EMPIRICAL FRAGILITY CURVES FOR REINFORCED CONCRETE AND TIMBER HOUSES, USING DIFFERENT INTENSITY MEASURES

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Abstract

Chile is a country affected by large scale seismic events, among which are those that occurred in the years 1960 (Valdivia, Mw=9.5, the biggest magnitude in history), 2010 (Maule, Mw=8.8), 2014 (Iquique, Mw=8.2) and 2015(Illapel, Mw=8.3) earthquakes. The 2010 Maule earthquake and tsunami caused damages in 370.051 houses. From these houses, 81.444 collapsed, 108.914 suffered severe damage, and 179.693 suffered slight damage. The 2014 earthquake caused damage in 9680 houses. Among these, 4.582 suffered severe damage and 38.100 inhabitants were estimated to be affected. The latest large earthquake in Chile occurred in 2015, affecting the Coquimbo Region. The estimated number of damaged houses in this earthquake is 6.763, where 1.420 houses collapsed. The damaged houses in this region represent 68% of the housing inventory. Chile has empirical data that can be used to estimated future damage. The estimation of the impact of earthquakes on the building inventory can support the development of risk reduction strategies. Past events are useful to calibrate risk models and they contribute to the understanding of the consequences of earthquakes. The objective of this study is to estimate empirical fragility curves of reinforced concrete and timber houses using damage information of the 2014 and 2015 earthquakes. The fragility curves are estimated using four Intensity Measures (IM) to identify which IM is better correlated with the observed damage. The methodology used has three-steps: (1) organize the damage observed for 2014 and 2015 earthquakes according to the Hazus damage scale (slight, moderate, extensive and collapse), (2) Using the following IMs: Modified Mercalli Intensity (MMI), Peak Ground Acceleration (PGA), Peak Ground Velocity (PGV) and Spectral Acceleration at a period of 0.3 seconds ($S_A(0.3)$), and (3)the empirical fragility curves are estimated using Maximum Likelihood Estimation and the methodology according to FEMA P-58. The obtained results indicate that, for the houses analyzed, SA(0.3) is the IM that better correlates with observed damage.

Keywords: Fragility Curves, Earthquakes, Data Survey, intensity measure, PGA, PGV, MMI, S.A(0.3)

1. Introduction

Everyday millions of people in the word are affected by different hazards, such as earthquakes, tsunamis, among others [1]. Chile is one of the countries with the largest level of damage due to natural disasters [2]. Recent earthquakes have encouraged governments and private sector around the world to develop seismic risk assessment to reduce the earthquake damage. For the estimation of seismic risk, it is necessary to consider seismic hazard, an exposure model and seismic fragility curves. The seismic hazard is the characterization of the movement of the soil in a certain place, which can be done either probabilistically or deterministically. The exposure model is the number of people and elements exposed to the effects of an earthquake. Finally, fragility curves provide the probability of exceedance a damage limit state of a structure given the intensity of the ground motion.

According to the method used to developed the fragility curves, three types of fragility curves may be distinguished [3]: analytical, empirical, and those based or expert judgement. In order to properly assess seismic risk, fragility curves need to represent the reality of the studied urban area. Empirical fragility curves are estimated from damage observation after seismic events and therefore, should provide a good damage prediction for a given level of earthquake intensity [3]. The method used to obtain these fragility curves consists on fitting a probability distribution function to the observed damage [4].

