Proceedings of the 9th U.S. National and 10th Canadian Conference on Earthquake Engineering
Compte Rendu de la 9ième Conférence Nationale Américaine et
10ième Conférence Canadienne de Génie Parasismique
July 25-29, 2010, Toronto, Ontario, Canada • Paper No 1095

DEVELOPMENT OF A SEMI-EMPIRICAL LOSS MODEL WITHIN THE USGS PROMPT ASSESSMENT OF GLOBAL EARTHQUAKES FOR RESPONSE (PAGER) SYSTEM

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ABSTRACT

The U.S. Geological Survey operates an automated system that immediately estimates an earthquake's impact on humans for events around the globe. The system, called PAGER, for Prompt Assessment of Global Earthquakes for Response, estimates the number of people exposed to potentially damaging shaking. PAGER's rapid estimates of an earthquake's impact, and supporting products, inform the decisions by governments, insurance agencies, and relief organizations to release aid funds, prioritize regions for closer reconnaissance, and mobilize rescue teams. PAGER now incorporates estimates of both economic and fatality losses using empirical methods based on countrywide losses from past earthquakes. Here, we focus on recent developments associated with engineering-based loss-estimation capabilities within the PAGER system. In particular, semi-empirical procedures are described that incorporate newly-derived, country-specific building inventories and vulnerability functions as well as day/night population distributions within these structures. These data sets, now available online, constitute the key ingredients for our semi-empirical model and form the foundation for PAGER's fully analytical loss model, described in a companion paper.

Introduction

With the evolution of the ShakeMap and "Did You Feel it?" systems at the USGS National Earthquake Information Center (NEIC) over the last decade, a focused effort has been made to move beyond simply providing each earthquake's location and magnitude to rapidly assessing the spatial pattern and amplitude of ground shaking (Wald et al., 2005) and producing useful information about the earthquake's potential impact (Wald et al., 2006). The ShakeMap system facilitates advancements in both the earthquake engineering and loss modeling communities, particularly the context of rapid post-earthquake loss modeling and assessments. Engineering-based earthquake loss estimation approaches have quickly adapted to directly utilize ShakeMap's output (e.g., Kircher et al., 2006; Wald et al., 2008a), which includes peak ground accelerations, velocities, spectral accelerations and instrumental intensities as well as their uncertainties (Wald et al., 2005, 2008a).

With the advent of the Global ShakeMap system (Wald et al., 2006), a mostly predictive,

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yet consistently and rapidly produced suite of shaking estimates, it was natural to build a rapid, global loss-estimation system that would be suited for estimating earthquake impacts in a variety of built environments around the world. The USGS PAGER system now fills this role and provides actionable earthquake loss information within the early hours after any significant earthquake around the globe. Rapidly and automatically computing loss estimations around the globe presents several formidable challenges in the realms of data acquisition (building inventory, population, demographics and occupancy), loss modeling (empirical to analytical), and communications (loss content and uncertainty, alerting and notifications, robust web presence). While the PAGER system has significant aspects in all these realms, as discussed elsewhere (Wald et al., 2008b), the focus here is on a subset of the engineering-based components of the PAGER loss models.

PAGER loss modeling is being developed comprehensively with a suite of candidate models that range from fully empirical to largely analytical approaches. Which of these models is most appropriate for use in a particular earthquake depends on how much is known about local building stocks and their vulnerabilities. For regions that have experienced numerous earthquakes with high fatalities historically, typically developing countries with dense populations living in vulnerable structures, enough data exist to calibrate fatalities from the historical earthquake record alone (Jaiswal et al., 2009a and 2009b). In such regions, building inventories are typically lacking, as are systematic analyses of their vulnerabilities; hence, analytical tools are inadequate for loss estimation. In contrast, for the most highly developed countries, particularly those with substantive building code implementation, structural responses are more suitably characterized analytically and building distributions and occupancy are more readily available (e.g., HAZUS methodology in NIBS-FEMA, 2006). Moreover, the success of such building codes typically has led to relatively few fatal earthquakes, making it difficult to use empirical calibration from past events alone. In such cases, fatality estimates are largely informed from analytically-derived collapse rates and inferred fatality ratios given a structural collapse. Finally, we consider an intermediate approach, the semi-empirical model, which, for each country, relies upon intensity-based damage and casualty observations made during past earthquakes and incorporates them into an engineering-based casualty estimation procedure focused primarily on estimating structural collapses that contribute to fatalities (see Jaiswal et al, under review).

