The Value of Observations for Reduction of Earthquake-Induced Loss of Life on a Global Scale

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Abstract – Earthquakes on global scale cause considerable losses both in terms of economic impact and human lives. A proper coordination of disaster response activities requires observation of affected areas for evaluation of spatial distribution of damage. We use several freely available datasets including global seismic hazard assessment, data on population, gross domestic product, and urban areas to calculate expected loss of life based on rescue efficiency derived from an optimal rescue resource distribution model, which by design includes the observation capacity as a parameter. Despite of the high practical importance, the quantification of the "observation quality – reduction of loss of life" relationship has not yet been performed for earthquakes on a global scale. Our validated quantitative results show that better Earth observations may potentially contribute to a global reduction of earthquake induced loss of life within the range 20% – 90% from the "business as usual" level.

Keywords: earthquake, Earth observations, disaster response, loss of life, global scale.

1. INTRODUCTION

Earthquakes cause substantial damage to infrastructure, economy, and human lives. Several catastrophic events during the past few years have sharply demonstrated the severity of earthquake consequences expressed particularly in human lives. According to the U.S. Geological Survey Historic Worldwide Earthquakes database, the earthquake in India, Gujarat dated 26 Jan 2001 has lead to more than 20 000 fatalities and more than 6 300 000 affected people; the earthquake in Pakistan, Bagh dated 8 Oct 2005 has caused more than 73 000 fatalities and more than 5 100 000 affected people; the earthquake in China, Sichuan dated 12 May 2008 has lead to more than 69 000 fatalities and more than 4 800 000 affected people. The statistics vividly shows how devastating and deadly an earthquake can be. Therefore, it is necessary to take all possible actions and better prepare to future earthquakes in order to reduce possible consequences especially in terms of loss of life.

1.1 Motivation

One of the major scientific problems regarding earthquakes is that according to the current state of the art it is impossible to reliably predict these disasters considerably in advance e.g. tens of minutes. This state of affairs does not allow the implementation of Early Warning Systems (EWS) providing enough time for safe evacuation of people from dangerous areas. In this paper we focus on the rescue operations in a few hours after an earthquake and study the dependence of the rescue resource distribution efficiency on the available amount of information about the damage incurred on the building stock. Basically, by knowing more precise information about the damage to the different parts of a city or region, one could better allocate rescuing resources necessary to save victims of an earthquake in the most affected areas.

1.2 Aims

Despite of the practical importance of improved information for disaster response, the quantification of the "observation quality – reduction of loss of life" relationship has not yet been performed for earthquakes on a global scale. Our aim is to develop a model that would allow for a quantitative global assessment of the value of improved observations for disaster response to earthquakes. More specifically, we aim at obtaining quantitative results measuring the feasible reduction of earthquake induced loss of life on a global scale that better Earth observations (EO) could contribute to. For that purpose we perform an assessment of the potential of the expected decrease having "business as usual" as a baseline. Additional sub-goal is to validate the model on a regional scale in several case studies to explore if there is an agreement between globally-derived predictions and the real-case data reported from the field. In this paper we do not specify the way of obtaining the EO data in order to avoid inessential constraints and leave enough space for all possible implementations and relevant methods. The research presented here is focused on post-disaster actions aimed at saving lives of the earthquake victims. The ex ante actions and reduction of economic loss are beyond the scope of this paper.

1.3 References to Related Work

The importance of rapid earthquake damage assessment and some real applications are presented in e.g. Midorikawa and Abe (2000). The application of earthquake warning systems providing very short warning times to secure potentially dangerous objects in Japan is presented in Meguro (2005). The papers presenting the empirically derived interdependence between technical characteristics of an earthquake as well as expected damage on different measurement scales include such early works as Ambraseys (1973) and more recent papers as by Karim and Yamazaki (2002). An overview of empirical methods and assessment techniques as well as earthquake engineering practices is presented in Seligson and Shoaf (2003).

1.4 Overview

The rest of the paper is organized as follows: section 2 presents the model and basic datasets. Section 3 presents both results of the global assessment as well as some regional case studies used for validation of the model. Section 4 draws up the conclusions.

