EARTHQUAKE CASUALTY MODELS WITHIN THE USGS PROMPT ASSESSMENT OF GLOBAL EARTHQUAKES FOR RESPONSE (PAGER) SYSTEM

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ABSTRACT

Since the launch of the USGS's Prompt Assessment of Global Earthquakes for Response (PAGER) system in fall of 2007, the time needed for the U.S. Geological Survey (USGS) to determine and comprehend the scope of any major earthquake disaster anywhere in the world has been dramatically reduced to less than 30 minutes. PAGER alerts consist of estimated shaking hazard from the ShakeMap system, estimates of population exposure at various shaking intensities, and a list of the most severely shaken cities in the epicentral area. These estimates help government, scientific, and relief agencies to guide their responses in the immediate aftermath of a significant earthquake. To account for wide variability and uncertainty associated with inventory, structural vulnerability and casualty data, PAGER employs three different global earthquake fatality/loss computation models. This article describes the development of the models and demonstrates the loss estimation capability for earthquakes that have occurred since 2007. The empirical model relies on country-specific earthquake loss data from past earthquakes and makes use of calibrated casualty rates for future prediction. The semi-empirical and analytical models are engineering-based and rely on complex datasets including building inventories, time-dependent population distributions within different occupancies, the vulnerability of regional building stocks, and casualty rates given structural collapse.

1. INTRODUCTION

In the last decade, destructive earthquakes have struck throughout the globe and tragically claimed over 200,000 lives (e.g., Bam 2003, Morocco 2004, Kashmir 2005, Indonesia 2006, Peru 2007, Wenchuan 2008, and L'Aquila 2009). Due to the complexity associated with a large earthquake in terms of hazards (including its size, location and rupture uncertainties, and spatially variable shaking characteristics), as well as with the built environment (building and infrastructure vulnerability and population exposure characteristics at the time of earthquake), it often requires days, weeks or sometime months before the scope and extent of an earthquake disaster is understood. Time is of the essence in the post-earthquake arena and any delays in understanding the scale of the disaster often hampers the post-disaster responses and proves costly both socially and economically. Several aspects of an earthquake, including those of a seismological, engineering, and socio-economical nature must be understood and incorporated effectively before the impact of an earthquake can be predicted. In the realm of rapid earthquake casualty and loss modeling, this requires comprehensive assessment of earthquake hazard, seismic vulnerability of built environment and associated exposure, and finally a framework that computes losses in real-time. Tools developed at the National Earthquake Information Center, including the USGS ShakeMap and Did You Feel It? systems, provide rapid ground shaking intensity estimates immediately after an earthquake anywhere in the world (Wald et al., 2008). The current Prompt Assessment of Global Earthquakes for Response (PAGER) system utilizes the USGS's near real-time earthquake solutions, and estimates population exposure at various levels of shaking intensities. Several datasets have been compiled during the development of PAGER system, such as i) PAGER-CAT, which tabulates earthquake magnitude, location, depth and fatality/loss information specific to individual earthquakes (Allen et al, 2009a), ii) Atlas of global earthquake ShakeMaps (shaking hazard maps) for the past 35 years (Allen et al, 2009b), and iii) EXPO-CAT, a catalog of estimated population exposure at different shaking intensities created by hindcasting present day population to date of the event. These products have provided unique opportunities to study past earthquakes and perform comprehensive loss assessment using several different approaches. With the addition of the new loss computation engine within the PAGER system, we propose development of a exposure- and fatality-based alert system which provides an estimation of the likelihood of a range of fatalities caused by an earthquake. Tools developed for PAGER can also be used for effective pre-disaster planning for major damaging earthquakes anywhere in the world. Such a system is of paramount importance, especially to inform early and rapid post-earthquake decisions about humanitarian assistance, before ground truth and news information are acquired.