Here we focus on recent developments in the PAGER semi-empirical loss model. Earthquake induced deaths from structural collapse depend upon the type of structural system, the number of stories, the time of day, the occupants' ability to respond, and several other factors. This article describes specific elements of the semi-empirical loss computation adopted within the PAGER system with emphasis on i) application of a global building inventory database and population distribution algorithm to compute population exposure within different construction types by time of day, ii) structure-specific vulnerability assessment, iii) fatality rates given collapse, and iv) grid-based fatality/loss computation. PAGER's methodologies and datasets are being developed in an open environment to support other loss estimation efforts and provide an avenue for outside collaboration and critique. Hence, the data and models described are freely available at the USGS PAGER web site.

Building Inventory and Population Exposure

A comprehensive database of building inventory and indoor population within each building type is fundamental to any engineering-based casualty loss estimation approach. PAGER's goal of rapid fatality estimation around the globe necessitated the compilation of a global building inventory database, covering the distribution of structures as well as structure-specific occupancies. Despite the dearth of resources on hand and limited publicly accessible datasets, Jaiswal and Wald (2008) attempted to develop the first open, peer-reviewed, publicly available global building inventory database. On a country-by-country level, the database contains estimates of the distribution of building types categorized by material, lateral force resisting system, and occupancy type (residential or non-residential, urban or rural) (Figure 1). The database draws on and harmonizes numerous sources such as UN databases, national housing censuses, the World Housing Encyclopedia and other published literature. While admitting to important limitations of the existing inventory data, the methodology allows a pathway for constant data improvements and updating through the spirit of open enhancement.

After the structural inventory distribution compilation, we addressed the occupancy distribution within each structure class. Human occupancy patterns are often strongly linked to time of day (e.g., Coburn and Spence 2002). Daytime work hours and nighttime hours strongly dictate building-specific occupancy (workplaces are occupied mostly during day time while homes are occupied during nighttime). This required analyses of country-specific demographic characteristics including age, fraction of the population employed, and workforce distribution by sector of employment, among other considerations. These demographic characteristics vary from country to country and within a country from region to region particularly between urban and rural settings.

The HAZUS inventory development methodology (NIBS-FEMA 2006) utilizes such demographic characteristics to compute the indoor population with specific occupancy type at 2 am (nighttime), 2 pm (daytime) and 5 pm (in transit), respectively. In order to compute the earthquake fatalities within the PAGER system at a global scale, it is necessary to estimate indoor occupancy within residential and non-residential buildings at the time of the event. We accomplish this by compiling the global demographic data through key available datasets including UN Statistics (UN 2006) and the CIA World Fact book (The World Factbook 2009).

In the occupancy estimation procedure adopted, we denote the fractions of work force and non-workforce populations as F_{wf}, and F_{nwf}, respectively. The total work force can be divided into three sectors namely the industrial sector, denoted as F_{ind}, the service sector, denoted as F_{ser}, and the fraction who work in agriculture, represented as F_{agr}. For the i^{th} grid cell, if the total population is P_i, Table 1 provides the default relationship implemented within the USGS PAGER system for estimating the population within urban and rural areas in each of the three occupancy categories by time of day.

