves. Journal of engineering mechanics. 2000;126:1224-31.
[32] Schiff AJ. Loma prieta, california, earthquake of october 17, 1989: Lifelines. US: Professional paper, U.S. Geological Survey; 1998.
[33] Schiff AJ. Northridge earthquake: lifeline performance and post-earthquake response. New York: American Society of Civil Engineers. 1995.
[34] Kuraoka S, Rainer J. Damage to water distribution system caused by the 1995 Hyogo-ken Nanbu earthquake. Canadian Journal of Civil Engineering. 1996;23:665-77.
[35] Dynes RR, Haas JE, Quarantelli EL. Some Preliminary Observation on Organizational Responses in the Emergency Period After The Niigata, Japan, Earthquake of June 16, 1964. Ohio state univ columbus disaster research center: DTIC Document; 1964.
[36] Evans N, McGhie C. The Performance of Lifeline Utilities following the 27th February 2010 Maule Earthquake Chile. Proceedings of the Ninth Pacific Conference on Earthquake Engineering Building an Earthquake-Resilient Society2011. p. 14-6.
[37] Knight S, Giovinazzi S, Liu M. Impact and Recovery of the Kaiapoi Water Supply Network following the September 4th 2010 Darfield Earthquake. Dept of Civil and Natural Resources Engineering University of Canterbury Final Year Projects. 2012.

[38] Giovinazzi S, Wilson T, Davis C, Bristow D, Gallagher M, Schofield A et al. Lifelines performance and management following the 22 February 2011 Christchurch earthquake, New Zealand: highlights of resilience. University of Canterbury. Civil and Natural Resources EngineeringUniversity of Canterbury. Geological Sciences, 20112011.
[39] Brocher TM, Baltay AS, Hardebeck JL, Pollitz FF, Murray JR, Llenos AL et al. The Mw 6.0 24 August 2014 South Napa Earthquake. Seismological Research Letters. 2015;86:309-26.
[40] O'Rourke T. Lessons learned for lifeline engineering from major urban earthquakes. Proceedings, Eleventh World Conference on Earthquake Engineering1996.
[41] Katayama T. Seismic behaviors of lifeline utility systems: Lessons from a recent japanese experience. Natural disaster science. 1980;2:1-25.
[42] Jennings PC. Engineering features of the San Fernando earthquake of February 9, 1971. California Institute of Technology; 1st Edition edition. 1971.
[43] Recovery I. The Oregon Resilience Plan. 2013.
[44] Jones LM, Bernknopf R, Cox D, Goltz J, Hudnut K, Mileti D et al. The shakeout scenario. US Geological Survey Open-File Report. 2008;1150:308.
[45] Nojima N. Restoration processes of utility lifelines in the great east Japan earthquake Disaster, 2011. 15th World Conference on Earthquake Engineering (15WCEE)2012. p. 24-8.
[46] ONEMI. Anlisis Multisectorial Eventos 2015: Evento Hidrometeorolgico Marzo-Terremoto/Tsunami Septiembre. Chile: Report by the government of Chile; 2015.
[47] Reed DA, Park J. Lifeline performance evaluation. 13th world conference on earthquake engineering. Vancouver, B.C., Canada2004.
[48] Yamazaki F, Meguro K, Tong H. General review of recent five damaging earthquakes in japan. Bulletin of Earthquake Resistant Structure Research Center. 1995:7.
[49] Eckel EB. Effects of the earthquake of March 27, 1964, on air and water transport, communications, and utilities systems in south-central Alaska: Chapter B in The Alaska earthquake, March 27, 1964: effects on transportation, communications, and utilities. Washington, D.C.: US Government Printing Office; 1967.
[50] Sharpe RL. July 16, 1990 Luzon (Philippines) earthquake. Cupertino, Calif., USA. 1994.
[51] Katayama T, Kubo K, Sato N. Quantitative analysis of seismic damage to buried utility pipelines. Proceedings Sixth World Conference Earthquake Engineering Institute Association Earthquake Engineering, New Delhi1977. p. 3369-75.
[52] Yasuda S, Tohno I. Sites of reliquefaction caused by the 1983 Nihonkai-Chubu earthquake. Soils and Foundations. 1988;28:61-72.
[53] Ahmadizadeh M, Shakib H. On the December 26, 2003, southeastern Iran earthquake in Bam region. Engineering structures. 2004;26:1055-70.
[54] C.N.E. Sismo 7.6 Mw (Magnitud de Momento) samara, region de guanacaste, sector peninsula de Nicoya. Comisin Nacional de Prevencin de Riesgos y Atencin de Emergencias Gobierno de Costa Rica; 2012.
[55] Gillies AG, Anderson DL, Mitchell D, Tinawi R, Saatcioglu M, Gardner NJ et al. The August 17, 1999, Kocaeli (Turkey) earthquake lifelines and preparedness. Canadian Journal of Civil Engineering. 2001;28:881-90.
[56] Soong TT, Yao GC, Lin C. Damage to Critical Facilities Following the 921 Chi-Chi, Taiwan Earthquake. MCEER/NCREE Reconnaissance Report. 2000:33-43.
[57] EERI. Preliminary Observations on the November 3, 2002 Denali Fault, Alaska, Earthquake. EERI Newsletter2003.