2. INPUTS FOR LOSS ESTIMATION

2.1 Hazard

Based on a certain predefined magnitude threshold (M>3.5 within US and M>5.5 at global scale) registered by National Earthquake Information Center and the Advanced National Seismic System, the USGS Global ShakeMap system is triggered automatically and produces shaking hazard map in terms of ground motion parameters (Modified Mercalli shaking intensity, peak accelerations, peak velocities and spectral accelerations at 0.3 and 1.0 sec period) at a resolution of approximately 1 sq km. The USGS ShakeMap system chooses the most appropriate ground motion prediction equation (GMPE) from a suite of GMPEs based on the seismogenic and tectonic conditions at the earthquake location. It uses conversion equations to transform ground motion estimates into other important shaking hazard parameters and also corrects the estimated ground motions for local site conditions (see Wald and Allen, 2007 for more details). This site-corrected shaking hazard forms the basis for vulnerability and loss estimation for the PAGER system.

2.2 Vulnerability

The PAGER system consists of three vulnerability models, namely empirical, semi-empirical, and analytical which are discussed in the section 3. The effective fatality rate within the empirical model is defined using a two-parameter lognormal cumulative distribution function, the coefficients of which are directly derived from past fatal earthquakes. The semi-empirical and analytical vulnerability models are forward predicting models in which the damage and loss analyses are based on site and structure-specific response analysis but applied at a regional scale. The semi-empirical model relies solely on fatalities caused due to building collapses and uses structure-specific collapse fragility functions defined in terms of Modified Mercalli shaking intensities (MMI), whereas the analytical model uses the HAZUS capacity-spectrum method to perform structural damage analysis.

2.3 Exposure

Several inputs are necessary in order to perform exposure analysis within the PAGER system. These are i) LandScan 2007 gridded population database (Bhaduri et al., 2002), ii) the Global Rural-Urban Mapping Project (GRUMP) database (CIESIN, 2004), iii) demographic data compiled by the United Nations, data published by population census of different countries, CIA fact book on workforce data by sector of employment (https://www.cia.gov/library/publications/the-world-factbook), and iv) the PAGER building inventory database, compiled using multiple sources and contributions from the WHE-PAGER project (Jaiswal and Wald, 2008). Details of grid based exposure analysis necessary for PAGER semi-empirical and analytical models are discussed in the next section.

3. LOSS ESTIMATION MODELS

Researchers in the past have attempted to perform earthquake casualty/loss estimation at local or regional levels and advocated various approaches depending upon type of data, spatial applicability, and modeling principles. These different techniques can be classified into variants of three distinct approaches, namely empirical, analytical, and hybrid (or semi-empirical) approaches. Empirical approaches generally utilize earthquake data associated with past fatal earthquakes to derive regression parameters to be used for future prediction. Analytical (also called mechanistic) approaches employ end-to-end modeling calculations comprising of hazard, structural, damage, and loss analyses. Hybrid approaches are either simplified analytical approaches or approaches in which damage statistics of past earthquakes are directly utilized in the realm of structural damage analysis via modeling observed damage as a function of shaking intensities. The following section provides a detailed description of the three loss computation models that have been implemented within the PAGER system.

3.1 Empirical Model

Jaiswal et al (2009) developed a new global empirical model that utilizes historical earthquake casualty data and provides a country or region-specific earthquake fatality rate as a function of shaking intensity. Unlike previous empirical approaches proposed by various researchers (Samardjieva and Badal, 2002; Nichols and Beavers, 2003) that advocates use of earthquake magnitude as a regression variable, Jaiswal et al.'s procedure utilizes shaking intensity, a spatially varying parameter and an indicator of direct impact of ground motion on built environment. Earthquake magnitude only indicates the size of an earthquake and sometimes can be completely misleading for comparison with damage due to large variability in the shaking hazard for a given magnitude and population exposure.

