WHE-PAGER PROJECT: A NEW INITIATIVE IN ESTIMATING GLOBAL BUILDING INVENTORY AND ITS SEISMIC VULNERABILITY

K.A. Porter[1], K.S. Jaiswal[2], D.J. Wald[2], M. Greene[3], and Craig Comartin[3]

[1] *Assoc. Res. Prof., Dept. of Civil, Environmental, & Architectural Eng., Univ. of Colorado, Boulder, USA*
[2] *United States Geological Survey, Golden CO, USA*
[3] *Earthquake Engineering Research Institute, Oakland CA, USA*
Email: keith.porter@colorado.edu, kjaiswal@usgs.gov, wald@usgs.gov, mgreene@eeri.org, ccomartin@comartin.net

ABSTRACT:

The U.S. Geological Survey's Prompt Assessment of Global Earthquake's Response (PAGER) Project and the Earthquake Engineering Research Institute's World Housing Encyclopedia (WHE) are creating a global database of building stocks and their earthquake vulnerability. The WHE already represents a growing, community-developed public database of global housing and its detailed structural characteristics. It currently contains more than 135 reports on particular housing types in 40 countries. The WHE-PAGER effort extends the WHE in several ways: (1) by addressing non-residential construction; (2) by quantifying the prevalence of each building type in both rural and urban areas; (3) by addressing day and night occupancy patterns, (4) by adding quantitative vulnerability estimates from judgment or statistical observation; and (5) by analytically deriving alternative vulnerability estimates using in part laboratory testing.

KEYWORDS: loss estimation, building inventory, seismic vulnerability, PAGER

1. EXISTING LOSS MODELS

Several automated post-earthquake alert systems have developed during the last decade: the California-oriented software EPEDAT (Eguchi et al. 1997), the Russian program EXTREMUM (Shakramanian 2000), the related QUAKELOSS program operated by WAPMERR, and the Global Disaster Alert and Coordination System (GDACS), the last three of which have global scope. Pre-event models are also used to hindcast losses in a post-earthquake mode, such as the US-centric software HAZUS-MH (NIBS and FEMA 2003), similar non-US programs (EQRM, Selena, and HAZTURK), and the commercial risk models developed by RMS, AIR, and EQECAT, the last of which spans approximately 90 of the world's 195 countries—the most of all the commercial models.

At least one model gives a qualitative alert level (GDACS); most provide numeric loss estimates: EPEDAT, EXTREMUM, and QUAKELOSS all estimate deaths and injuries. EPEDAT, HAZUS-MH, and commercial loss models also estimate economic loss and lifeline damage. All but the commercial models are open to some degree, in that they provide documentation at little or no price. The math behind EXTREMUM is extensively documented. The math and the underlying data of HAZUS and several of its non-US imitations are available. In at least two cases, an Australian version of HAZUS called EQRM and the Norwegian version called Selena, the software code is freely available for download. Some models offer probabilistic loss estimates: the commercial loss models provide mean loss estimates and estimates of the loss distribution, as does EPEDAT. QUAKELOSS offers a range.

2. LOSSPAGER OBJECTIVES

The US Geological Survey's Prompt Assessment of Global Earthquakes for Response (PAGER) program currently provides rapid estimates of the number of people exposed to various levels of strong motion. When its next release is made in late 2008, PAGER will also include the ability to estimate fatalities. It will be the first among those noted here to offer all the features mentioned: global applicability including all required data; open methodology, open databases, open computer source code; probabilistic treatment of loss; and free, automated, rapid, post-event dissemination of the fatality estimate. One possible form of the product is shown in Figure 1.

