RESTORATION CURVES TO ESTIMATE THE DOWNTIME OF CRITICAL INFRASTRUCTURES

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ABSTRACT

Modeling the performance of critical infrastructures and their interdependencies is an important task in the resilience assessment. In this paper, restoration curves for four critical lifelines (power, water, gas, telecommunication, and transportation) have been developed using a probabilistic approach. To do that, a large database on infrastructure downtime has been collected for most of the earthquakes that occurred in the past century. The restoration curves have been grouped based on the earthquake magnitude and the level of development of the country in which the earthquake occurred. The curves are 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.

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Modeling the performance of critical infrastructures and their interdependencies is an important task in the resilience assessment. In this paper, restoration curves for four critical lifelines (power, water, gas, telecommunication, and transportation) have been developed using a probabilistic approach. To do that, a large database on infrastructure downtime has been collected for most of the earthquakes that occurred in the past century. The restoration curves have been grouped based on the earthquake magnitude and the level of development of the country in which the earthquake occurred. The curves are 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.

Introduction

The performance of infrastructures after earthquakes includes their capacity to absorb the shock and their willingness to bounce back to the initial state. While the structural damage following the disaster can be easily computed using fragility curves, the structural performance during the restoration phase is still at an early stage of research. After an earthquake, the functionality of damaged structures stops partially or totally until they are recovered. This period is known as the Downtime. The downtime is an essential parameter to estimate the resilience of a system. 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" [1-3]. Several attempts have been made to evaluate the resilience of large systems using indicators and modeling approaches [4-9] but none of these approaches considered the downtime as a complex variable.

Under the resilience context, downtime is the time span between the moment that the earthquake hits ($t_0=0$), when the functionality $Qi(t)$ drops to $Qi(0)$, until the time when the functionality of the utility is completely restored [3]. Some of the factors that can influence the downtime are: the structural inspection, the assessment of damage, the finance planning, the

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bidding process, the repair effort, and the engineering consolation [10].One of the first attempts to evaluate the disruption time following an event was done by Basöz and Mander (1999) [11]. 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 [12]. 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 electronic tool PACT, which estimates the required repair time of buildings based on the damaged structural and non-structural components as well as on the building's contents. 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 [13]. Moreover, Almufti and Willford (2013) have suggested a modified downtime methodology based on the results coming from PACT. All details can be found in the REDi rating system report [14]. Also, a performance-based earthquake engineering method to estimate the downtime of infrastructures using fault trees has been introduced [15]. This method is applicable only when the downtime is mostly controlled by the non-structural systems damage. It also assumes that the restoration starts immediately after the event and the damaged components are repaired in parallel.

Generally, the downtime of infrastructures varies according to several factors, such as the characteristics of the exposed structure, the earthquake intensity, and the resources to recover the damaged structure. Having so many factors makes the process of estimating the downtime even harder. Therefore, there is a need to have a simple and practical model for estimating the downtime of infrastructures. This work aims at developing an empirical probabilistic model for estimating the downtime of four lifelines (power, water, gas, telecommunication, and transportation) following an earthquake. First, a large database has been gathered from a wide range of literature [16; 17]. This database contains real information on a large number of earthquakes that took place in the last century as well as on the downtimes of the affected infrastructures. Fragility restoration functions were derived from the database using a probabilistic analysis. For each of the lifelines, a group of fragility curves were obtained in accordance with the earthquake magnitude and the level of development of the country in which the earthquake occurred. Those functions were 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.

Downtime Database of Lifelines

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 according to Richter scale of magnitude. A number of other damaging earthquakes that occurred during the same period have been collected but they were 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 some useful illustrations for the recovery behavior of the examined lifelines.

Table 1. Summary of the analyzed earthquakes.

Earthquake	Year	Country	Magnitude	Reference
Loma Prieta	1989	USA	6.9	[18]
Northridge	1994	USA	6.7	[19]
Kobe	1995	Japan	6.9	[20]
Niigata	2004	Japan	6.6	[21]
Maule	2010	Chile	8.8	[22]
Darfield	2010	New Zealand	7.1	[23]
Christchurch	2011	New Zealand	6.3	[24]
Napa	2014	USA	6	[25]
Michoacán	1985	Mexico	8.1	[26]
Off-Miyagi	1978	Japan	7.4	[27]
San Fernando	1971	USA	6.6	[28]
The Oregon Resilience Plan	2013	USA	9	[29]
LA Shakeout Scenario	2011	USA	7.8	[30]
Tohoku	2011	Japan	9	[31]
Niigata	1964	Japan	7.6	[32]
Illapel	2015	Chile	8.4	[33]
Nisqually	2001	USA	6.8	[34]
Kushiro-oki	1993	Japan	7.8	[35]
Hokkaido Toho-oki	1994	Japan	8.2	[35]
Sanriku	1994	Japan	7.5	[35]
Alaska	1964	USA	9.2	[36]
Luzon	1990	Philippines	7.8	[37]
El Asnam	1980	Algeria	7.1	[38]
Tokachi-oki	1968	Japan	8.3	[39]
Valdivia	1960	Chile	9.5	[40]
Nihonkai-chubu	1983	Japan	7.8	[41]
Bam	2003	Iran	6.6	[42]
Samara	2012	Costa Rica	7.6	[43]
Arequipa	2001	Peru	8.4	[40]
Izmir	1999	Turkey	7.4	[44]
Chi-Chi	1999	Taiwan	7.6	[45]
Alaska	2002	USA	7.9	[46]