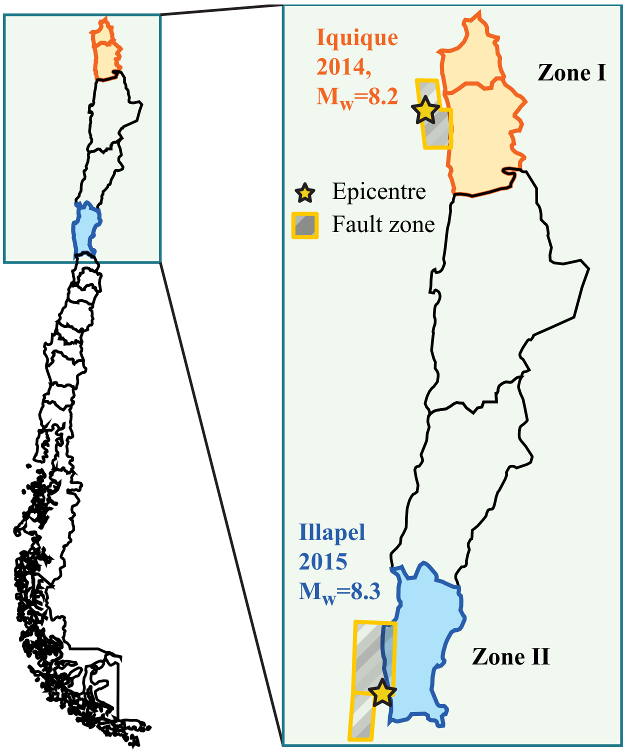
Seismic risk analysis procedures containing seismic hazard and vulnerability analysis are generally used to identify high risk areas that require further investigation. A crucial component of seismic vulnerability analysis is the fragility curves for which currently there is no agreement on the ground motion intensity measure to use. There are two main categories of ground motion intensity measures (IM) that are used in empirical vulnerability and fragility assessment: (1) those based on macroseismic intensity (e.g., Modified Mercalli Intensity (MMI)), (2) and those based on instrumental quantities (e.g., peak ground acceleration) [4] (Rossetto et al. 2014).

The choice of IM to be employed in the risk analysis is structure – specific. In principle, it is mainly determined by the desired properties of the selected IM (e.g., sufficiency and efficiency) and also considering issues such as robustness to GM scaling [5]. In earthquake engineering practice, the Peak Ground Acceleration (PGA) and Spectral Acceleration (Sa(T)) are commonly used IMs (Suzuki & Iervolino 2019). PGA is convenient because hazard models are typically developed in terms of PGA (Suzuki and Iervolino 2019), but Sa(T) is generally considered more efficient than PGA, and sufficient in several situations [6]. Hence, it is often used as the IM for the development of fragility functions; however, fragility expressed in terms of spectral acceleration at different vibration periods cannot be directly compared. Another IM used is Modified Mercalli Intensity (MMI), a macrosesismic intensity scale based on how strongly the ground shaking experienced in an area is, as well as building damage observations. This means that this IM can be obtained in any site where there are people that can make observations, and there are damaged buildings from which observations can be made. In fact, the same damage survey that is used to collect fragility or vulnerability data can also be used to estimate macroseismic intensity [4]. Finally, Akkar and Özen (2005) [7] indicate that Peak Ground Velocity (PGV) is an IM that effectively correlates earthquake magnitude, effective ground-motion duration, and frequency contents of ground motions which can provide information for the variation of deformation demands on the simple degree of freedom system.

This article presents a set of empirical fragility curves that can be used in Chile for seismic vulnerability assessment of reinforced concrete and timber houses calculated using different intensity measures (PGA, PGV, Sa(0.3) and MMI). The databases involved in this study were obtained from the 2014 Iquique and 2015 Illapel earthquakes, which occurred in the north of the country. The official data survey of damaged houses during the 2014 and 2015 earthquakes are used to estimate these fragility curves.

2. Damage data from the 2014 Iquique and 2015 Illapel earthquakes

The damage data from the 2014 and 2015 earthquakes was obtained from databases compiled by the Ministry of housing and urbanism (MINVU). Figure 1 shows the rupture zones and the regions of the country affected by these two earthquakes. Earthquake damage was classified according to the Hazus [8] damage scale which proposes four damage states (slight, moderate, extensive and collapse). A damage level was assigned to each house based on cost ratio, which is defined as the ratio of repair cost to building replacement cost [9]. Repair cost ratios defined by Hazus were used in this study. Slight damage (S) was assigned to a cost ratio of less than 20%, moderate damage (M) to a cost ratio of less 50%, extensive damage (E) to a cost ratio of less than 100%, and collapse (C) was assigned to a cost ratio of 100% or more. No damage (N) was considered when the cost ratio was 0%. The houses have one or two floors and between 45 and 55 square meters. It is important to indicate that the damage was self-reported, which is to say that victims of the earthquake reported damage directly to MINVU.