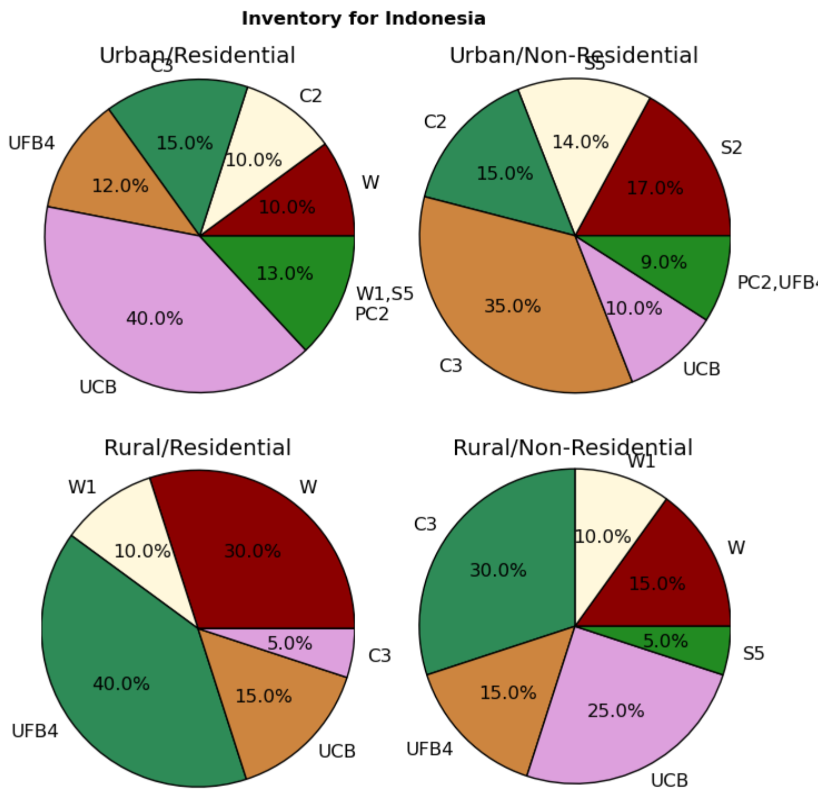

Figure 1. Building inventory distribution showing variations within different built environments for Indonesia (The building codes shown in the picture refers to PAGER-STR types which can be readily referred at - http://pager.world-housing.net/wp-content/uploads/2009/09/LISTING-OF-PAGER-CONSTRUCTION-TYPES-AND.pdf. The Indonesia specific generic structure types abbreviation are: W & W1 for wood, UCB & UFB4 are unreinforced masonry, C2 & C3 for reinforced concrete, PC2 for precast and S2 & S5 for steel frame constructions).

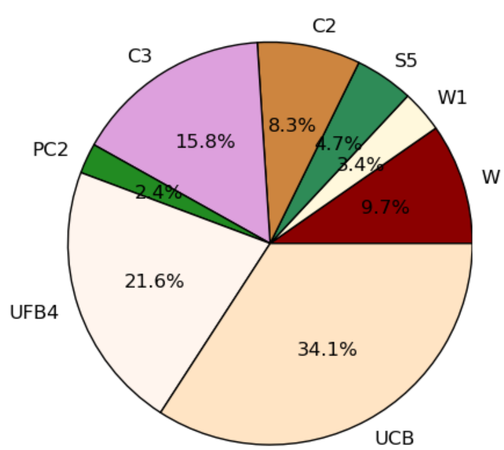

Figure 2. Estimated population distribution for the M7.6 Sept 30, 2009 Sumatra earthquake using population and building inventory databases. Most of the indoor population is estimated to reside within unreinforced masonry (UFB4), block masonry (UCB), and non-ductile reinforced concrete buildings (C3) at the time of event.

Table 1. Distribution of total population within a population grid cell into occupancy categories by day, night and transit hours.