Table 2 lists the complete database used to create the restoration curves of each lifeline. The different earthquakes are listed in a random order. It is notable that each earthquake has caused damage to multiple infrastructures 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. However, the affected infrastructures required 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 different amount of time to recover: 2 and 0.5 days respectively. In addition, 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.

Table 2. The number of affected infrastructures and the corresponding downtimes.

Earthquakes	Lifelines affected							
	Power		Water		Gas		Telecom.	
	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)

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

Methodology

The main challenge faced in this work is to illustrate the gathered data in the form of restoration curves. Typically, the procedure followed for constructing restoration curves is similar to that of fragility curves. The restoration process is one of the most uncertain variables in the resilience analysis; therefore, it is necessary to approach it in probabilistic terms. This is done by performing a statistical analysis to the raw data, trying to fit it to a statistical distribution. Nevertheless, choosing the right distribution can be a hard task due to the high number of distributions that exist in the literature. The gamma distribution was found to be the optimal fit to most of the database; hence, it is used to build the restoration curves. The probability distribution (PDF) of the gamma distribution is given by:

$$f(x) = \frac{1}{\beta^{\alpha}\Gamma(\alpha)} x^{\alpha-1} e^{-x/\beta} \tag{1}$$

where $\Gamma(.)$denotes the gamma distribution, α is the shape parameter, which allows the gamma distribution to take variety of shapes, β is the scale parameter whose effect is to stretch (greater than one) or squeeze the distribution (less than one). It is important to note that the exponential distribution is a special case of the gamma distribution function when the shape parameter α is set equal to 1. To obtain the values of α and β, it is first necessary to compute the mean and the standard deviation μ_D and σ_D. The mean value μ_D denotes the average value of a database consisting of n entries, and it is defined by:

$$\mu_D = \frac{\sum_{i=1}^{n} x_i}{n} \tag{2}$$

while the standard deviation σ_D is the dispersion of a random variable of the database with respect to the mean value. The value of the standard deviation is obtained using the following formula:

$$\sigma_D = \sqrt{\frac{\sum_{i=1}^{n} (x_i - \mu_D)^2}{n-1}} \tag{3}$$

After obtaining both μ_D and σ_D, the parameters α and β can be estimated using Eq. 4, 5.

$$\beta = \frac{\sigma_D^2}{\mu_D} \tag{4}$$

$$\alpha = \frac{\mu_D^2}{\beta} \tag{5}$$

It is important to note that the restoration curves developed for different damage states within the same sample should not intersect in order to describe meaningful results. Intersection of restoration curves may occur when the restoration curves are fitted independently of one another [47]. So, in order to avoid the intersection of the restoration curves corresponding to different damage states, the same standard deviation has been assumed [48;49].

Restoration Curves

Restoration curves were developed for the power, water, gas, and telecommunications systems using the collected data. The curves are plotted based on *the number of days required to restore full service to customers that lost service immediately after the earthquake* (horizontal axis), and *the likelihood that the utility will be completely restored to the customers* (vertical axis). To provide a better understanding of the restoration process, the collected data has been divided based on two categories:

Category I: Earthquake Magnitude

Figure 1 shows the restoration curves of 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 1 where 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 seems to have the shorter downtime as the curves reach the probability of 100% just 60 days after the event, unlike the other infrastructures, which needed at least 100 days to achieve a restoration probability of 100%. 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. This behavior is shown in Figure 1 where the restoration probability of the telecommunication system did not reach 100% even after 100 days. Lastly, the gas and the water systems are almost identical where both reach a restoration probability of 100% after 100 days.

Category II: First world countries vs developing countries

Figure 2 shows the restoration curves of the database grouped according to the level of development of the countries. From the figure, it is clear that the infrastructure restoration rate in the developing countries is lower than in the developed countries for all four lifelines. Moreover, the recovery rate of the power system for both groups of countries is the highest compared to that of other lifelines, usually because the functionality of the different lifelines is greatly dependent on the power lifeline.