Fig.1. Resilience curve

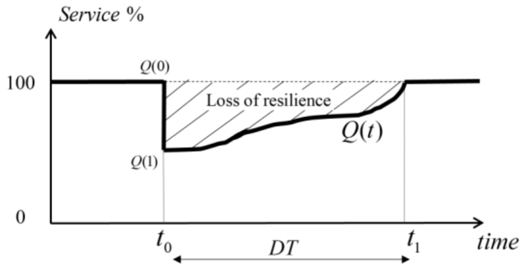

Fig.2. Location of the earthquakes considered in the study

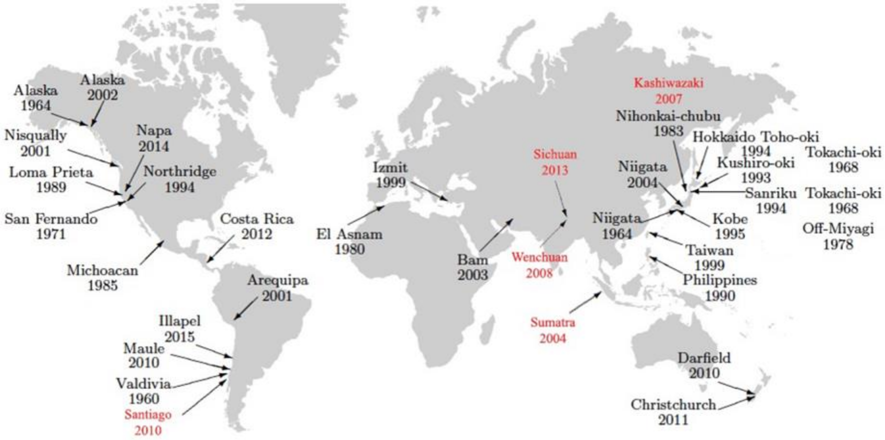

Fig.3. Distribution of the analyzed earthquakes by location

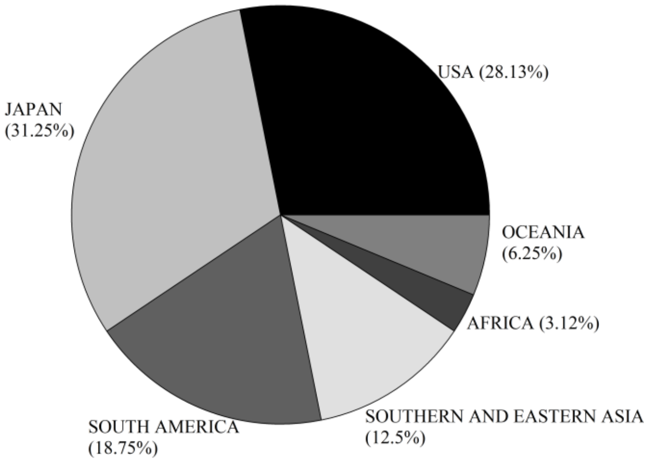

Fig.4. Cumulative frequencies with three theoretical CDF fitting distributions for (a) the water distribution infrastructure, and (b) the power network infrastructure for the data corresponding to EM 6-6.9