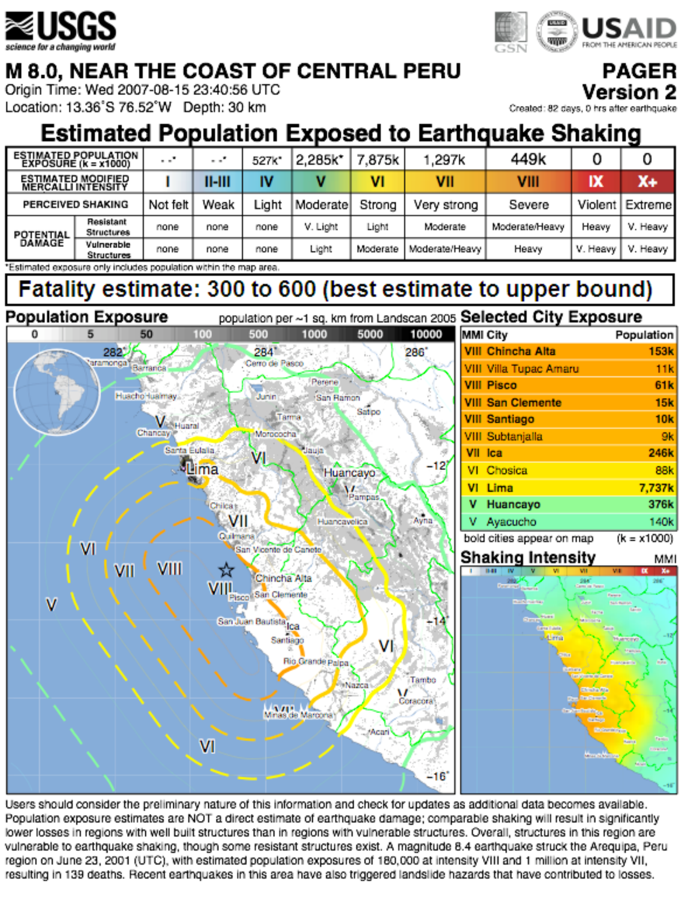


Figure 1. A possible form of the lossPAGER report

PAGER's goal is to inform early and rapid post-earthquake decisions about humanitarian assistance, before ground truth and news information are available. It can also examine hypothetical scenarios for planning purposes. In the last development stage before release of lossPAGER, two features are being developed and tested: a global building stock model, and a global vulnerability model. Both involve collaboration with the World Housing Encyclopedia (http://www.world-housing.net/), a joint effort of the Earthquake Engineering Research Institute (EERI) and the International Association of Earthquake Engineering (IAEE). Before detailing these efforts, let us review post-earthquake loss modeling, to understand the need for the WHE-PAGER effort.

3. LOSS MODEL COMPONENTS

Quantitative earthquake loss models generally work the same way:

(1) Determine magnitude and location of the event. In its post-earthquake mode, PAGER monitors the USGS's near real-time global earthquake solutions, automatically identifying possibly important events. A finite fault model is generated for large events. See http://earthquake.usgs.gov/eqcenter/eqinthenews/2008/us2008ryan/finite_fault.php

(2) Apply ground-motion prediction equations to estimate shaking intensity on a gridded basis or at points such as city centroids. PAGER uses a roughly 1-km grid. Depending on earthquake magnitude, focal depth, and seismic domain (plate boundaries or continental interior), PAGER employs Youngs (1997) intraslab, Youngs (1997) interface, or Boore et al. (1997), with site classification from Wald and Allen (2007) and locally corrected for instrumental observations or Did You Feel It? reports.

(3) Determine the population at each location (i.e., each gridcell or point). PAGER employs the LandScan 2006 gridded global population database (Bhaduri et al. 2002).

(4) Many models assign the population (or other value exposed) at each location to various building types, accounting for time of day. Two of PAGER's three vulnerability models do so. A PAGER effort created a country-by-country building stock estimate that employs housing census data from the United Nations and elsewhere, supplemented with information from WHE experts, as detailed later.

(5) Where building types are used, apply vulnerability functions to each combination of population, building type, and intensity level, to estimate loss at each location. Sum to estimate total societal loss. One PAGER model, referred to as the empirical model, does not rely on building stock. Instead it uses country-specific empirical relationships between shaking intensity and fatality rate. As detailed in a separate paper in these proceedings by these same authors, the empirical model is derived from hindcasting losses in 981 earthquakes since 1973 where

the number of shaking-related deaths is approximately known. Two other models—the so-called "semi-empirical" and another referred to as "analytical"—draw upon the expertise of WHE participants, as described later. All three models are detailed in Porter et al. (2008).

(6) Some models propagate uncertainty, others do not. Uncertainty propagation is not discussed here.