2. MODEL AND DATA

An important part of the model is the functional dependence of rescue efficiency on available observations, rescue resources, and damage caused by an earthquake to the buildings. The rescue efficiency is defined as follows:

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$$rescue\ efficiency = \frac{number\ of\ saved\ victims}{total\ number\ of\ victims}. \qquad (1)$$

Here under the "total number of victims" we assume the people who were not immediately killed by an earthquake and who could be potentially saved by providing timely medical treatment. We model the rescue efficiency based on the stochastic simulation approach. We assume that a city (or a region affected by an earthquake) is divided into *N* blocks (or sub-regions) and there are *n* houses in each of those blocks. We assume that the probability of a house to collapse during an earthquake is *p*. So, the number of collapsed buildings in the i^{th} block is a binomially distributed random variable $x_i \sim \text{Bin}(n, p)$. Let's assume that the number of rescue brigades is limited to *R* and that one brigade can rescue the victims from one collapsed building. The problem of optimal resource distribution consists in maximization of the overall rescue efficiency by assigning certain number of rescue brigades r_i to each of the blocks (i=1,…,N) under the given resource limitation *R*. According to (1) this leads to the following calculation formula:

$$rescue\ efficiency = \begin{cases} \dfrac{\sum_{i=1}^{N} \min(x_i, r_i)}{\sum_{i=1}^{N} x_i}, & \sum_{i=1}^{N} x_i \neq 0, \\ 1, & \sum_{i=1}^{N} x_i = 0. \end{cases} \qquad (2)$$

Here we used the number of collapsed houses as a proxy for the number of victims in need of rescue. This assumption is reasonable if all the houses have similar construction and have equal number of inhabitants, so that the average number of victims per house shows up both in the numerator and the denominator and cancels out. The minimum function in the numerator reflects the fact that a rescue brigade cannot save more victims than actually available in the i^{th} block. A parameter describing observation capacity can naturally be included into the earthquake aftermath rescue efficiency model presented above. One can imagine that the information about the damage from the i^{th} block may not be available. Let denote by *K* the number of blocks with the known information about the damage – known value of x_i. The quality of observation may be expressed as the ratio of the number of blocks with known damage information to the total number of blocks:

$$quality\ of\ observations = \frac{K}{N}. \qquad (3)$$

There could be different reasons why $K \neq N$. For instance, if the observation system used for the purposes of damage assessment is based on satellite imagery, some parts of the affected area could be obscured by clouds so that no information could be obtained for those parts. The earthquake rescue efficiency estimation model presented above includes resource constraint *R* as an important parameter. This parameter can describe the availability of trained staff and special rescue equipment, the proximity to hospitals and their respective capacity, and many other relevant factors. For the sake of simplification we assume that the amount of rescue resources is initially sufficient to save all the victims of an earthquake. This assumption might seem over-optimistic, since many earthquake reports show the lack of rescue resources especially in case of large earthquakes. Taking that into account, we make an alternative "pessimistic" assumption about the vulnerability of the rescue resources to the earthquake, namely, that the amount of available rescue resources decreases with the increasing probability of collapse, so we use $(1-p)R$ instead of *R* for this case. Based on those two "optimistic" and "pessimistic" assumptions we get two assessments of the rescue efficiency for each value of *p* and also for the two values of quality of observations (perfect observations and no observations). By running the Monte-Carlo simulations of the model described above, we estimate the dependence of the rescue efficiency on quality of observations and probability of collapse *p*. The results of this modeling* are illustrated on the Figure 1.

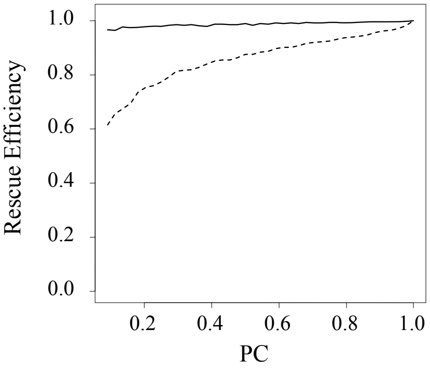

Figure 1. Rescue efficiency depending on probability of collapse (PC), "non-vulnerable" resources (dashed line – without observations, solid line – with observations).

2.1 Global Datasets

The model uses four global datasets describing spatial distribution of population, urban extents, gross domestic product (GDP), and global seismic hazard. The datasets have different spatial resolution, so that some preliminary steps as rescaling and unifying of coordinate systems are needed to operate them on the same scale. As a part of the model input, we use the global population and urban extent data provided by CIESIN (2004a and 2004b). The assumption on the buildings' type in the grid cell and their probabilities of collapse in case of an earthquake are based on those datasets. The assessment of GDP per capita was calculated based on population projection for 2025 provided by CIESIN (2002a) and downscaled projection of GDP for 2025 made by CIESIN (2002b). This indicator was used in the model to classify grid cells into 'rich' and 'poor' classes. For the purposes of the earthquake hazard assessment we used the global seismic hazard map GSHAP (2000).