3.1.1 Empirical Fatality Rate: Fatality rate (ν), which is function of shaking intensity (*S*), can be expressed in terms of a two-parameter lognormal distribution function as follows:

$$\nu(S) = \Phi\left[\frac{1}{\beta}\ln\left(\frac{S}{\theta}\right)\right] \tag{1}$$

where Φ is the standard normal cumulative distribution function. The fatality rate depends on the two free parameters of the cumulative distribution function of the lognormal distribution namely, θ and β. Let $P_i(S_j)$ denote an estimated population exposed to shaking intensity S_j for an event *i*. Then the expected number of fatalities $E[L]$ can be denoted as

$$E_i[L] \approx \sum_j \nu_i(S_j).P_i(S_j) \tag{2}$$

In order to estimate the total number of fatalities from any given earthquake, we need to find i) population exposure at each shaking intensity level, and ii) the fatality rate associated with the shaking intensity. Suppose O_i is the number of recorded deaths for an earthquake *i*; we can determine the parameter of the distribution function (i.e., estimated fatality rate) in such a way that the residual error (i.e., error estimate between estimated and recorded deaths) is minimized. Jaiswal et al. propose a norm that provides a search space for minimizing the residual error associated with both low and high fatality earthquakes simultaneously. The objective function to determine the residual error is given as

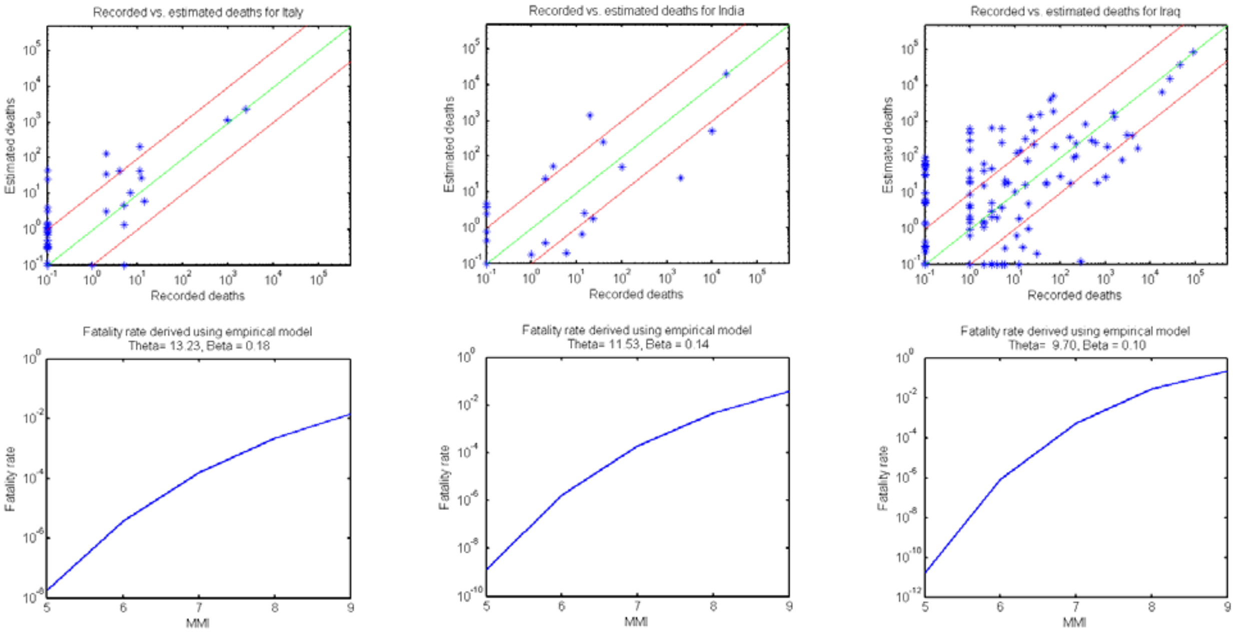
$$\varepsilon = \ln\left(\sqrt{\frac{1}{N}\sum_{i=1}^{N}(E_i - O_i)^2}\right) + \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left[\ln(E_i / O_i)\right]^2} \tag{3}$$