Occupancy	Day (10 am to 5 pm)	Night (10 pm to 5 am)	Transit (other times)
	Urban Areas		
Indoor residential	$P_i *(0.4* F_{nwf} +0.01* F_{wf} * F_{ind} +0.01* F_{wf} * F_{ser} +0.01* F_{wf} * F_{agr})$	$P_i *(0.999* F_{nwf} +0.84* F_{wf} * F_{ind} +0.89* F_{wf} * F_{ser} +0.998* F_{wf} * F_{agr})$	$P_i *(0.75* F_{nwf} +0.20* F_{wf} * F_{ind} +0.25* F_{wf} * F_{ser} +0.45* F_{wf} * F_{agr})$
Indoor nonresidential	$P_i*(0.25* F_{nwf} +0.89* F_{wf} * F_{ind} +0.89* F_{wf} * F_{ser}+ 0.34* F_{wf} * F_{agr})$	$P_i*(0.15* F_{wf} * F_{ind} +0.10* F_{wf} * F_{ser}+ 0.001* F_{wf} * F_{agr})$	$P_i*(0.25* F_{wf} * F_{ind} +0.25* F_{wf} * F_{ser}+ 0.01* F_{wf} * F_{agr})$
Outdoor	$P_i*(0.35* F_{nwf} +0.10* F_{wf} * F_{ind} +0.10* F_{wf} * F_{ser} +0.65* F_{wf} * F_{agr})$	$P_i*(0.001* F_{nwf} +0.01* F_{wf} * F_{ind} +0.01* F_{wf} * F_{ser} +0.001* F_{wf} * F_{agr})$	$P_i*(0.25* F_{nwf} +0.55* F_{wf} * F_{ind} +0.50* F_{wf} * F_{ser} +0.54* F_{wf} * F_{agr})$
	Rural Areas		
Indoor residential	$P_i *(0.4* F_{nwf} +0.05* F_{wf} * F_{ind} +0.05* F_{wf} * F_{ser} +0.01* F_{wf} * F_{agr})$	$P_i *(0.999* F_{nwf} +0.89* F_{wf} * F_{ind} +0.89* F_{wf} * F_{ser} +0.998* F_{wf} * F_{agr})$	$P_i *(0.80* F_{nwf} +0.10* F_{wf} * F_{ind} +0.15* F_{wf} * F_{ser} +0.65* F_{wf} * F_{agr})$
Indoor nonresidential	$P_i*(0.25* F_{nwf} +0.85* F_{wf} * F_{ind} +0.85* F_{wf} * F_{ser}+ 0.04* F_{wf} * F_{agr})$	$P_i*(0.10* F_{wf} * F_{ind} +0.10* F_{wf} * F_{ser}+ 0.001* F_{wf} * F_{agr})$	$P_i*(0.20* F_{wf} * F_{ind} +0.20* F_{wf} * F_{ser}+ 0.01* F_{wf} * F_{agr})$
Outdoor	$P_i*(0.35* F_{nwf} +0.10* F_{wf} * F_{ind} +0.10* F_{wf} * F_{ser} +0.95* F_{wf} * F_{agr})$	$P_i*(0.001* F_{nwf} +0.01* F_{wf} * F_{ind} +0.01* F_{wf} * F_{ser} +0.001* F_{wf} * F_{agr})$	$P_i*(0.20* F_{nwf} +0.70* F_{wf} * F_{ind} +0.65* F_{wf} * F_{ser} +0.34* F_{wf} * F_{agr})$

where:

- P_i is the total population within a grid cell i
- F_{wf} is the fraction of the total population that is part of the workforce
- F_{ind} is the fraction of the total workforce that is employed in the industrial sector
- F_{agr} is the fraction of the total workforce that is employed in the agricultural sector
- F_{ser} is the fraction of the total workforce that is employed in the service sector
- F_{nwf} is the fraction of the total population that is not part of the workforce

To illustrate our population distribution approach, let us assume that 100 people are within a 1 km x 1 km grid cell in an urban area of Indonesia. Considering the demographic dataset for Indonesia, we estimate during daytime that approximately 22 people are inside residential dwellings (including single, multifamily or other types of residences) and 43 are inside non-residential dwellings (constituting workplaces); those remaining are outdoors. During commuting hours this occupancy pattern changes to approximately 56 people in homes, only 7 at work places, and 37 outdoors. At night the algorithm computes nearly 97 out of 100 occupying homes and only 3 at workplaces, with fewer than half of 1% outdoors. This distribution changes within rural areas based on demographics and coefficients associated with rural areas (Table 1).