	Earthquake	
Parameter	Iquique 2014	Illapel 2015
Regional zone	II	III
Magnitude [Mw]	8.2	8.3
Rake [°]	107	83
Longitude [°]	-70.796	-71.674
Latitude [°]	-19.610	-31.573
Depth [km]	25.5	25.5
Strike [°]	358	353
Dip [°]	12	19

Regional zone	**Regions**
Zone I	I, XV
Zone II	IV

Fig. 1 – Affected regions after the 2014 and 2015 earthquakes and associated rupture characteristics

The database from the 2014 Iquique earthquake contains information on 1,685 reinforced concrete and timber damaged houses (N_{ds}) located in the two regions affected by the earthquake and which are highlighted in Figure 1 (Regions I and XV). According to the exposure model by Santa María et al. (2017) [10] 32,819 houses are located in this area (N_{em}). Therefore, the database with damage information represents 5.13% of the total inventory of houses. Table 1 shows the number of reinforced concrete and timber houses in this database.

Table 1 – Damage information of houses by building class due to the 2014 earthquake

Taxonomy	N_{ds}	N_{em}	N_{ds}/N_{em} (%)	Houses per damage state (%)				
				N	S	M	E	C
Reinforced Concrete	1,218	14,008	8.70%	91.30%	5.44%	2.85%	0.34%	0.06%
Timber	467	18,811	2.48%	97.52%	1.61%	0.71%	0.14%	0.02%

The database from the 2015 Illapel earthquake contains information on 1,418 reinforced concrete and timber damaged houses (N_{ds}) from Coquimbo. According to the Santa Maria et al. (2017) [10] exposure model, 51,964 houses are located in this area (N_{em}). Therefore, damaged houses represent 2.73% of the total inventory of houses. Table 2 shows the number of reinforced concrete and timber houses of this data base.

Table 2 – Damage information of houses by building classes due to the 2015 earthquake

Taxonomy	N_{ds}	N_{em}	N_{ds}/N_{em} (%)	Houses per damage state (%)				
				N	S	M	E	C
Reinforced Concrete	169	21,460	0.79%	99.21%	0.35%	0.11%	0.26%	0.06%
Timber	1249	30,504	4.09%	95.91%	2.57%	0.48%	0.45%	0.59%

3. Ground motion intensity

Peak ground motion parameters (e.g., Peak Ground Acceleration (PGA), Velocity (PGV) and Displacement (PGD)) are often used as intensity measures (IM) in empirical fragility and vulnerability assessment studies (e.g [11]). Spectral acceleration (Sa) and displacement (Sd) at the fundamental vibration period can also be used as the intensity measures but are less frequent (e.g. [4]). PGA and Sa(T) are the most commonly used IMs in the estimation of fragility curves [6] [12], but these IMs do not necessarily have the best correlation with observed damage.

For this reason the IMs selected to estimate the fragility curves in this study were PGA, PGV, Sa(0.3) and MMI, and this decision was made due to the availability of records and USGS ShakeMaps [13].The raw data describing ground shaking are published by the USGS and freely downloadable from the USGS web page *(https://www.usgs.gov/natural-hazards/earthquake-hazards/earthquakes)*. This data provides point by point values of intensity measures, for four different IMs: Peak Ground Acceleration (PGA), Modified Mercalli Intensity (MMI), Peak ground Velocity (PGV) and Spectral Acceleration at 0.3s (SA(0.3)). These point by point IMs were interpolated with the Geographic Information System (GIS) software QGIS (QGIS Geographic Information System. Open Source Geospatial Foundation project. https://qgis.org) to obtain a continuous IM field. In doing so, specific IM values were obtained for each damaged and undamaged house in this study.