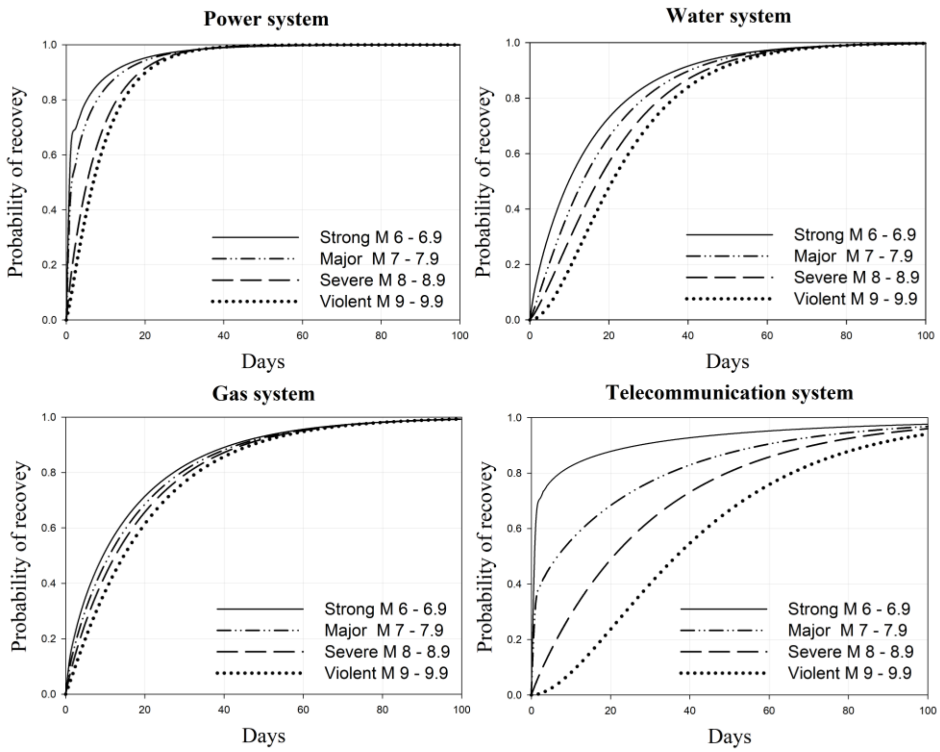

Figure 1. Restoration curves of the lifelines based on the earthquake magnitude.

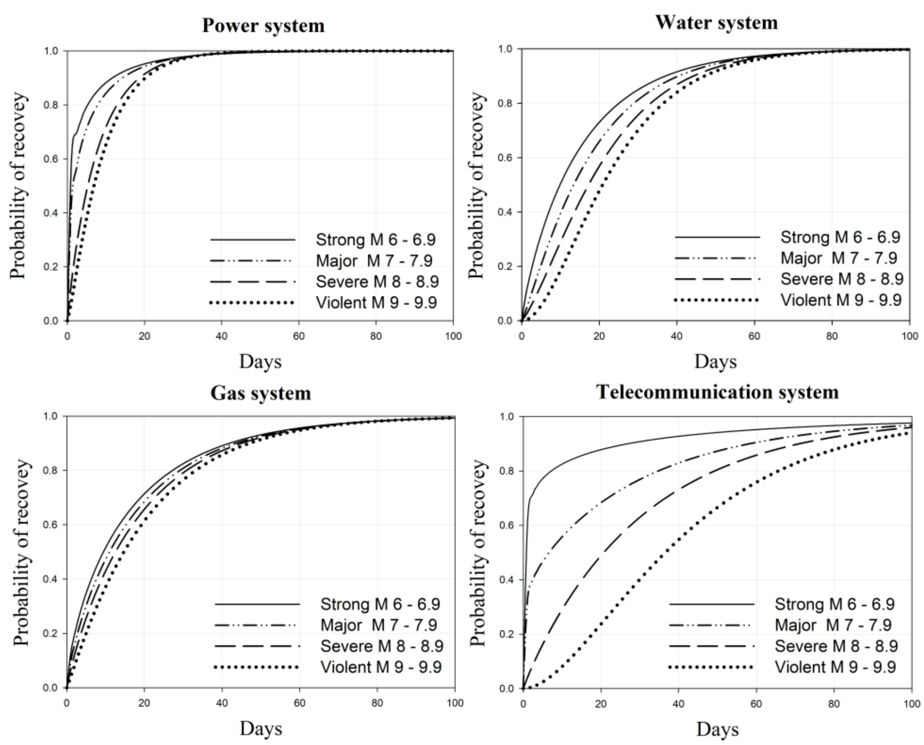

Figure 2. Restoration curves of the lifelines based on the level of development of the countries.

Conclusions

Downtime estimation is one of the most ambiguous aspects in the resilience engineering. Estimating the resilience of infrastructure 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 earthquakes. This model used a large set of database for earthquake events that occurred over the last few decades. 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 likelihood that the utility will be completely restored to the customers (vertical axis).

With the absence of such models in the literature, this work will provide a useful tool that can be used by decision makers to estimate the downtime of infrastructures. It will also allow them to evaluate the infrastructures resilience because the downtime is a key parameter in the resilience assessment. Future work will be oriented towards extending the database to include more earthquakes. In addition, special attention will be given to the infrastructure interdependency to improve the accuracy of the restoration curves. Other lifelines, such as the transportation system, will also be analyzed once satisfactory data of a considerable amount of earthquakes is collected.

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