We use a standard iterative search algorithm available in Matlab Ver., R2007a for minimizing the objective function in which E_i is defined in terms of Equation 2 which contains fatality rate (ν) defined using θ and β as described in Equation 1. It is assumed that the recorded number of deaths from an earthquake in the catalog is free from any errors and is generally obtained from a well documented, peer reviewed source of literature or dataset for a particular earthquake. Figure 1a and 1b demonstrates the result of using Equation 3 for Italian and Indian earthquakes between 1973 and 2007. Earthquakes with zero recorded deaths have been taken as 0.1 deaths for calculation purposes, and earthquakes without a recorded number of deaths (zero or otherwise) are ignored. Except for a few outliers, the model estimates the fatalities for most of the events within 1 order of magnitude, with approximately equal accuracy at low and high recorded deaths.

3.1.2 Uncertainty Estimation: The total uncertainty in hindcasting the median loss estimates for past fatal earthquakes is represented using the error term (ζ), where:

$$\zeta = \sqrt{\frac{1}{N-2}\sum_{i=1}^{N}\left[\ln(E_i + 0.5 / O_i + 0.5)\right]^2} \tag{4}$$

The error term is a combined measure of total variability associated with catalog earthquakes (in which each earthquake has certain inherent errors associated with their epicentral location, ShakeMap's estimates of ground motion, accuracy of estimated population exposure, accuracy in terms of catalog fatality count or other socio-economic factors) and each of them cannot be separated easily unless sufficient data are collected on each of these factors to isolate and model their independent contributions. It is expected that such error will always be part of the total error in predicting future fatalities for that region or country.



(a) (b) (c)

Figure 1 Empirical fatality model derived using historical (1973-2007) fatal earthquakes.

For PAGER alert purposes, we also need to provide the probability estimate associated with different alert levels such that the actual deaths may exceed certain predefined alert thresholds (see Jaiswal et al., 2009). The probability P that the actual death d may be between predefined thresholds a and b is given as:

$$P(a < d \leq b) = \Phi\left[\frac{\log(b) - \log(E)}{\xi}\right] - \Phi\left[\frac{\log(a) - \log(E)}{\xi}\right] \quad (5)$$

3.1.3 Regionalization: In order to estimate the empirical fatality rate for countries with few or no fatality data, Jaiswal et al. (2009) proposes aggregation of fatal events from like-countries at a regional level through a scheme that focuses on likely indicators of comparable country vulnerability. The regionalization scheme combines the information specific to geography, building inventory (Jaiswal and Wald, 2008), and socio-economic similarities defined using Human Development Index (HDI), and climatic classification scheme by Koppen Climate maps (Kottek et al 2006). Socio-economic conditions and climate affect the way people live and also tend to influence building construction and maintenance practices. Figure 1c demonstrate the development of region-based fatality model for Iraq combining regional earthquakes that have occurred in neighboring countries such as Iran, Pakistan, and Afghanistan.

We illustrate the spatial variation of seismic-hazard independent mortality by estimating fatalities per 1000 people when exposed at shaking intensity IX in Figure 2. Clearly, future large earthquakes in countries like Iran, Pakistan and other south Asian countries will tend to produce the highest fatalities, whereas countries like United States, Canada, and Australia remain less vulnerable irrespective of their seismic hazard. It is worth noting that due to the lack of sufficient large earthquakes in eastern south America, we tend to underestimate the seismic vulnerability. The PAGER empirical model (v1.0) has been implemented within the *lossPAGER* system since beginning of 2008. Figure 3 illustrates out of a total 139 earthquakes, 100 were non-fatal for which the empirical model predicted zero fatalities (therefore all are shown in lower left corner of fig 3 at 0.1 deaths).