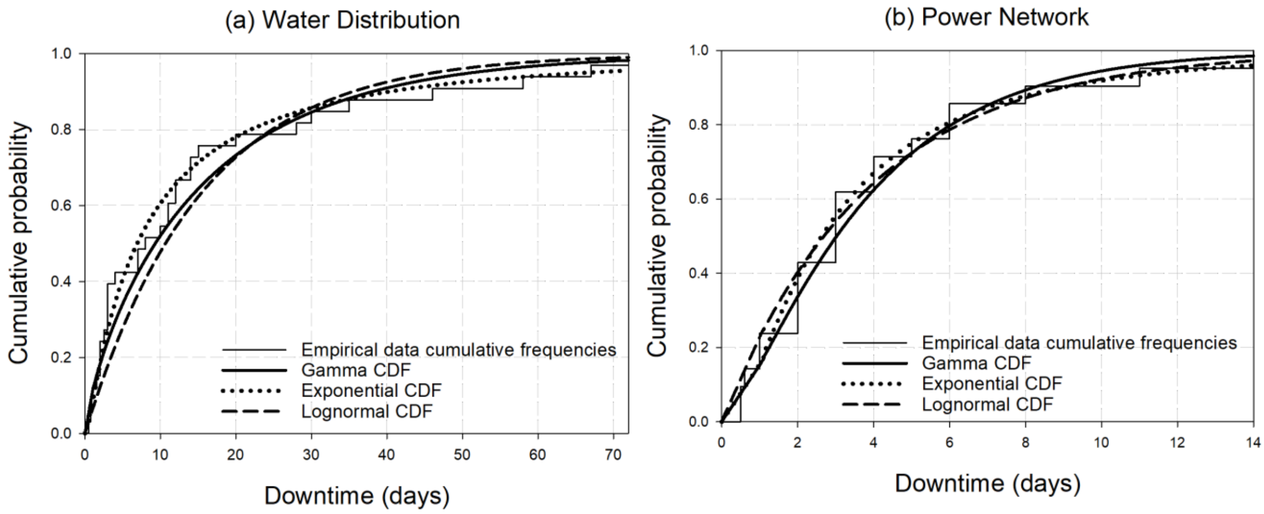

Fig.5. Histograms and PDF fitting distributions for (a) the water distribution infrastructure, and (b) the power network infrastructure for the data corresponding to EM 6-6.9