On April 1st, 2014, at 20:46:45 local time, a magnitude Mw=8.2 earthquake with an epicenter located off the coast of Iquique and Pisagua took place in the north of Chile [14]. Figure 2 shows the IM maps prepared with the information published by USGS for this earthquake.

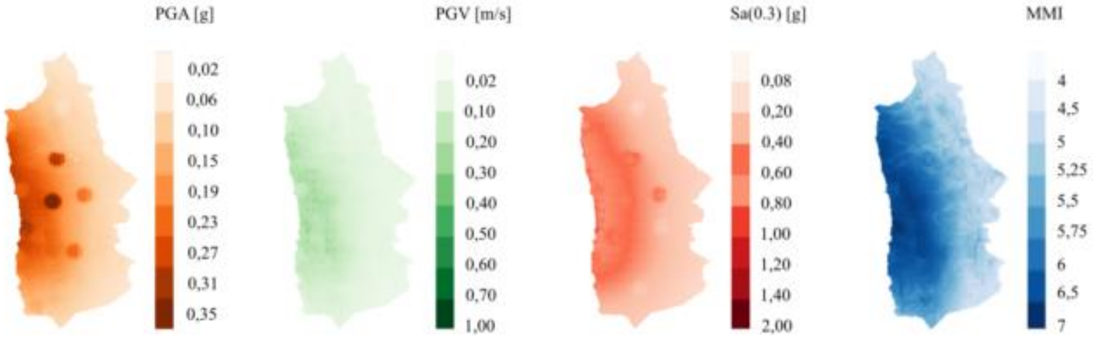


Fig. 2 – PGA, PGV, Sa(0.3) and MMI maps for the 2014 Iquique earthquake.

On September 16th, 2015, at 19:54 local time, a magnitude Mw=8.3 earthquake with an epicenter located off the coast of Coquimbo took place in the north of Chile [15]. Figure 3 shows the IM maps prepared with the information published by USGS for this earthquake.

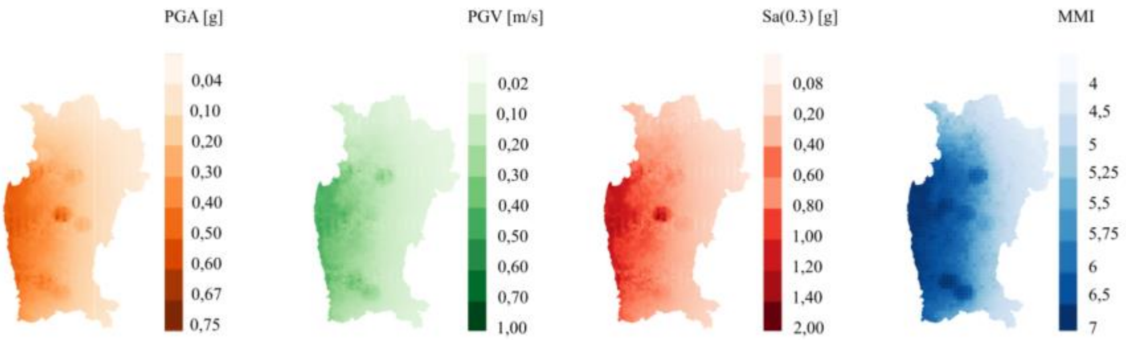


Fig. 3 – PGA, PGV, Sa(0.3) and MMI maps for the 2015 Illapel earthquake

The Pearson correlation coefficient (ρ) is used to assess which of the IMs best correlate with the observed damage. The Pearson correlation coefficient ranges from -1 to 1, and represents the extent of a linear relationship between two data sets (in this case, IM and damage) [16]. The Pearson correlation coefficient is calculated using the following equation:

$$\rho = \frac{n(\sum_i^n X_i Y_i) - (\sum_i^n X_i)(\sum_i^n Y_i)}{\sqrt{[n\sum_i^n X_i^2 - (\sum_i^n X_i)^2][n\sum_i^n Y_i^2 - (\sum_i^n Y_i)^2]}} \qquad (1)$$

Table 3 shows the Pearson correlation coefficient for each taxonomy and IM. The largest value of ρ was obtained using Sa(0.3) for both reinforced concrete and timber houses.