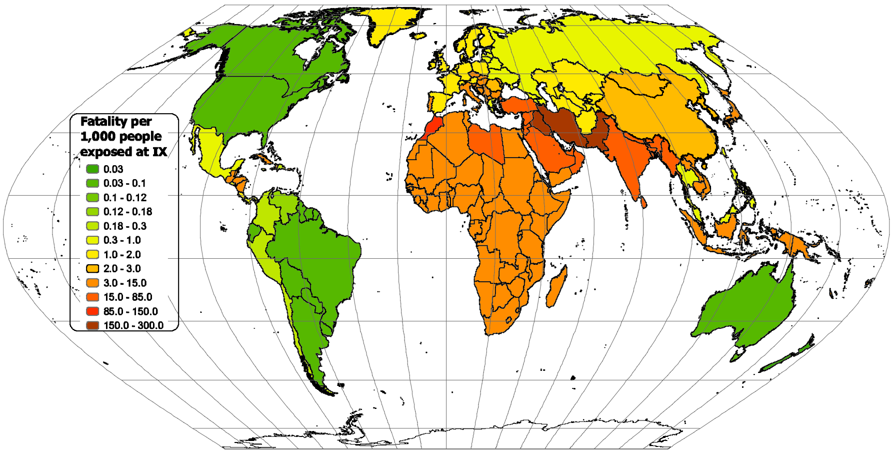


Figure 2 PAGER empirical model showing earthquake fatalities estimated per 1,000 people exposed at MMI IX irrespective of shaking hazard.

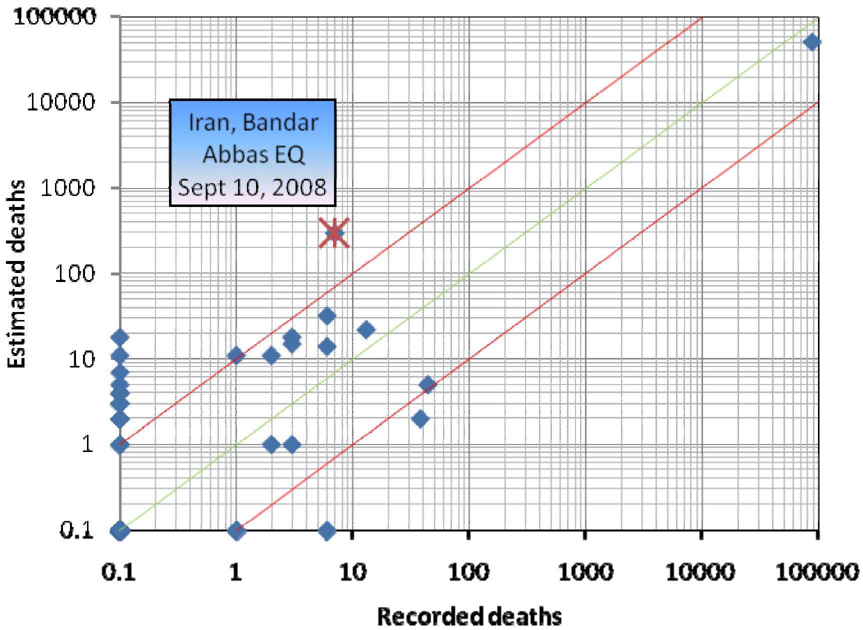


Figure 3 Fatality prediction using empirical model for global earthquakes recorded in 2008. The model overestimated fatalities for the Bandar Abbas earthquake in Iran which killed 7 and injured 47 people.

3.2 Semi-Empirical Model

As forward estimation model, earthquake vulnerability within the semi-empirical model is defined in terms of probability of collapse of a particular structure type given the input shaking intensity. Let us assume that there are a total of n grid cells with m structure types. 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 for which 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 earthquake. If the collapse fragility or mean collapse ratios associated with each structure type j at intensity S_i are expressed as $CR_j(S_i)$, then we can express the total estimated fatalities $E[L]$ over n grid cells as:

$$E[L] \approx \sum_{i=1}^{n} \sum_{j=1}^{m} P_i . f_{ij} . CR_j(S_i) . FR_j \tag{6}$$