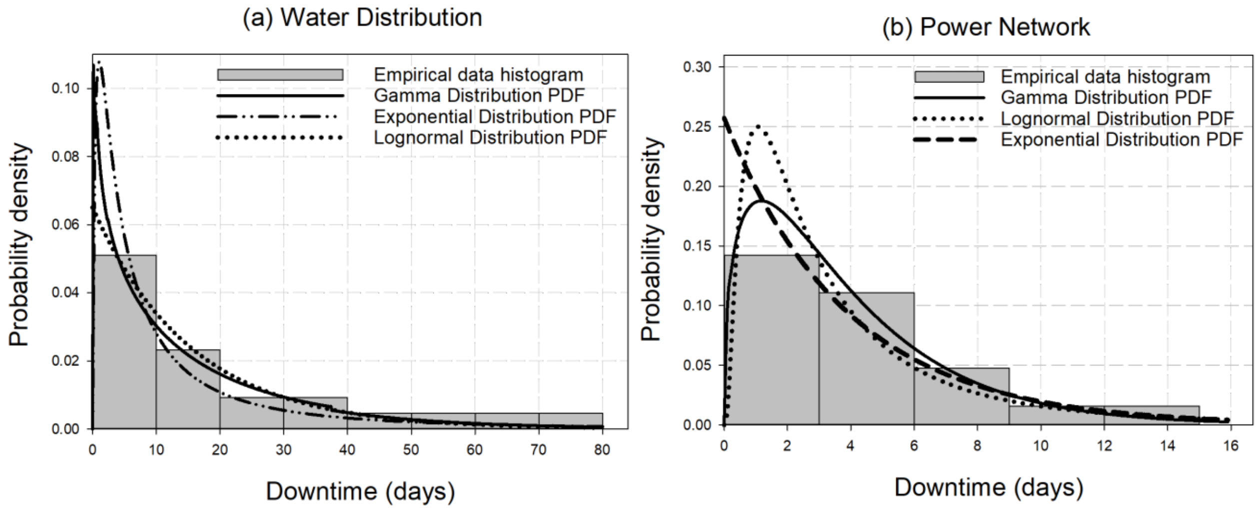

Fig.6. Restoration curves of the lifelines based on the earthquake magnitude

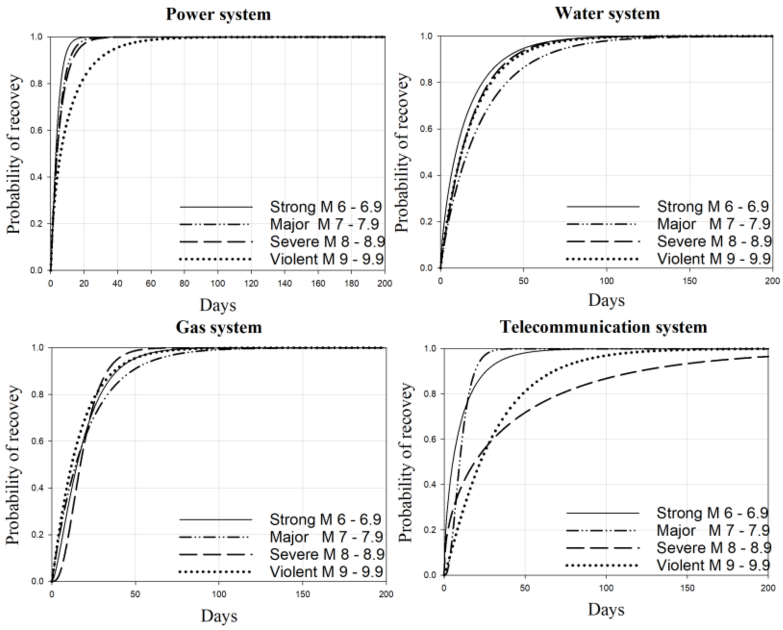

Fig.7. Restoration curves of the lifelines based on the level of development of the countries

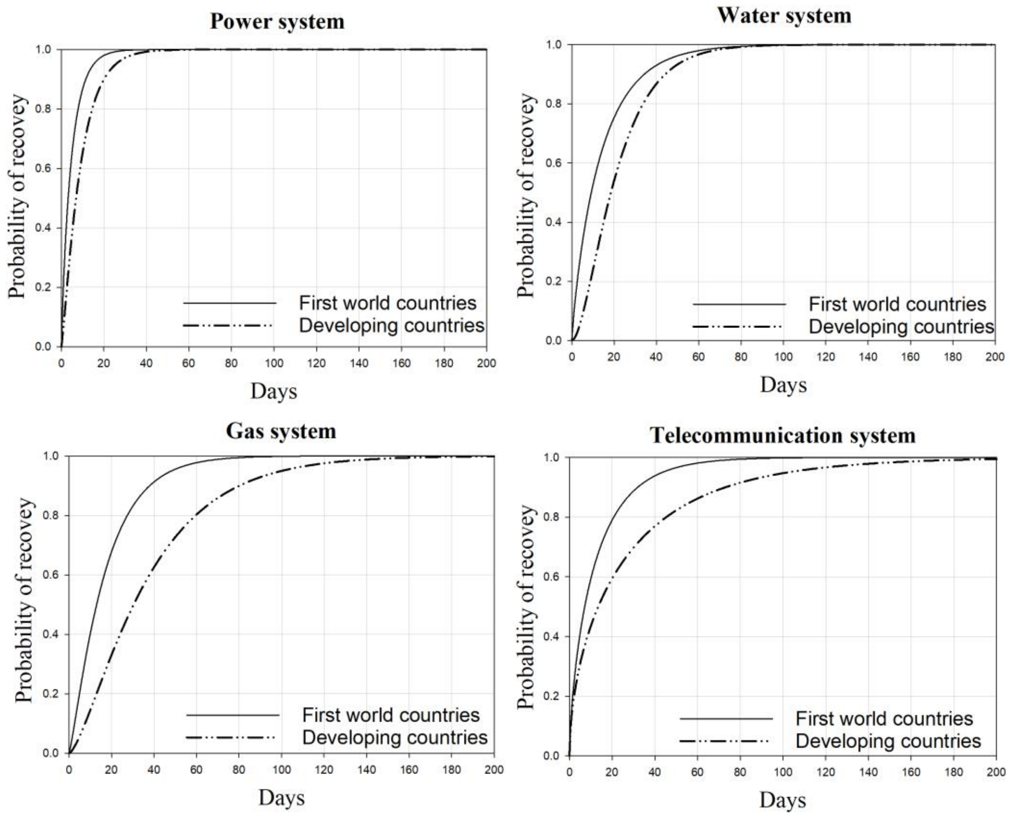

Fig.8. Restoration curves of the lifelines of the USA, Japan, and countries in South America