2.2 Modeling Damage and Loss of Life

The global earthquake damage assessment model is based on the global datasets described above and the application of thresholds for distinguishing between urban/rural and 'rich/poor' areas, probability of collapse estimation, and rescue efficiency assessment based on the quality of EO as defined in (3). For the purposes of the damage modeling we use the intensity scale developed by the Japan Meteorological Agency (JMA). The

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* The modeling of the earthquake rescue efficiency was performed together with Elena Moltchanova from the National Public Health Institute, Helsinki, Finland.

probability of collapse, which is at the core of the model, is calculated according to the Table A. The JMA intensity – PGA relationship we used for conversion is described by the formula

$$\log_{10}(PGA) = 0.5\, I_{JMA} - 0.347 \qquad (4)$$

according to Ambraseys (1973) which is quite similar to the relationship presented in the more recent paper by Karim and Yamazaki (2002), yet seems to be more relevant on global scale as compared to the modern adjustments of JMA scale. The values in the Table A are suggested to quantify the official verbal descriptions of the JMA intensity.

Table A. Probability of collapse depending on building type and JMA intensity.

JMA intensity (PGA, m/s^2) / Building type	**5.5 (>2.5)**	**6.0 (>4.5)**	**6.5 (>8.0)**
Wooden, poor	0.25	0.5	0.75
Wooden, resistant	0	0.1	0.25
Concrete, poor	0	0.25	0.5
Concrete, resistant	0	0.1	0.25

After calculating the probability of collapse, the expected number of mortalities *EM* per grid cell is calculated using the formula

$$EM = POP \times PC \times PV \times (ID + SR \times RE)\,, \qquad (5)$$

where *POP* is the population in the grid cell, *PC* is the probability of collapse depending on PGA according to the Table A, *PV* is the ratio of the seriously injured victims conditional on collapse, *ID* is the ratio of the victims (out of seriously injured) who immediately die because of the severity of the earthquake-caused traumas, *SR* is the ratio of seriously injured victims who are subject to rescue, so that $ID + SR = 1$ by definition. *RE* is the rescue efficiency as defined in (2). According to the estimates suggested by Seligson and Shoaf (2003), in our model *PV*=0.30 and *SR*=0.67.

3. RESULTS

The model is able to calculate the earthquake-caused mortalities estimation on different scales. Below we present the global assessment and also several assessments for regional-scale case studies.

3.1 Global Assessment

We applied our model on the global scale and compared the assessment with the historical data over the last 30 years to evaluate the performance of the model. The benchmarking period is 1980-2008. The calculation methodology for the estimation of the earthquake-caused mortalities on the global scale implemented in the model delivers quite satisfactory results presented in the Table B, where for reported mortality statistics we used the data according to the EM-DAT database (the OFDA/CRED International Disaster Database, Université catholique de Louvain, Brussels, Belgium) for the period 1980-2008 (April). Modeled data are rescaled back to 1980-2008 and adjusted to population for comparison purposes. The upper and lower assessment values correspond to non-vulnerable and vulnerable resources. After the application of the PGA threshold presented by the GSHAP map and calculating the expected number of mortalities *EM* as described above, we apply the following scaling coefficients:

$$EM_{rescaled} = EM \times (GP_{1980} + GP_{2008})/2/GP_{2000} \times 0.1 \times 28/50\,.$$

Here, GP_{1980} and GP_{2000} are population for 1980, 2000, and GP_{2008} is a projection for 2008 according to the U.S. Census Bureau (2008). The probability 0.1 of PGA threshold exceedance during 50 years (provided by GSHAP) is rescaled to calculate the estimation within a 28 years time period. We assume that only a 500-year event, i.e. the PGA value exceeding GSHAP threshold, may cause a substantial damage, implicitly reflecting by this the local building practices, which should normally take into account local seismic conditions.

Table B. Global assessment of earthquake caused mortalities for the period of 1980-2008 (reported mortalities are according to the EM-DAT database for the period 1980 – April 2008).

