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MODELLING OF THE EARTHQUAKE SOCIO-ECONOMIC AND LEGAL CONSEQUENCES AT THE URBAN SCALE

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Abstract

In moderate-to-low seismic hazard regions, assessing the socio-economic consequences of an earthquake at an urban scale is a costly, difficult but essential task. However, public authorities have the duty to take into account this risk and mitigate it according to their resources. Thus, the positioning of the level of responsibility in the implementation of the earthquake regulations and the induced economic cost are a key issue. The responsibility of the authorities but also that of insurers in their approach to prevent is at the forefront when natural disasters happen. The modification of the seismic regulation has a direct impact on the level of responsibility. In this study, the impact of prevention's policies implemented is translated in terms of decision variables thanks to the qualitative analysis of the interviews conducted with elected representatives, insurers, technicians, lawyers and first-aid workers. Decision variables selected are damages to structures, the number of deaths, injuries, homeless people to be managed, the repairing's costs for damaged buildings or their destruction / reconstruction, the impact on economic activity (business interruption) and responsibility. Thus, in this study, a losses database from the world earthquakes between 1967 and 2018 with magnitude greater than 4.3 has been prepared. In addition to the social losses (dead, wounded...) and economic losses (direct and indirect costs, number of buildings destroyed or damaged...), the ground motion footprint provided by USGS Shake-Map are considered. In this talk, we first analyzed the relevancy of information contained in the databases, related to earthquakes and induced losses and we propose a first analysis of the flat file from the database, in terms of loss prediction and consequences. Then the completeness of our catalog of social and economic losses is tested thanks to the creation of a synthetic database of losses of the 22 856 earthquakes between 1967 and 2015 affecting at least one country from the ISC-gem database. Finally, from these data, we propose a more realistic loss models and we develop occurrence models for social and economic losses.

Keywords: socioeconomic loss database; loss modelling; earthquake; government; liability.

1. Introduction

The world's population is increasingly exposed to natural hazards, mainly because of population growth, which is increasingly concentrated in urban areas [1, 2]. While earthquakes represent 15% of natural disasters, they generate 45% of economic losses and 78% of victims [3]. The economic, societal and health impacts may be significant depending on the region impacted and its population [4, 5, 6, 7]. Faced with a vulnerable population and a changing urban environment [2, 5, 8], it is important to find new solutions for earthquake prevention [1]. For loss prediction models, magnitude is not the only parameter to consider for the prediction of earthquake's consequences. It is also important to take into account economic exposure (i.e. wealth) and the population at risk [4, 5, 6, 7, 9, 10]. To create empirical loss prediction models, regression laws can be performed on single or multiple parameters related to hazard, exposure and consequences [11, 12, 13, 14] provided by global international databases or specific regional databases. Exposure parameters (the exposed population and regional and per capita GDP) have a strong influence on earthquake's consequences [1, 15, 16]. Consequence prediction needs to take into account local exposure variables (exposed population and regional GDP). These exposure variables need to be assessed according to the area affected by each earthquake and adjusted to the socio-economic situation of the exposed area at the time of the earthquake. In the following, we analyze the occurrence of human and economic seismic losses due to 1967-2018 earthquakes. We derived models allowing the determination of exposure parameters (economic and human). This work aims to be applied for scenarios in moderate seismic prone regions. To constitute the flat file of this study, we compiled Hazard-related variables from the ShakeMap catalogue [17] and loss-related variables from the international reference databases. Theses variables are adjusted to obtain an homogeneous flat file. Thanks to this flat file, we produced probabilistic occurrence models for human and economic losses.

2. Method

2.1. Database of 445 seismic event

The aim of this study is to derive loss models, for this purpose the flat-file on which tests will be carried out must be consistent in terms of data. The constructed database thus contains information on hazards, exposure and consequences of seismic events. In this study, seismic events were selected according to two conditions:

(1) to have a spatial representation of the impacted area (ShakeMap or a macroseismic intensity map);

(2) to cause economic or social losses.

In this study, the Shakemaps, a spatial footprint, makes it possible to characterize the hazard by distributing the impact of the earthquake according to the intensity of ground movement [18, 19]. The Shakemaps provide seismological information (epicentre, magnitude, maximum intensity, depth), information related to time and place (date, spatial coordinate points).

The 445 seismic events in our file are located around the world in regions of high seismicity (59%), moderate seismicity (37%) and low seismicity (4%) (areas defined by [20]). Several types of earthquakes are represented, including subduction earthquakes [21, 22]. Among the affected regions, Latin America and Asia are the most impacted by seismic events.