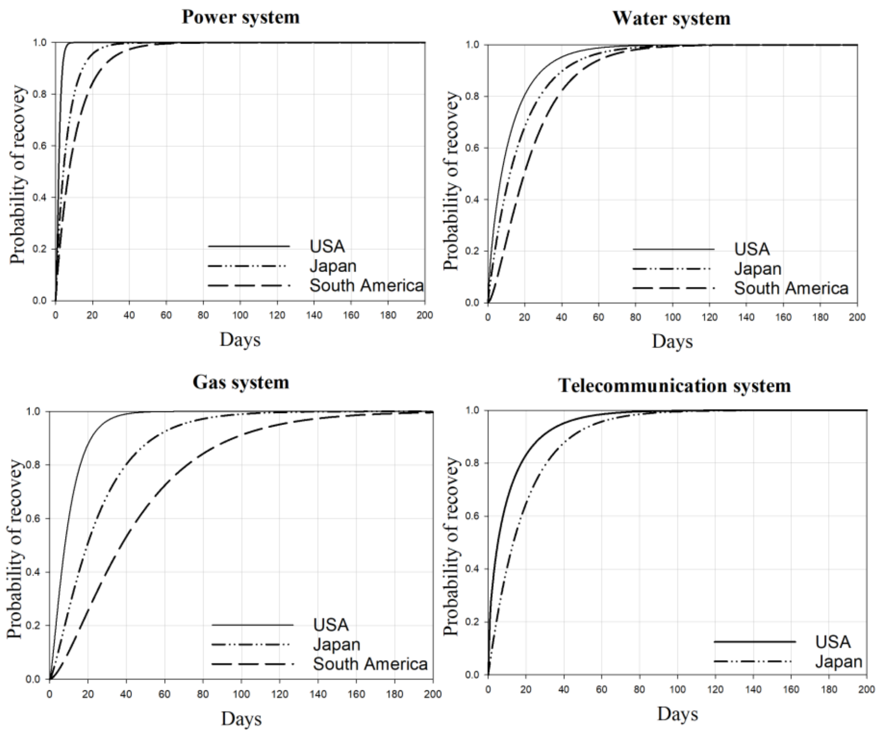

Table 1. Summary of the analysed earthquakes

Earthquake	Year	Country	Magnitude	Reference
Loma Prieta	1989	USA	6.9	[32]
Northridge	1994	USA	6.7	[33]
Kobe	1995	Japan	6.9	[34]
Niigata	2004	Japan	6.6	[35]
Maule	2010	Chile	8.8	[36]
Darfield	2010	New Zealand	7.1	[37]
Christchurch	2011	New Zealand	6.3	[38]
Napa	2014	USA	6	[39]
Michoacán	1985	Mexico	8.1	[40]
Off-Miyagi	1978	Japan	7.4	[41]
San Fernando	1971	USA	6.6	[42]
The Oregon Resilience Plan	2013	USA	9	[43]
LA Shakeout Scenario	2011	USA	7.8	[44]
Tohoku	2011	Japan	9	[45]
Niigata	1964	Japan	7.6	[25]
Illapel	2015	Chile	8.4	[46]
Nisqually	2001	USA	6.8	[47]
Kushiro-oki	1993	Japan	7.8	[48]
Hokkaido Toho-oki	1994	Japan	8.2	[48]
Sanriku	1994	Japan	7.5	[48]
Alaska	1964	USA	9.2	[49]
Luzon	1990	Philippines	7.8	[50]
El Asnam	1980	Algeria	7.1	[24]
Tokachi-oki	1968	Japan	8.3	[51]
Valdivia	1960	Chile	9.5	[23]
Nihonkai-chubu	1983	Japan	7.8	[52]
Bam	2003	Iran	6.6	[53]
Samara	2012	Costa Rica	7.6	[54]
Arequipa	2001	Peru	8.4	[23]
Izmir	1999	Turkey	7.4	[55]
Chi-Chi	1999	Taiwan	7.6	[56]
Alaska	2002	USA	7.9	[57]