Figure 2 shows occupancy load estimated within different PAGER-STR types for the M7.6 Sept 30, 2009 Sumatra earthquake (0.73^{o}S 99.86^{o}E Depth: 81 km) which struck at 5:16 pm local time. While we employ default coefficients at a country level for the countries in which detailed demographic data are not available, for many of these countries the country-level demographic data are sufficient to provide the approximate grid-level occupancy pattern according to time of day. This approximate approach is similar to the NIBS-FEMA population distribution methodology (refer to Table 13.2 of HAZUS technical manual) adopted for estimating occupancy within five broad occupancy categories from the total census tract population using demographic data. Even in the US, while census population data is of relatively high resolution, determining day and night time residential population distributions at the census tract level is fraught with uncertainty and requires numerous assumptions.

The PAGER inventory database provides the distribution of housing/dwelling units rather than the distribution of buildings by urban-residential, urban-non-residential, rural-residential and rural-non-residential occupancy types. In most census databases, the housing/dwelling units represent independent abodes for a single household/family. In general, the dwelling type distribution can be considered as a proxy for population distribution by dwelling structure types, however, the same is not true in case of building distributions by structure type. This is mainly because several single family or multi-family dwellings may be housed within a single building and the number of dwelling units within a building may vary from building to building.

While the distribution of building types (by their structural system) is important for earthquake damage and loss analysis, they can also be used to directly represent the total population distribution within a given area or city by different building types. Often, researchers use the data on total floor areas of a building to approximately estimate the occupancy load during day, night and transit times (ATC-13 1985; NIBS-FEMA 2006). Such information is extremely difficult to gather at the city or state level and oftentimes a variety of input data is used to relate the approximate floor area for single and multi-family buildings, e.g., energy usage within a household or income levels. Such data are extremely difficult to compile on a global scale and often are unavailable, especially for developing countries. The PAGER inventory database developers recognized this limitation and developed the dwelling-type distribution instead of building distribution. In addition, the World Housing Encyclopedia (WHE)-PAGER expert judgment survey also provided direct estimates of the population distribution by PAGER structure type for 30+ countries of the world (Jaiswal and Wald 2009).

Though it is possible to develop a detailed dataset comprising building type distributions as well as their day/night occupancies through comprehensive engineering field surveys, such efforts have not been feasible on a global scale. Nevertheless, the framework described for PAGER population distribution, which works on a grid level, is flexible enough to allow updates to the occupancy coefficients as any new demographic data become available.

Building Vulnerability Functions

Building collapse is the dominant contributor to earthquake fatalities (Coburn and Spence 2002). Thus, addressing collapse fragility for global building types is pivotal to PAGER's ability to accurately estimate the fatalities for global earthquakes in near-real time. Within the framework of our semi-empirical approach, the seismic vulnerability is modeled using the structure-type specific collapse-fragility functions. Due to the lack of publicly available data on global building inventories and their collapse fragility at different shaking intensity, the PAGER developers collaborated with experts around the world through EERI's World Housing Encyclopedia under the auspices of a joint WHE-PAGER project (D'Ayala et al., 2010). Each country-specific expert provided the estimate of probability of collapse of predominant structure types as a function of modified Mercalli intensity. The approach was analogous to the ATC-13 methodology to solicit expert judgment on building damageability as a function of shaking intensity. It was recognized that soliciting expert judgment or retrieving damage data specific to building collapses (which causes most fatalities) was more feasible than statistical compilation of data specific to lesser damage states (such as slight, moderate, or extensive damage).