Economic losses due to earthquakes have increased over the last 60 years [1], so the time period in our flat file deemed is between 1967-2018. The magnitude range is between [4.3; 9.0]. The mean value is 6.5, which also defines a moderate earthquake. The statistical analysis of the flat file shows that the seismic events causing the most losses are earthquakes of moderate magnitude (68% between 5.6 and 7.2).

The authoritative international databases in the field have provided data on socio-economic consequences. These international databases are the US National Oceanic and Atmospheric Administration database [23], the International Disaster Database on Emergency Events Database [3], the damaging earthquake database [24], the Inventory system of the effects of disasters [25], the Global Earthquake Model

[26] and the Global Facility for Disaster Reduction and Recovery database [20]. For the earthquakes selected to constitute our flat-file, i.e. those for which a ShakeMap is available, the parameters considered are number of victims F (438 events) and direct economic losses L$ (364).

The economic losses must be homogenized to a base year, 2016, in order to be able to compare them and derive loss prediction models [27, 28]. The use of an economic index measures inflation between two periods, the earthquake period and the base year period, and thus the change in the value of the economic loss. The analysis of economic indices shows a similar evolution between 1967 and 2018. In this study, our choice of economic index is based on the French and American consumer price index and the French and American construction index provided respectively by the National Institute of Statistics and Economic Studies (INSEE) [29] and the United States Census Bureau [30]. From the various indices, we determined the average economic index *Ide*. By applying this index *Ide* to the economic losses in our flat-file, we were able to adjust and obtain the losses in 2016 in US$ ($L\$_{2016}$).

2.2. Data related to exposition

International databases do not provide exposure-related data (population, area and GDP). However, these variables are essential for developing loss prediction models [14, 28], the total exposed area (A_{exp}), exposed population (Pop_{exp}) and exposed GDP (GDP_{exp}) in the year of the earthquake are therefore calculated in our study using Shakemaps.

The exposed population was calculated using the Shakemaps, the geolocalised database of the world population in 2015 given by the European Commission [31] and by the demographic table providing the population by country since 1950 [32]. The population exposed in the year of the earthquake could therefore be calculated for each seismic event in the file.

We tested the local evolution of the exposed population and the exposed area by intensity over a 50-year period and on 26 earthquakes in Western Europe (France, Italy and Belgium) for which the exposed population and the exposed area by intensity were known. Thanks to this analyze, models of exposed area and exposed population could be developed for earthquakes of magnitude between [4,9;7]. The total exposed population is then directly determined by the geographical area exposed to intensity ≥ V. A regression-based empirical model is used to measure the exposure according to the intensity (Eq. (1)).

$$Y = a \,.\, exp(b \,.\, I) \; + \varepsilon \tag{1}$$

where a and b are the regression coefficients, ε is the mean square error (RMSE), I is intensity and Y corresponds to Pop_I/Pop_{exp} or A_{exp}. Fig. 1 presents the distribution of Pop_I/Pop_{exp} and A_{exp}.

By selecting earthquakes within the perimeter of this test (magnitude range), the exposed area as a function of intensity can be evaluated at first order.

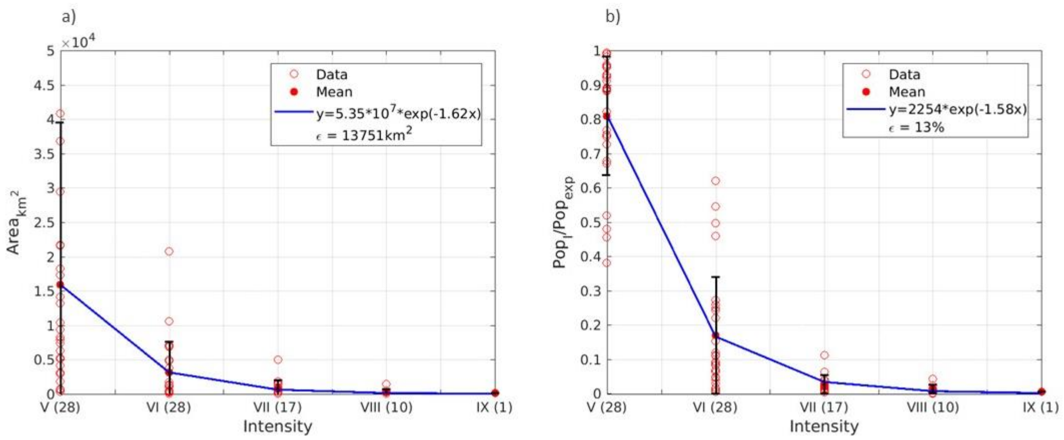

Fig. 1 – a) Exposed area A_{exp} for each macroseismic intensity of the earthquakes tested. b) Exposed population relative to the total exposed population Pop_I/Pop_{exp} for each macroseismic intensity of the earthquakes tested. The number in brackets indicates the number of samples. The solid line corresponds to the model fitted to the data according to Eq. (1)