3.2.1 Collapse Ratios (*CR) or Collapse Fragility Functions*

In order to estimate the collapse fragility, PAGER collaborated with WHE experts from twenty-six countries to gather country-specific vulnerability data for the most common building types (Porter et al, 2008). After performing rigorous analysis of building-specific fragility functions on country-specific data and hindcasting losses for past fatal earthquakes, we developed a suite of PAGER structure-type (PAGER- STR) specific collapse-fragility functions (Jaiswal and Wald, in prep.) that can be used within the PAGER semi-empirical model. The collapse fragility defined in terms of shaking intensity *S* is given as:

$$CR_j(S) = A_j \times 10^{\left(\frac{B_j}{S-C_j}\right)} \tag{7}$$

The parameters A_j, B_j, C_j can be determined for each structure type *j* either from structure specific collapse statistics obtained from past earthquakes or retrieving best fit parameters to the expert judgment data gathered through the WHE-PAGER project. Table 1 summarizes the parameters obtained for some PAGER structure types from WHE-PAGER survey data.

Table 1 Collapse fragility parameters for selected building types (Jaiswal and Wald, in prep.).

Building Type	***A***	***B***	***C***	***FR***
Adobe buildings	2.33	-1.35	5.92	0.06
Mud wall buildings	3.16	-2.17	4.86	0.06
Nonductile concrete moment frame	3.40	-5.57	5.27	0.15
Precast framed buildings	0.96	-2.52	5.88	0.10
Block or dressed stone masonry	8.89	-4.84	5.26	0.08
Rubble or field stone masonry	5.85	-4.64	4.87	0.06
Brick masonry with lime/cement mortar	21.02	-5.36	5.53	0.06
Steel moment frame with concrete infill wall	0.53	-7.11	4.00	0.14

3.2.2 Fatality Rates (*FR*) *Given Structural Collapse*: Building collapses are the main contributor to total fatalities worldwide (Spence, 2007) and the PAGER fatality estimates are mainly deduced from modeling the collapse fragilities of different structure types within the current framework. Although the fatality rates tend to vary from one earthquake to another, even given similar levels of ground motions or building vulnerabilities, these rates still are derived by performing statistical analysis on casualty data of several earthquakes. For most United States (US) construction types, the fatality rates given collapse are directly taken from the HAZUS (NIBS-FEMA, 2006) casualty rates associated with injury severity level 4 at the complete damage state. However for non-US construction types, we used generic casualty rates recommended by UCAM for injury category-5 (deaths) associated with damage grade D5 (partially or totally collapsed) under the auspices of LessLoss project as shown in Table 1.

3.3 Analytical Model

The analytical model implemented in the current USGS PAGER system is based on HAZUS capacity-spectrum methodology that estimates the response of a structure from spectrum demand and spectral-capacity curves (NIBS-FEMA, 2006). The demand spectrum represents the site adjusted input ground motion typically derived from elastic acceleration response spectra, whereas the spectral capacity of a structure is expressed in terms of idealized curvilinear curve defined by yield and ultimate control points. The capacity-spectrum method provides the estimate of median response of an idealized nonlinear single degree of freedom (SDOF) oscillator where the spectral-capacity and demand curves intersect. This point is referred to as the performance point and it is obtained by adjusting the response to account for site soil amplification and hysteretic energy dissipation through an iterative procedure. The spectral displacement S_d associated with the performance point forms an input to fragility functions that gives the probability of different damage states. The damage and casualties associated with slight, moderate and extensive damage states are ignored for PAGER purposes since they form a very small fraction of total fatalities. Porter (2009) simplifies the iterative process for PAGER purposes and directly tabulates the mean-collapse fragilities and indoor fatality rates as a function of 5% damped spectral accelerations at 0.3 and 1.0 sec periods. The fatality rates given structural collapse (FR) are same as in case of the semi-empirical approach.