Experts contributing to the survey were encouraged to solicit or draw on regional expertise substantiating their judgment with past observed damage data or research. In most cases, they relied on their experience of the performance of specific structure classes in past earthquakes, and where such information was missing, they were asked to provide professional judgment. Our preliminary analysis of the survey data indicated that there were large variations of experts' judgment on the collapse probability for the same class of structures (Jaiswal and Wald 2009). The large variation in collapse probability estimates even for the same class of structure is expected, due to potentially large variations in building design and construction practices from country to country and even within a country (rural vs. urban; pre- or post-code or degree of code enforcement). However, many contributions appeared to be biased towards overestimating structure vulnerabilities. Vulnerability estimates for engineered structures were usually consistent among countries, while for non–engineered, non-codified, and vernacular building types, they tended to differ more significantly and estimates were usually higher than the equivalent class of vulnerability defined by EMS-98 (Grunthal et al., 1998). Other contributing factors were likely cultural bias or the lack of confidence in assigning the performance of non-seismically designed buildings, again leading to a conservative judgment.

Efforts are underway to refine the WHE-PAGER Phase I survey data through a) revisiting some of the contributions and removing or assigning lower weights to the questionable contributions, b) improving the survey form by providing more detailed guidelines with illustrations for the definition of collapse for framed versus masonry construction, and c) performing rigorous statistical analysis of the range of results. In the meantime, within the framework of the semi-empirical approach, we have implemented the selected contributions by the PAGER-STR type (usually, the *lowest* collapse rate per structure type). As we go forward we are modifying the expert-based collapse fragility functions using the following procedure that allows direct inclusion of detailed collapse rates for specific structures based on specific observations (e.g., Jaiswal et al., under review).

In order to compute the collapse fragility estimate at non-discrete levels, and also to update them using locally available collapse vulnerability data of past earthquakes, we express the collapse vulnerability at modified Mercalli (MM) intensity $[X] = [x_1, x_2, x_3, \ldots\ldots x_n]$ using a functional form as below:

$$F(x_i) = A_j \times 10^{\left(\frac{B_j}{x_i - C_j}\right)} \tag{1}$$

where A_j, B_j, and C_j are parameters to be estimated by fitting the prior expert-judgment of experts for building type 'j'. Dowrick (1991) and Dowrick et al (2001) have proposed the above functional form for modeling the mean damage ratio as a function of shaking intensity for New Zealand buildings. If structure-specific collapse fragility data $[Y] = [y_1, y_2, y_3, \ldots\ldots y_n]$ at shaking intensity $[X] = [x_1, x_2, x_3, \ldots\ldots x_n]$ are available, we can estimate the collapse fragility parameters (A_j, B_j, and C_j) using standard minimization techniques to minimize the following residual error:

$$\varepsilon^2 = \sum_i \left[Y(x_i) - F(x_i)\right]^2 \tag{2}$$

Table 2 provides collapse fragility parameters for selected building types along with the correlation coefficient obtained for each building type. In addition, if the structure-specific collapse fragility data have variable quality (common for damage data collated during post-earthquake reconnaissance studies) we assign weights $[W] = [w_1,\ w_2,\ w_3 \ldots\ldots\ldots w_n]$ and minimize the weighted residual error given as:

$$\varepsilon^2 = \sum_i w_i * \left[Y(x_i) - F(x_i)\right]^2 \tag{3}$$

In order to measure how well the data fit the chosen fragility function, we estimate the correlation coefficient (R^2) as:

$$R^2 = 1 - \frac{\mathrm{var}\left[Y(x) - F(x)\right]}{\mathrm{var}\left[Y(x)\right]} \tag{4}$$

The correlation coefficient ranges between 0 and 1 with higher correlation coefficient value (close to 1.0) indicating the better data-fit.

Efforts are underway to model the uncertainty of collapse fragility at each intensity level using the probability distribution as a prior distribution and then using collapse vulnerability data to estimate the posterior distribution (Jaiswal et al., under review). Such intensity-level specific uncertainties along with uncertainty in hazard estimates allow computation of the overall uncertainty in both the fatality and overall loss calculations.

Table 2. Collapse fragility parameters for selected building types.