Economic loss models improve and become more robust when the economic exposure parameter, GDP per capita, is taken into account. *GDP* per capita is the value of *GDP* divided by the number of people in the country. The World Bank tables [32] providing the GDP of each country since 1960 have been used to calculate the GDP of the exposed area in US$ 2010 [28] (Eq. (2)).

$$GDP_{exp\_y} = \sum_{c=1}^{M} GDP_{capita\_y\_c} * Pop_{exp\_y\_c} \quad (2)$$

where GDP_{exp_y} is the *GDP* exposed in year *y* of the earthquake and $GDP_{capita\_y\_c}$ is the *GDP* per capita in year *y* of the earthquake of the country concerned *c*. $Pop_{exp\_y\_c}$ is the exposed population in year of the earthquake of the country concerned. GDP_{exp_y} is then adjusted to the US$ 2018 currency using the *Ide* economic conversion index.

Finally, through analysis of the flat file, earthquakes of moderate magnitude [5,6;7,2] (68% of the flat file), contribute to 46% of total economic losses and 39% of total social losses. Earthquakes of low probability and high consequence (M>8), contribute only modestly to the total global losses (30% of economic losses and 2% of social losses) for the time period considered.

3. Loss occurrence models

3.1. Catalogue completeness

Using the flat file, we aimed to verify occurrence models of annual socio-economic losses. In order to derive occurrence models, it is necessary to verify the completeness of the catalogue. To do that, we have to verify if our catalogue contains all seismic events inducing losses. The ISC-GEM earthquake catalogue produced by the International Seismological Centre (ISC) [26, 34] is considered as complete. We therefore tested the completeness of our file against this catalogue.

The ISC-GEM database lists 35,712 global seismic events between 1904 and 2015. First, we assumed that only earthquakes whose epicentre was within a country caused losses. Then, to fit the period covered by our consequences database, only the earthquakes between 1967 and 2015 were retained, i.e. 22,856 events over the last 48 years (ISC1).

Secondly, we assumed that earthquakes only cause losses if a population (and therefore economic property) is exposed. For the 22,856 earthquakes of ISC1, we calculated the population exposed to intensities ≥ V, according to the following procedure. First, from the initial database, we use the Intensity Prediction Equation (IPE) to obtain the epicentral intensity. The functional form of the IPE relationship used in this study is given by Stromeyer and Grünthal (2009) [35]. Secondly, we use the exposed area prediction model and thirdly, we calculated exposed population in the year of the earthquake with the procedure described above. Finally, the reduced ISC2 database of events with population exposure corresponds then to 14,002 events over the period 1967-2015.

Using ISC1 and ISC2, we have calculated occurrence models. These models were obtained according to a functional form derived from the model proposed by Gutenberg-Richter (1949) [36]. This model uses the cumulative magnitude-frequency distribution. This distribution represents the number of earthquakes with a magnitude greater than or equal to a given magnitude.

Comparing the earthquake annual rate with their magnitude, we found the following equations.

$$\log N(m > M)_{ISC1} = 7{,}3 - 1{,}0 * M \quad (3)$$

$$logN(m > M)_{flat-file} = 5{,}1 - 0{,}7 * M \quad (4)$$

$$logN(m > M)_{ISC2} = 7{,}0 - 1{,}0 * M \quad (5)$$

ISC1 database contains more events than ISC2. Thus the value of *a* is higher for the ISC1 database. The coefficient *b* indicates the relative ratio between small and large earthquakes. As expected for complete catalogue (ISC1 and ISC2), the *b* value is close to 1 [37]. However, for the model deduced from the flat file, this value is 0.7. This indicates a lack of seismic events causing consequences compared with the overall number of earthquakes during this period. The completeness magnitude of an occurrence model is defined by the minimum magnitude beyond which all earthquakes are taken into account. It corresponds to the lowest magnitude at which slope failure is observed. Completeness magnitude is estimated at about 5.5, 5.5 and 6.4 for the ISC1, ISC2 databases and our file. Eq. (3), Eq. (4) and Eq. (5) converge for magnitudes greater than 7.6. Our catalogue is certainly not complete under this magnitude. Given the available data, we are not able to improve the completeness of our catalogue. However, the amount of annual data available for a range of magnitudes is stable. This enables a definition of a minimum threshold for loss occurrence.