3.4 Grid-based loss Computation

Both semi-empirical and analytical models employ grid-based fatality computation (Figure 4) in which we determine the density class of a particular cell i using the GRUMP dataset, then determine the fraction of indoor population in residential and non-residential (work places, e.g., commercial, service, industry, schools, administrative buildings, etc.) occupancies based on local time of day and a demographic dataset. We assume three time domains, namely: Day time (10 am-5 pm), Night time (10 pm-5 am), and Transit time (5 am-10 am and 5 pm-10 pm), used for the purpose of determining the fraction of the total population in residential and non-residential buildings. The total outdoor population determined at the time of the earthquake is ignored at this stage due to the lack of availability of vulnerability functions and casualty rates specific to lifeline systems or with outdoor populations. Once the total indoor population in both residential and non-residential is determined, we classify them into different PAGER structure types using country-specific inventory defined in terms of density (urban/rural) and occupancy (residential/non-residential) types. The total indoor population by PAGER structure type is determined as a function of time of day, population density characteristics, and occupancy type, and forms an input for damage and loss estimation as described in the previous section. We estimate the total fatalities from each PAGER structure type using either the semi- empirical model (in which the intensity associated with grid cell i is used) or using the analytical approach (in which the spectral acceleration at 0.3 and 1.0 sec time periods is used). We then sum the total fatalities over all the structure types of grid cell i and later over all grid cells associated with a particular earthquake.

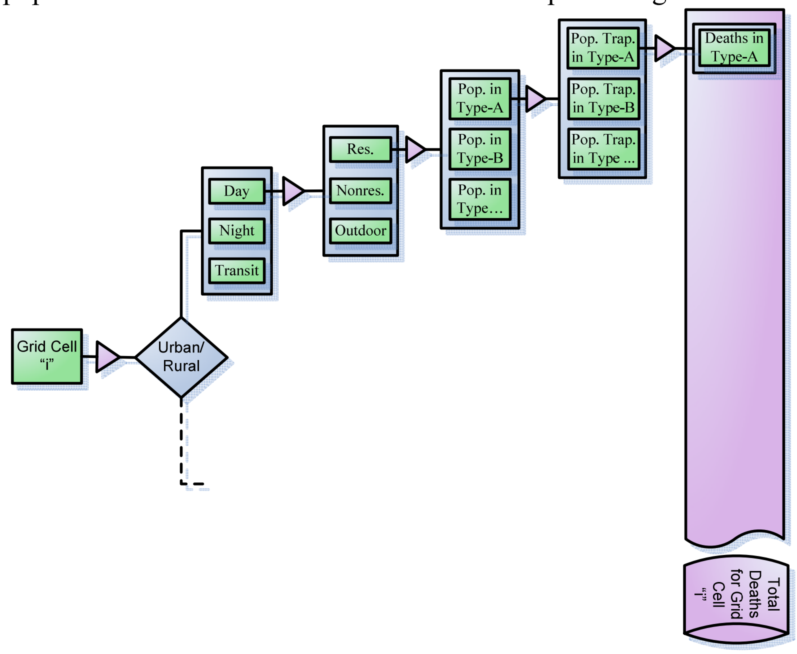


Figure 4 Grid-based fatality computation for PAGER engineering loss estimation models

4. CONCLUSIONS

Rapid earthquake loss estimation tools such as PAGER that provide the estimation of likelihood of building and infrastructure damage, deaths, and financial losses after an earthquake help responders understand the scale of disaster and determine the demand in terms of humanitarian needs in the aftermath of a disaster. The PAGER empirical model accommodates the total variability through a country-specific error term obtained by hindcasting deaths in past earthquakes. While the availability of data on large and fatal earthquakes in the past serves as a backbone for the empirical model, these datasets also provide a useful benchmark for calibrating losses using both hybrid and analytical approaches. The analytical model uses fragility functions that relate the probability of various damage states or collapse given the response of the building type to certain input ground shaking. In the case of the analytical approach, the vulnerability parameters associated US building types are adopted from the HAZUS model; however it is extremely difficult to gather the complex structural parameters needed to define the vulnerability and performance for non-US construction types. The WHE-PAGER project (through a network of international experts) is working towards developing protocols for collection of critical parameters using a unified approach and developing strategy to encourage researchers worldwide to contribute data through an open-source environment to improve the vulnerability modeling capabilities.