Table 3 – Pearson correlation for each IM

Taxonomy	Intensity Measure	ρ
Reinforced Concrete	PGA	0.906
	PGV	0.912
	Sa(0.3)	0.969
	MMI	0.839
Timber	PGA	0.831
	PGV	0.763
	Sa(0.3)	0.970
	MMI	0.838

4. Fragility curves

Fragility functions are used to calculate the probability that a component, element, or system will be damaged as a function of a predictive demand parameter, such as story drift or floor acceleration [17]. The analytical expression used in this paper to derive fragility curves is based on the assumption that earthquake damage distributions can be represented by the cumulative standard lognormal distribution function [18]. This assumption has traditionally been used in the field of earthquake engineering for the construction of fragility curves because of its mathematical convenience in characterizing the uncertainties associated with the structural capacity and seismic demand [19]. The structural capacity and seismic demand are considered as independently and identically distributed lognormal random variables. The mathematical form for such function is represented by the following equation:

$$F_i(D) = \Phi\left(\frac{ln(D/\theta_i)}{\beta_i}\right) \ (2) \qquad (2)$$

where $F_i(D)$ is the conditional probability that the component will exceed a certain damage state "i" or a more severe damage state as a function of the demand parameter D, Φ denotes the standard normal cumulative distribution function, θ_i is the median value of the probability distribution, and β_i denotes the logarithmic standard deviation. According to Lallemant et al. (2015) [19], the Maximum Likelihood Estimation (MLE) procedure can be used to estimate fragility curves using earthquake damage data. Previous studies have used MLE to estimate fragility curves of buildings and bridges (e.g. [20]–[28]). The MLE method consists on estimating the parameters of the distribution that maximize the probability of occurrence of the observed data. The function needed for this analysis uses the following equation:

$$\hat{\theta},\hat{\beta} = \arg max_{\theta,\beta} = \sum_{i=1} \left[n_i ln \left(\Phi \left(\frac{\ln\left(\frac{IM_i}{\theta}\right)}{\beta} \right) \right) + (N_i - n_i) ln \left(1 - \Phi \left(\frac{ln\left(\frac{IM_i}{\theta}\right)}{\beta} \right) \right) \right] \qquad (3)$$

where $\hat{\theta}$ and $\hat{\beta}$ are the estimates of θ and β, n_i is the number of damaged houses out of the total number of houses (N_i) at a ground motion intensity $IM = IM_i$.

The fragility curves estimated in this study were derived according to recommendations by FEMA (2012) [17]. First, the lognormal parameters ($\hat{\theta}$ and $\hat{\beta}$) were determined using Equation 3. The existence of outliers was verified according to the methodology indicated in appendix H.3.2 of FEMA (2012) [17]. Then, a goodness-of-fit test for a significance level of 5% according to appendix H.3.3 of FEMA (2012) [17] was used. The final step was to fix the fragility curves that crossed, applying the method by FEMA (2012) [17]. Figure 4 shows a diagram that explains how the fragility curves were calculated for each house type (i.e. reinforced concrete and timber) using the data surveys from both the 2014 (Table 1) and 2015 (Table 2) earthquakes.

