RESTORATION TIME OF INFRASTRUCTURES FOLLOWING EARTHQUAKES

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Abstract:

Estimating the downtime of infrastructures following a disastrous event is one of the most important, yet uncertain aspects in the resilience evaluation process. This paper proposes an empirical probabilistic model for estimating the downtime of lifelines following earthquakes. First, a large database has been collected from a wide range of literature. This database contains data on downtimes of infrastructures collected for a number of earthquakes that took place in the past century. Fragility restoration functions have been derived using the gamma distribution, which was selected because of its fit with the distribution of the collected data. For each of the lifelines, different fragility functions have been obtained for different earthquake magnitudes. The functions were represented 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: Downtime, Restoration curves, Infrastructures, Seismic resilience, Recovery.

1 Introduction

Estimating the downtime infrastructures is a subject on which scientists and policy makers have recently put much attention. The downtime can be defined as the time required to achieve a recovery state after a disastrous event; therefore, it is strictly linked with the indirect losses of the damaged infrastructure. Furthermore, the downtime is also an essential parameter to estimate resilience. 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]. Under this 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] (Figure 1). Some of the factors that can affect the downtime are: the structural inspection, the assessment of damage, the finance planning, the bidding process, the repair effort, and the engineering consolation [4].

One of the first attempts to evaluate the disruption time following an event was done by Basöz and Mander (1999) [5]. 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 [6]. 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 [7]. 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 [8]. Also, a performance-based earthquake engineering method to estimate the downtime of infrastructures using fault trees has been introduced [9]. 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, 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 infrastructure. With all of these factors, the process of estimating the downtime becomes even harder. Therefore, it is crucial to have a simple model for estimating the downtime of infrastructures. 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 studied in this work (power, water, gas, and telecommunication). First, a large database has been collected from a wide range of literature. The database contains real data on a number of seismic events that occurred in the last century as well as on the downtimes of the affected infrastructures. Fragility restoration functions have been obtained using the gamma distribution, which has been selected because of its fit with the distribution of the collected data. For each of the lifelines, a group of fragility curves has been derived in accordance with the earthquake magnitude, and they 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.