	Reported mortality statistics	Non-vulnerable resources	Vulnerable resources
Without EO	300 000	297 000	582 000
With EO		29 000	447 000
Relative reduction:		90%	23%

The data reported by the statistics is quite well within the lower and upper bounds of the model's predictions taking into account the data on the China's Sichuan earthquake (12 of May 2008, 69 000 mortalities reported). The results presented in the Table B, show the importance of observations and the substantial potential for their use in reducing the number of fatalities on a global scale. However, the effect of using this vitally important information is limited by the available amount of rescue resources (trained personal and necessary equipment), which is reflected by the column "Vulnerable resources". The promising first results from the model presented in Table B cannot be used alone as a proof of the validity of the predictions, since Table B compares the average result of some distribution with only one sample value. Nonetheless, Table B provides useful information on the performance of the model under current assumptions and presents the potential benefits of EO.

3.2 Case Studies

For the purposes of the model validation on a smaller (regional) scale, we performed several case studies, for which the PGA maps and mortality statistics are available. Above we mentioned thresholds used to classify grid cells into classes for the purposes of the earthquake damage estimation. In the following case studies we use an additional threshold. Now we have two PGA datasets available to us – one is the GSHAP map (as we used it before), and the other is the real PGA map corresponding to the respective event. The reason for using GSHAP data, even in case when real data exist, is to be able to reflect the preparedness of each particular area to an event of certain magnitude. Since GSHAP reflects the magnitude of a 500-year event, we assume that buildings in the corresponding areas are well prepared and resistant to the earthquakes of smaller magnitude. The case studies presented below include the following earthquakes: Iwate earthquake (Eastern Honshu, Japan, 14.06.2008), Great Sichuan earthquake (Sichuan province, China, 12.05.2008), Kashmir earthquake (Kashmir, Pakistan, 8.10.2005), Gujarat earthquake (Gujarat, India, 26.01.2001), Loma Prieta earthquake (California, USA, 17.10.1989), San Fernando earthquake (California, USA, 09.02.1971). The results are summarized in the Table C, where we see that for the earthquakes in the USA and Japan the model gives good low assessments, with slight underestimations for Iwate and San Fernando, whereas the lower and upper estimations (VR+/-) for the EO scenario (EO+) for Loma Prieta earthquake provide good approximation of the reported fatalities. For larger earthquakes we see a reasonable approximation for Sichuan and Gujarat (both reported values are within the upper and lower boundaries for EO+ and EO–).

Table C. Performance of the model for the case studies when not using EO (EO–) and using EO (EO+) for non-vulnerable (VR–) and vulnerable (VR+) rescue resources (10^3 fatalities).

Earthquake	Mortalities Reported	EO–		EO+	
		VR–	VR +	VR–	VR +
Iwate	0.012	0	0	0	0
Great Sichuan	> 69	65	269	8.6	257
Kashmir	> 86	15	41	1.8	37
Gujarat	> 20	13	32	1.4	28
Loma Prieta	0.063	0.65	0.7	0.03	0.16
San Fernando	0.065	0	0	0	0

In the Kashmir case-study area, the model reported an underestimated assessment, which is most probably due to considerable number of strong aftershocks having cumulative destructive impact on the area as reported by Naeem et al. (2007). This disagreement with the reported numbers is not a flaw of the model because the main dataset of the model (GSHAP) does not contain any earthquake aftershock/duration-related information. Generally speaking, the case studies demonstrate reasonable performance of the global modeling approach even for the assessment of particular regional-scale events.

4. CONCLUSION

In this paper we presented an assessment tool to quantify the value of improved Earth observations to reduce human fatalities resulting from earthquakes. We purposely tried to keep the global model as simple and transparent as possible. The series of simplifying assumptions we made was necessary to make the model applicable to the available datasets. The suggested model leaves wide open space for possible improvements e.g. better resource constraints, stochastic modeling of an earthquake occurrence, etc., defining directions to go next. The highly aggregated and simplified global earthquake damage assessment framework described in our paper is quite transparent, yet it explicitly includes the naturally defined quality of Earth observations as a parameter and demonstrates the way of quantitative assessment of the importance of those observations. We validated the model on a regional scale in several case studies and found a good agreement of global predictions with the data reported from the field. However, the adjustments to the model for using more precise relevant local data and improving its estimations seem to be a challenging direction for further research. We anticipate this paper to be a starting point for more sophisticated models for measuring the earthquake-related value of information.

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