Building Type	*A*	*B*	*C*	Fatality Rate *(FR)*
Adobe buildings	10.76	-5.34	4.05	0.06
Mud wall buildings	2.56	-1.69	5.18	0.06
Nonductile concrete moment frame	3.42	-5.03	5.62	0.15
Ductile reinforced concrete frame	4.81	-5.62	5.99	0.15
Precast framed buildings	0.85	-2.35	5.90	0.10
Block or dressed stone masonry	9.52	-4.89	5.32	0.08
Rubble or field stone masonry	6.17	-4.58	5.03	0.06
Brick masonry with lime/cement mortar	8.03	-7.59	4.60	0.06
Steel moment frame with concrete infill wall	0.44	-6.10	4.40	0.14
Light wood-frame designed for earthquake load	1.30	-6.40	4.92	0.007
Heavy post and beam wood-frame	0.67	-1.69	5.72	0.013

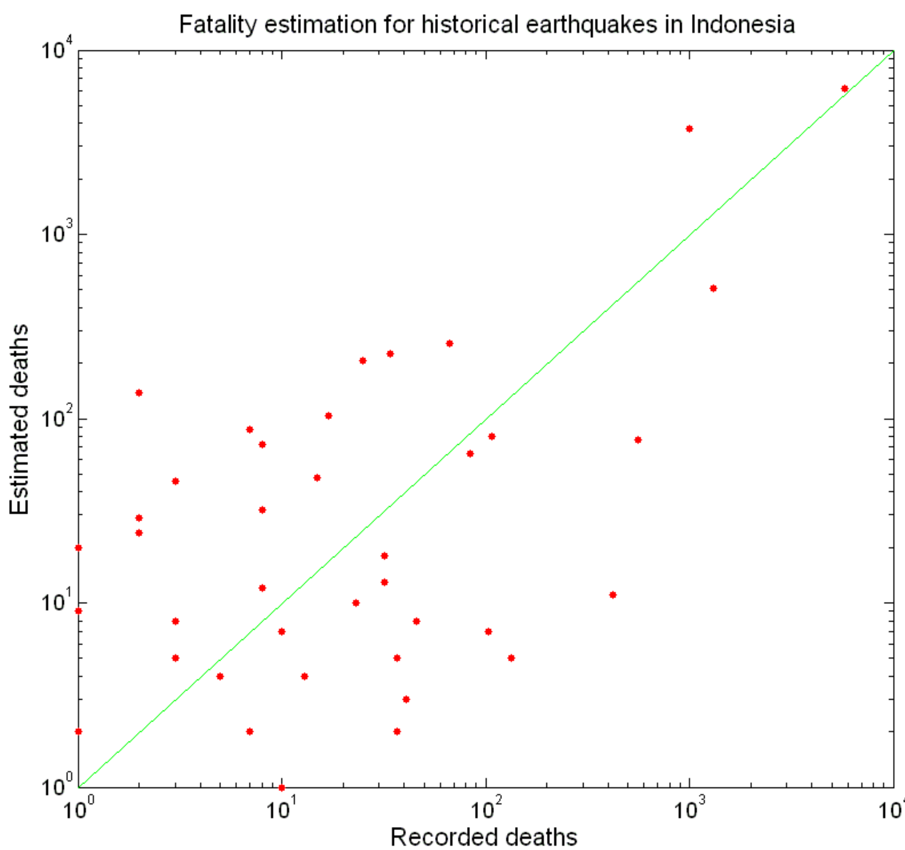

Figure 3. Hindcasting fatalities for historical earthquakes (1973-2007) using the semi-empirical model.