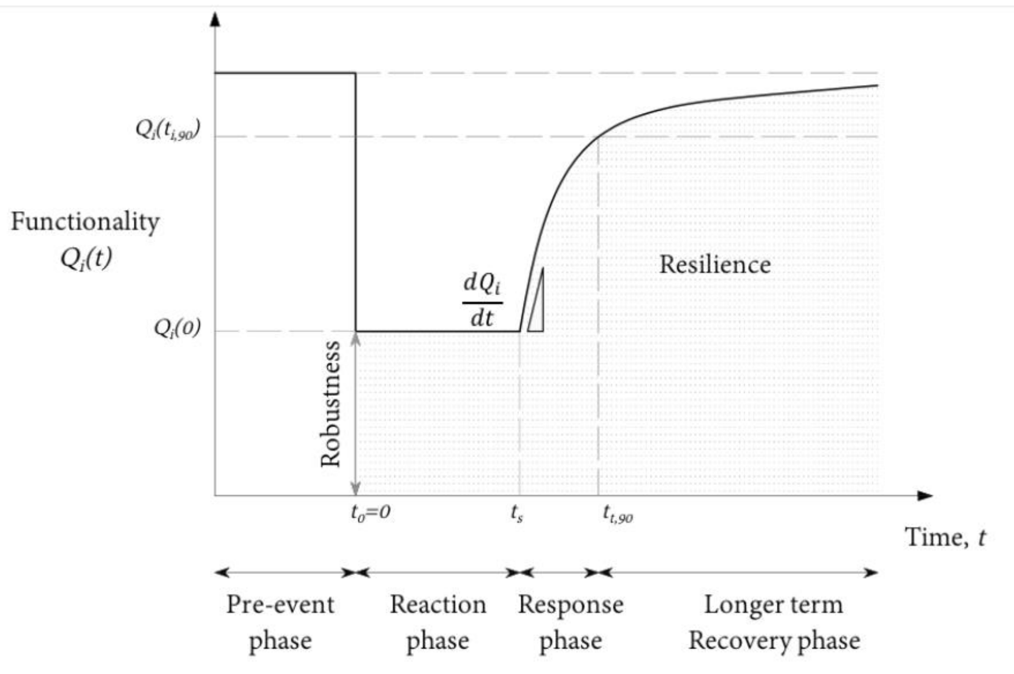

Figure 1: Resilience concept

2 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 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 behaviour of the examined lifelines.

Table 1: Summary of the analyzed earthquakes

Earthquake	***Year***	***Country***	***Magnitude***	***Reference***
Loma Prieta	1989	USA	6.9	[10]
Northridge	1994	USA	6.7	[11]
Kobe	1995	Japan	6.9	[12]
Niigata	2004	Japan	6.6	[13]
Maule	2010	Chile	8.8	[14]
Darfield	2010	New Zealand	7.1	[15]
Christchurch	2011	New Zealand	6.3	[16]
Napa	2014	USA	6	[17]
Michoacán	1985	Mexico	8.1	[18]
Off-Miyagi	1978	Japan	7.4	[19]
San Fernando	1971	USA	6.6	[20]
The Oregon Resilience Plan	2013	USA	9	[21]
LA Shakeout Scenario	2011	USA	7.8	[22]
Tohoku	2011	Japan	9	[23]
Niigata	1964	Japan	7.6	[24]
Illapel	2015	Chile	8.4	[25]
Nisqually	2001	USA	6.8	[26]
Kushiro-oki	1993	Japan	7.8	[27]
Hokkaido Toho-oki	1994	Japan	8.2	[27]
Sanriku	1994	Japan	7.5	[27]
Alaska	1964	USA	9.2	[28]
Luzon	1990	Philippines	7.8	[29]
El Asnam	1980	Algeria	7.1	[30]
Tokachi-oki	1968	Japan	8.3	[31]
Kanto	1923	Japan	7.8	[32]
Valdivia	1960	Chile	9.5	[33]
Nihonkai-chubu	1983	Japan	7.8	[34]
Bam	2003	Iran	6.6	[35]
Samara	2012	Costa Rica	7.6	[36]
Arequipa	2001	Peru	8.4	[33]
Izmir	1999	Turkey	7.4	[37]
Chi-Chi	1999	Taiwan	7.6	[38]
Alaska	2002	USA	7.9	[39]

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 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. 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 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	(30)	2	(14), (9)	2	(15), (9)
Napa	1	(2)	6	(20), (0.9), (0.75), (2,5), (12), (11)	1	(1)	-	-
Michoacán	4	(4), (1), (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), (40)	8	(47), (47), (1), (26), (7), (1), (47), (47)	6	(54), (2), (30), (35), (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), (2), (3)	3	(14), (14), (10)	-	-	3	(5), (1), (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	(5)	-	-	-	-
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	(1)	2	(5), (29)	1	(1)	1	(10)
Chi-Chi	3	(4), (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.

3 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.

After some investigations, 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 Γ(.) 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:

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

On the other hand, 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 with 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 Equations (4) and (5).

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

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

Afterwards, the restoration curves for each lifeline have been created using the software MATLAB® (Guide 1998). 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 each curve corresponding to a specific damage state is fitted independently of one another [40]. So in order to avoid the intersection of the restoration curves corresponding to different damage states, the same standard deviation has been assumed, as suggested in the method described in [41], 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 derivation that is assumed the same for all fragility curves.

4 RESTORATION CURVES

Restoration curves were developed for the power, water, gas, and telecommunications systems based on the quantitative data obtained from the collected earthquakes. 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). The restoration curves of the studied infrastructures are presented in Figure 2. 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), and this has led to obtaining four independent restoration curves for each lifeline. It is important to note that more groups with a smaller magnitude range could have been created; however, in this study, the database was not large enough, and therefore it was preferred to limit the number of groups to only four.