Table 2. The number of affected infrastructures and the corresponding downtime for each lifeline

	Lifelines affected							
	Power		Water		Gas		Telecom.	
Earthquakes	No.	DT (days)	No.	DT (days)	No.	DT (days)	No.	DT (days)
Loma Prieta	2	(2), (0.5)	10	(14), (4), (3), (1.5), (2), (1), (3), (3), (7), (4)	5	(30), (16), (11), (10), (10)	6	(3), (4), (0.1), (3), (3), (1.5)
Northridge	3	(3), (0.5), (2)	6	(7), (2), (58), (12), (67), (46)	4	(7), (30), (5), (4)	3	(1), (2), (4)
Kobe	5	(8), (3), (2), (5), (6)	3	(0.5), (8), (73)	3	(84), (11), (25)	3	(1), (5), (7)
Niigata	4	(11), (4), (1)	3	(14), (28), (35)	3	(28), (35), (40)	-	-
Maule	6	(14), (1), (3) (10), (14)	4	(42), (4), (16), (6),	2	(10), (90)	4	(17), (7), (3), (17)
Darfield	3	(1), (2), (12)	2	(7), (1)	1	(1)	3	(9), (2), (3)
Christchurch	3	(14), (0.16)	1	(3)	2	(14), (9)	2	(15), (9)
Napa	1	(2)	6	(20), (0.9), (0.75), (2,5), (12), (11)	1	(1)	-	-
Michoacán	4	(4), (10), (3), (7)	4	(30), (14), (40), (45)	-	-	1	(160)
Off-Miyagi	2	(2), (1)	1	(12)	3	(27), (3), (18)	1	(8)
San Fernando	1	(1)	-	-	2	(10), (9)	1	(90)
The Oregon Resil. Plan	1	(135)	1	(14)	1	(30)	1	(30)
LA Shakeout Scenario	1	(3)	1	(13)	1	(60)	-	-
Tohoku Japan	7	(45, (3), (8), (2), (2), (4)	8	(4.7), (47), (1), (26), (7), (1), (47), (47)	6	(54), (2), (30), (3.5), (13), (18)	3	(49), (21), (49)
Niigata	2	(24)	3	(15), (4), (10)	2	(180), (2)	-	-
Illapel	1	(3)	1	(3)	-	-	-	-
Nisqually	3	(2), (6), (3)	-		-	-	-	-
Kushiro-oki	1	(1)	3	(6), (3), (5)	2	(22), (3)	-	-
Hokkaido Toho-oki	1	(1)	3	(9), (3), (5)	-	-	-	-
Sanriku	1	(1)	3	(14), (12), (5)	-	-	-	-
Alaska	3	(2), (0.75), (1)	5	(14), (5), (1), (7), (14)	3	(1), (5), (2), (14)	2	(1), (21)
Luzon	3	(7), (20), (3)	3	(14), (14), (10)	-	-	3	(5), (10), (0.4)
El Asnam	-	-	1	(14)	-	-	-	-
Tokachi-oki	1	(2)	-	-	2	(30), (20)	-	-
Kanto	2	(7), (5)	1	(42)	2	(180), (60)	1	(13)
Valdivia	1	(5)	1	(50)	-	-	-	-
Nihonkai-chubu	1	(1)	1	(30)	1	(30)	-	-
Bam	1	(4)	3	(14), (10)	-	-	1	(1)
Samara	1	(1)	1	(2)	-	-	1	(1)
Arequipa	1	(1)	3	(32), (34)	-	-	-	-
Izmit	1	(10)	2	(50), (29)	1	(1)	1	(10)
Chi-Chi	3	(40), (14), (19)	1	(9)	1	(14)	1	(10)
Alaska 2002	2	(2), (0.5)	10	(14), (4), (3), (1.5), (2), (1), (3), (3), (7), (4)	1	(3)	6	(3), (4), (0.1), (3), (3), (1.5)

Note: No = the number of affected infrastructures; DT = the downtime in days.