4. WHE COLLABORATION ON BUILDING INVENTORY

Step 4 requires an estimate of the distribution of people in various structure types at the time of the earthquake. PAGER personnel have developed a building-stock model using housing census and other statistical data from the United Nations and other sources (Jaiswal and Wald 2008). The database is intended to depict, on a country-by-country basis, the fraction of the population present in the country's predominant structure types at three times of day (midday, late night, and during transit hours). A building categorization system was developed that merges FEMA's system (useful in the United States and much of the developed world; see for example FEMA 154, 2002); that of EMS-98 (Grünthal 1998), which includes several types that are absent from the United States; and that of the World Housing Encyclopedia, whose 33 types provide detail into various categories of earthen, stone, and brick masonry. PAGER personnel developed such an inventory from United Nations housing census and other data, but generally found the data lacking in information about non-residential construction. It also generally lacked engineering information such as construction materials, lateral force resisting systems, height, building-code requirements, and building code enforcement, the sort of data common in the World Housing Encyclopedia.

PAGER personnel identified 30 high-priority countries needing inventory development, and offered small honoraria for contributors from these countries to do the following: (a) identify the dominant building types in their country; and then for each, estimate four fractions: (b) fraction of the urban population who dwell in each type; (c) fraction of the urban population working in each type; (d) ditto, rural residences, (e) ditto, rural workplaces, (f) average number of occupants per building, at peak usage, and (g) the basis for the estimates. A standard form was employed. Figure 2 illustrates a portion of the form dealing with inventory and fragility, completed by Robin Spence and addressing Ireland. EERI identified and solicited contributions by particular individuals. In some cases, WHE experts used judgment to estimate building stocks. In others such as Italy, statistical samples were available and formed the basis for the inventory estimates (Goretti 2008). Figure 3 presents a sample estimate from Italy, as viewed through a graphical user interface developed for this project. Estimates and sources are documented in Jaiswal and Wald 2008. By the end of the 1-year project, contributions were received for Algeria, Chile, China, Colombia, Cyprus, England, France, Germany, Greece, India, Indonesia, Ireland, Italy, Japan, Macedonia, Mexico, Nepal, New Zealand, Pakistan, Peru, Russia, Slovenia, Spain, Switzerland, Thailand, and Turkey. A second-round of the building inventory data-collection process has begun that will add several other countries/regions that have had significant numbers of deaths in the last 100 years, e.g., Iran, Guatemala, and Taiwan.

Material (choose from drop-down list)	Construction Subtype (Choose from drop-down list--refer to instructions to see complete list)	Probability of collapse (%) of building type when subjected to the specified shaking intensity				Fraction of pop. who LIVES in this type		Fraction of pop. who WORKS in this type		Peak avg # of occs per building
		IX 0.65-1.24g	VIII 0.34-0.65g	VII 0.18-0.34g	VI 0.092-.18g	urban	rural	urban	rural	
Masonry	Unreinforced brick masonry in mud mortar	15%	4%	0.6%	0	25%	30%	50%	50%	2-6 per dwelling
Masonry	Unreinforced brick masonry in cement mortar with reinforced concrete floor/roof slabs	6%	1%	0.1%	0	74%	70%	20%	30%	2-6 per dwellilng
Structural concrete	Concrete moment resisting frames designed for gravity loads only	11%	2%	0.2%	0	1%		20%	15%	50-200 per bldg
Steel	Steel moment resisting frame with brick masonry partitions	1.5%	0.2%	0	0			10%	5%	50-200 per bldg

Figure 2. Portion of a WHE response form dealing with inventory and fragility, with entries by Spence for Ireland