The restoration curves of the lifelines are characterized by a similar behaviour. 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 result 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, which delays its restoration until the power system is recovered. This behaviour is shown in Figure 4, 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 of them reach a restoration probability of 100% after 100 days.

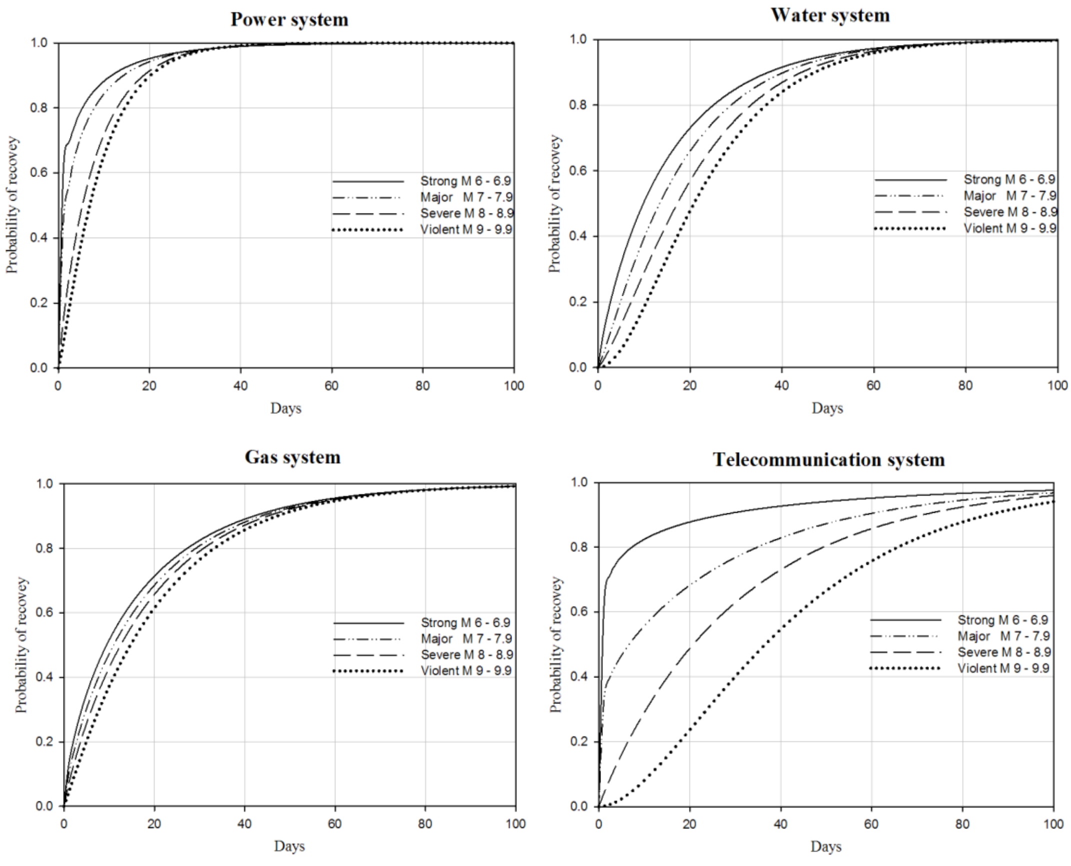

Figure 2: Restoration curves of the four lifelines

5 CONCLUDING REMARKS

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 is based on a large set of database for earthquake events that occurred over the last few decades. Different types of statistical distribution have been tested, and the gamma distribution has been chosen as it has the best fit to the collected data. Four main lifelines were considered in this work (power, water, gas, and telecommunication). For each of them, a group of four 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).

Given that such models are still missing in literature, this work will provide a very useful tool to estimate the downtime of infrastructures when struck by earthquakes. It will also allow evaluating the infrastructures' resilience as the downtime is a key parameters 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 will increase 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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