Fatality Rates and PAGER Grid-Based Earthquake Fatality Loss Computations

Establishing accurate fatality rates (*FR*) given structural collapse for each building type is a difficult task as they tend to vary from one earthquake to another, even within the same construction type. Rigorous statistical analysis is necessary with appropriate correction for sampling or observational bias. The PAGER fatality rate estimates are mainly deduced from combining the fatality rates suggested by researchers for different parts of the world (Spence 2007; Spence and So 2009). For US construction types, we assigned fatality rates directly from the HAZUS (NIBS-FEMA 2006) associated with injury severity level 4 at the complete damage state. However for non-US construction, we used generic casualty rates recommended by the Cambridge University Earthquake Damage Database (CUEDD) for injury category-5 (deaths) associated with damage grade D5 (partially or totally collapsed) developed under the auspices of LessLoss project (also shown in Table 2).

PAGER's semi-empirical and analytical loss models employ grid-based fatality calculations. The shaking intensity (expressed in terms of MMI) associated with each grid cell i is denoted as S_i and j is an index representing each structure type and FR_j is the fatality rate given collapse. Let P_i denote the total population at grid cell i, and f_{ij} denote the fraction of the population at location i in structure type j at the time of the event. If the mean collapse ratios associated with each structure type j at intensity S_i are expressed as $CR_j(S_i)$, we can express the total estimated fatalities $E[L]$ over n grid cells as:

$$E[L] \approx \sum_{i=1}^{n}\sum_{j=1}^{m} P_i f_{ij} CR_j(S_i) FR_j \quad (5)$$

The total deaths due to secondary hazards (e.g., landslide, fire-following earthquake, liquefaction) and also due to non-collapse damage states of the buildings are not included in this computation. The grid spacing, approximately 1 km x 1 km, is dictated by the LandScan population data (Bhaduri et al., 2002) we employ. In addition, a global population density (urban/rural) map (CIESIN 2004) is overlaid on the Landscan grid to identify density type. The total population within each grid cell is distributed into different residential and non-residential occupancy categories and structure types. Finally, using the structure-specific collapse vulnerability functions and fatalities rates, we estimate the total fatalities and the number of collapse by structure type. Both the number of fatalities by structure type and the total number of collapsed buildings are useful for assessing the scale of disaster and for estimating response and sheltering demands.

We used the procedure described above to hindcast the fatalities from historical earthquakes in Indonesia using the semi-empirical model (Figure 3). The model-estimated deaths appear to have higher accuracy for highly fatal earthquakes whereas for most of the smaller events, the deviation is within ±1 order of magnitude. Though currently less accurate than our empirical model, this level of accuracy is useful at a global scale given the large uncertainties associated with the input data sets.

Conclusions

PAGER's semi-empirical loss modeling procedure incorporates newly-derived, country-specific building inventories and vulnerability functions as well as day/night population distributions within these structures. The data sets presented are available online at the USGS PAGER web site (http://earthquake.usgs.gov/earthquakes/pager/). The building inventory and population distribution efforts described are also directly applicable to our developing analytical loss model, which requires these as fundamental input. The analytical model replaces the expert-derived, intensity-based collapse vulnerability functions with analytical functions based on response spectral values rather than the shaking intensity in regions where such functions are well described. PAGER's fully analytical loss model, described by Porter et al., (2008) and Porter (2009), is further explored in D'Ayala et al., (2010).

Operationally, the PAGER system relies on the empirically-based loss approach (Wald et al., 2008b), yet we are computing losses with the semi-empirical approach detailed here. Over time we are gaining confidence with results and experience in portraying the losses as a function of dominant construction types. For most countries, there are clearly dominant building type "culprits" that dominate fatalities. Such building-specific analyses are not possible with the empirical loss approaches. PAGER's inventory and population exposure algorithm provide a simple and consistent framework for earthquake fatality and loss computation. Ongoing efforts focus on improving building inventories for specific high-risk countries and further examining several key high-risk building vulnerability functions based on analyses of their performance during past earthquakes.

Acknowledgements

The authors gratefully acknowledge the contributions made by WHE-PAGER survey participants. We thank P. Earle and K. Porter for their stimulating discussions during various phases of this investigation, and M. Hearne who performed the software implementation of the semi-empirical model in the PAGER system for real-time loss computation. Thanks to Stuart Sipkin and Margaret Hopper for internal reviews of the manuscript.

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