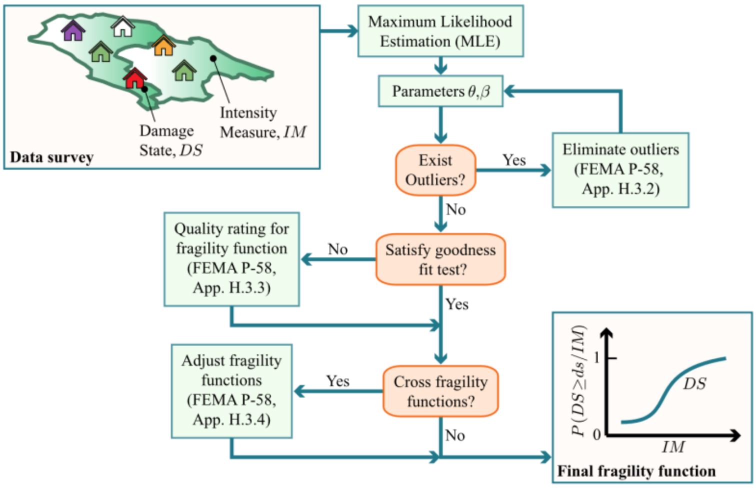


Fig. 4 – Diagram describing the derivation process of the fragility functions

Figure 5 shows the fragility curves obtained for reinforced concrete and timber houses with the process described in Fig. 4, using PGA, PGV, Sa(0,3) and MMI as intensity measure.

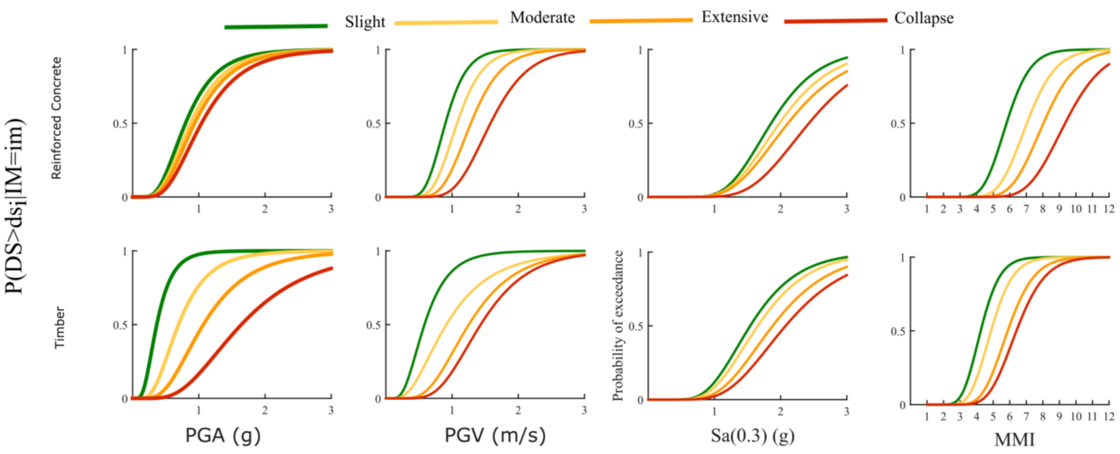


Fig. 5 – Reinforced concrete and timber fragility curves per PGA, PGV, Sa(0.3) and MMI as IMs

4. Conclusions

This study presents empirical fragility curves for reinforced concrete and timber houses calculated using PGA, PGV, Sa(0.3) and MMI as intensity measures. These fragility curves were estimated using the data surveys of 2014 and 2015 Chile earthquakes and the *ShakeMaps* published in the USGS web page.

The fragility curves were obtained using MLE and recommendations by FEMA P-58. According to this process, it was not necessary to remove outliers, the goodness-of-fit test passed with a significance level of 5%, and the fragility curves that crossed were fixed according to FEMA P-58.

The correlation between intensity measures and observed damage was calculated using the Pearson correlation coefficient. In this study, the highest correlation was obtained for Sa(0.3). Therefore, Sa(0.3) was the best IM to calculate fragility curves and estimate the number of damaged houses in Chile.

5. Acknowledgements

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