Table 3. Downtime data points and corresponding frequencies for the water and power infrastructures with EM 6-6.9

WATER	DT (days)	0.5	0.75	0.9	1	1.5	2	2.5	3	4	7	8	10	11	12	14	15	20	28	30	35	46	58	67	73
	Freq.	1	1	1	1	1	3	1	4	1	2	1	1	2	2	2	1	1	1	1	1	1	1	1	1
POWER	DT (days)	0.5	0.6	1	2	3	4	5	6	8	11	14													
	Freq.	2	1	2	4	4	2	1	2	1	1	1													

Table 4. *Kolmogorov-Smirnov* goodness-of-fit test for the water and power infrastructures for EM=6-6.9

Theoretical distribution	Water distribution network for EM=6-6.9		Power network for EM=6-6.9	
	D_n	D_n^{α} ($\alpha = 0.05$, $n = 24$)	D_n	D_n^{α} ($\alpha = 0.05$, $n = 11$)
Gamma distribution	0.098	0.245	0.0745	0.395
Exponential distribution	0.122		0.0811	
Lognormal distribution	0.216		0.0837	

Table 5. *Chi-square* goodness-of-fit test for the water and power infrastructures for EM=6-6.9

Theoretical distribution	Water distribution system, EM=6-6.9			Power network, EM=6-6.9		
	Chi-square χ_f^2	$f = k - 1$	$C_{1-\alpha,f}$ ($\alpha = 0.05$)	Chi-square χ_f^2	$f = k - 1$	$C_{1-\alpha,f}$ ($\alpha = 0.05$)
Gamma distribution	6.23	5	11.07	5.45	3	7.81
Exponential distribution	7.8	4	9.48	13.98	2	5.99
Lognormal distribution	10.51	5	11.07	15.08	3	7.81

Table 6. The distributional parameters derived for Category 1 restoration curves

	Power system				Water system			
Parameters	*M=6-6.9*	*M=7-7.9*	*M=8-8.9*	*M=9-9.9*	*M=6-6.9*	*M=7-7.9*	*M=8-8.9*	*M=9-9.9*
α	1.4319	0.94975	1.19011	0.627072	0.749101	0.901529	1.02229	0.950171
β	2.71367	5.84364	4.27133	17.3425	20.5155	27.2454	17.8171	19.805
	Gas system				Telecommunication system			
Parameters	*M=6-6.9*	*M=7-7.9*	*M=8-8.9*	*M=9-9.9*	*M=6-6.9*	*M=7-7.9*	*M=8-8.9*	*M=9-9.9*
α	1.57458	0.997162	3.2153	1.0926	0.622306	3.07575	0.475536	1.17455
β	12.009	20.7863	5.90924	15.1473	16.1094	3.51134	92.0014	25.9674

Note: M = the earthquake magnitude in Richter scale.

Table 7. Classification of the countries based on their level of development

First world countries	developing countries
USA	*Chile*
Japan	*Mexico*
New Zealand	*Philippines*
	Algeria
	Chile
	Iran
	Costa Rica
	Peru
	Turkey
	Taiwan

Table 8. The distributional parameters derived for Category 2 restoration curves

Parameters	Power system		Water system	
	First world countries	*Developing countries*	*First world countries*	*Developing countries*
α	0.883805	1.25039	0.845769	1.86575
β	5.46925	7.35006	16.8706	11.963
	Gas system		Telecommunication system	
Parameters	*First world countries*	*Developing countries*	*First world countries*	*Developing countries*
α	1.23635	1.50336	0.671797	0.546505
β	14.0461	25.6092	18.7854	50.4214

Table 9. The distributional parameters derived for Category 4 restoration curves

Parameters	Power system			Water system		
	USA	*Japan*	*South America*	*USA*	*Japan*	*South America*
α	2.24621	0.931013	0.936271	0.774639	0.973	1.5892
β	0.881828	6.71312	11.4201	15.4265	17.924	15.4952
	Gas system			Telecommunication system		
Parameters	*USA*	*Japan*	*South America*	*USA*	*Japan*	*South America*
α	1.40685	1.36345	1.59156	0.535494	1.00736	0.497757
β	7.26358	18.6439	29.3214	19.7517	18.9853	135.943