REFERENCES

Allen, T.I., Marano, K., Earle, P.S., and Wald, D.J. (2009a). PAGER-CAT: A composite earthquake catalog for calibrating global fatality models, *Seismological Research Letters* 80:1, 57-62.

Allen, T. I., D. J. Wald, P. S. Earle, A. J. Hotovec, K. Lin, K. D. Marano, and M. Hearne (2009b) An Atlas of ShakeMaps and population exposure catalog for earthquake loss modeling, *Bull. Earthquake Eng.*, (in press).

Bhaduri, B., Bright, E., Coleman, P., and Dobson, J. (2002). LandScan - Locating people is what matters: *Geoinformatics* 5:2, 34-37.

Center for International Earth Science Information Network (CIESIN), Columbia University; International Food Policy Research Institute (IFPRI), the World Bank; and Centro Internacional de Agricultura Tropical (CIAT), (2004). Global Rural-Urban Mapping Project (GRUMP): Palisades, NY: *CIESIN, Columbia University* (Available at http://sedac.ciesin.columbia.edu/gpw).

National Institute of Building Sciences-Federal Emergency Management Agency (NIBS-FEMA) (2006). HAZUS-MH MR2 Technical Manual: Federal Emergency Management Agency (http://www.fema.gov/plan/prevent/hazus/hz_manuals.shtm).

Jaiswal, K. and Wald, D.J. (2008). Creating a Global Residential Building Inventory for Earthquake Loss Assessment and Risk Management, *U. S. Geological Survey Open File Report* 2008-1160, 113 pp.

Jaiswal, K., Wald D. J. and Hearne, M. (2009). Estimating casualties for large worldwide earthquakes using an empirical approach, *U. S. Geological Survey Open File Report* (in press).

Jaiswal, K., and Wald, D.J., in preparation, Estimating casualties for large worldwide earthquakes using semi-empirical approach: U.S. Geological Survey Open File Report.

Kottek, M., Grieser, J., Beck, C., Rudolf, B. and Rubel, F. (2006). World Map of the Koppen-Geiger climate classification updated, *Meteorologische Zeitschrift* 15:3, 259-263.

Nichols, J.M. and Beavers, J.E. (2003). Development and calibration of an earthquake fatality function, *Earthquake Spectra* 19:3, 605-633.

Porter, K. (2009). Cracking an open safe: HAZUS vulnerability functions in terms of structure-independent spectral acceleration: *Earthquake Spectra* 25:2, 361-378.

Porter, K., Jaiswal, K., Wald, D.J., Greene, M. and Comartin, C. (2008). WHE-PAGER Project: A new initiative in estimation global building inventory and its seismic vulnerability *Proceedings of the 14th World Conference on Earthquake Engineering* Beijing, China.

Samardjieva, E. and Badal, J. (2002). Estimation of the expected number of casualties caused by strong earthquakes, *Bull. Seism. Soc. Am.* 92:6, 2310-2322.

Spence, R. (2007). Saving lives in earthquakes: successes and failures in seismic protection since 1960, *Bulletin of Earthquake Engineering* 5, 139-251.

United Nations (2006). Population growth and distribution (http://unstats.un.org/unsd/demographic /products/indwm/tab1c.htm) March 2007.

Wald, D. J., and T. I. Allen (2007*).* Topographic slope as a proxy for seismic site conditions and amplification*, Bull. Seism. Soc. Am.,* 97 *1379-1395*.

Wald, D.J., Earle, P.S., Allen, T.I., Jaiswal, K., Porter, K., and Hearne, M. (2008). Development of the U.S. Geological Survey's PAGER System (Prompt Assessment of Global Earthquakes for Response), *Proceedings of the 14th World Conference on Earthquake Engineering* Beijing, China.