3.2. Socio-economic occurrence models: tests

To predict the minimum consequences, we derived an occurrence model based on the flat file data. One form of occurrence models was tested on the 445 seismic events between 1967 and 2018 in the flat file, according to the functional form Eq. (6) [36]:

$$logN(Y > X) = a - b * log(X) \quad (6)$$

where $N(Y>X)$ represents the number Y of earthquakes with a social (F) or economic (L\$) loss greater than or equal to a given loss X (F_i, L\$), expressed as an annual rate of occurrence ζ on Fig.2. Eq. (6) assumes F/Pop_{expmax} equal to 1, so the number of victims F cannot exceed the exposed population Pop_{exp}, and $L\$/GDP_{expmax}$ equal to 10^3, so that the losses L\$ can exceed GDP_{exp}.

The model (Eq. (6)) fitted to the data is shown in Fig.2 for $L\$/GDP_{exp}$ and F/Pop_{exp}. The *a* and *b* coefficients are a=9.0 10^{-3} and b=5.7 10^{-2} for social losses and a=1.7 10^{-2} and b=1.1 10^{-2} for economic losses. Residue distributions for model and social or economic losses follow a normal distribution. Residue analysis shows more dispersion in social losses. This can be explained by uncertainties related to social consequences (e.g. difficulty in counting the number of victims after earthquake).

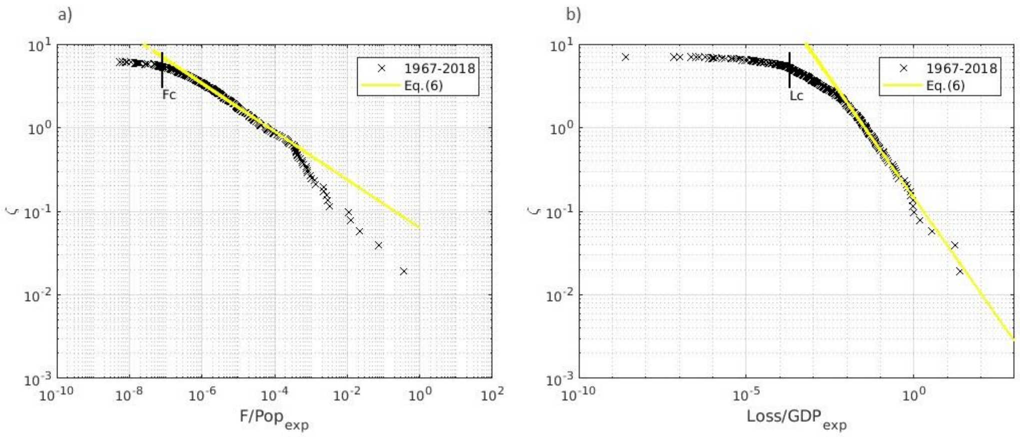

Fig. 2 – Representation of the frequency-loss distribution of seismic events and occurrence models. (a) annual rate ζ of fatalities according to exposure (F/Pop_{exp}), (b) annual rate ζ of economic losses according to exposure ($L\$/GDP_{exp}$)

The completeness of our flat file rated *Fc* equal to 8.0 10^{-8} for F/Pop_{exp} and *Lc* in the order of 2.0 10^{-4} for $L\$/GDP_{exp}$. These occurrence models show an annual $L\$/GDP_{exp}$ rate of 3.6 10^{-2}, and an annual F/Pop_{exp} rate of one death per 10,000 exposed people.

4. Conclusions

A database of 445 global seismic events has been constructed using the international databases that take into account the economic and social consequences. The work done in this study has focused much on building up the base of past seismic events. It constitutes a reference of homogeneous events, enriched with seismological information essential to the realization of models of occurrences of the exposed population and the exposed area. These exposure variables are essential in improving loss prediction models. Data collection has led to the consideration of different approaches to adjust the economic losses of past earthquakes to current values and to exposed GDP, and the loss of life to the exposed population at the time of earthquakes.

Finally, the development of occurrence models can be essential in the implementation of decision-making tools based on the representation of socio-economic losses in relation to the exposed population and to the exposed GDP. These models are only valid for a complete event catalogue, which will require loss modeling. However, they can also be improved by working according to the specific geographical or tectonic areas, notably for moderate seismic prone countries, to refine local or regional loss prediction models. Having a fast and efficient model for estimating economic and human losses can also be of paramount importance in the aftermath of seismic disasters. It is a measure that can be taken into account in the chains of operation to allow a return to the fast normal and in the decision-making of the decision makers in order to anticipate the seismic risk.

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