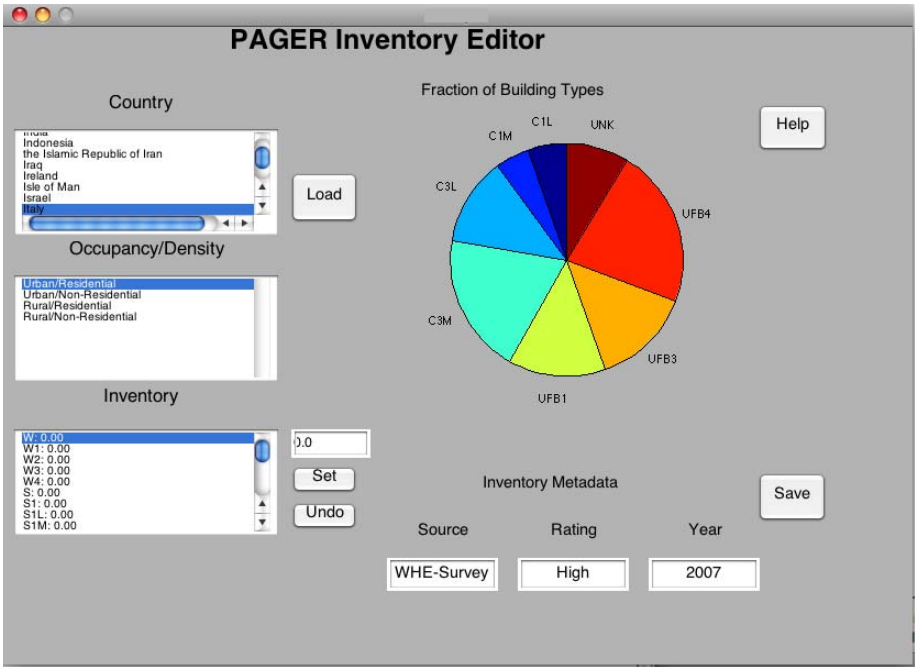


Figure 3. Sample building stock for Italy.

5. WHE COLLABORATION ON COLLAPSE FRAGILITY

In estimating building stocks, WHE experts also provided estimates of collapse probability for an average specimen of each type, at each of 4 intensity levels: MMI/EMS/MSK 6, 7, 8, and 9; equated in the form with peak ground acceleration ranges of 0.092-0.18g, 0.18-0.34g, 0.34-0.65g, and 0.65-1.24g. By comparing the collapse probability of similar construction in different countries, a degree of cross-validation was possible. It was found that within given structure types, whose seismic vulnerability one might judge not to vary from country to country, experts differed significantly. For example, Figure 4 shows the collapse fragility of unreinforced fired brick masonry construction as estimated by WHE experts for 16 countries. Contributors were shown these results and, as in standard Delphi process, were offered an opportunity to revise their contribution.

We examined how accurately we hindcast fatality estimates for earthquakes in a given country when we used just the WHE fragility functions developed specifically for that country. In many cases we found that our estimates were more accurate when we employed fragility functions from other counties. In particular, accuracy was often better when we used the fragility function for a given structure type that was the lowest from among all the fragility functions for that type, regardless of which country it came from. In current work, we are offering the WHE contributors the opportunity to compare their initial estimates with those of other WHE experts, and revise them if desired, as in a Delphi process (e.g., Dalkey et al. 1970). We are re-evaluating the selection of fragility functions for each structure type, based in part on these 2nd-round responses.

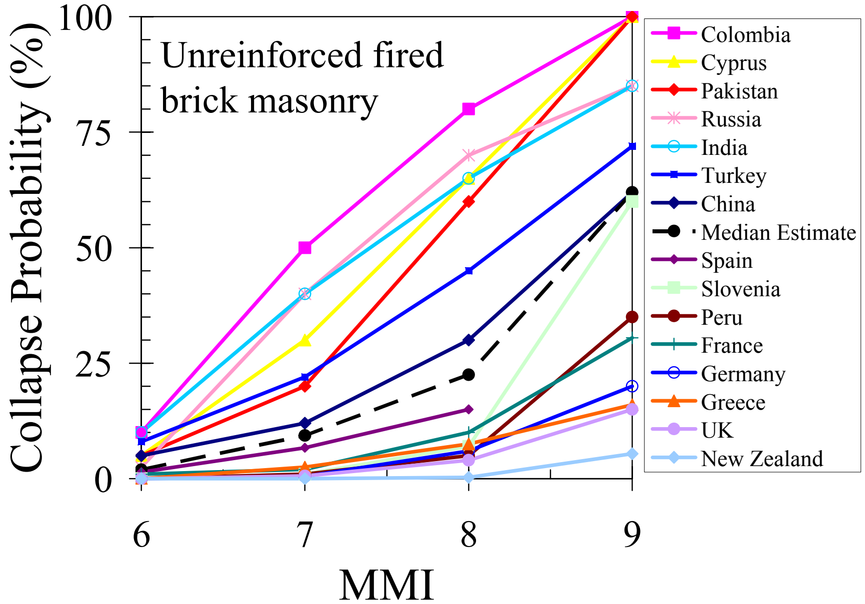


Figure 4. Collapse fragility of unreinforced fired brick masonry construction, estimated by 16 WHE experts.

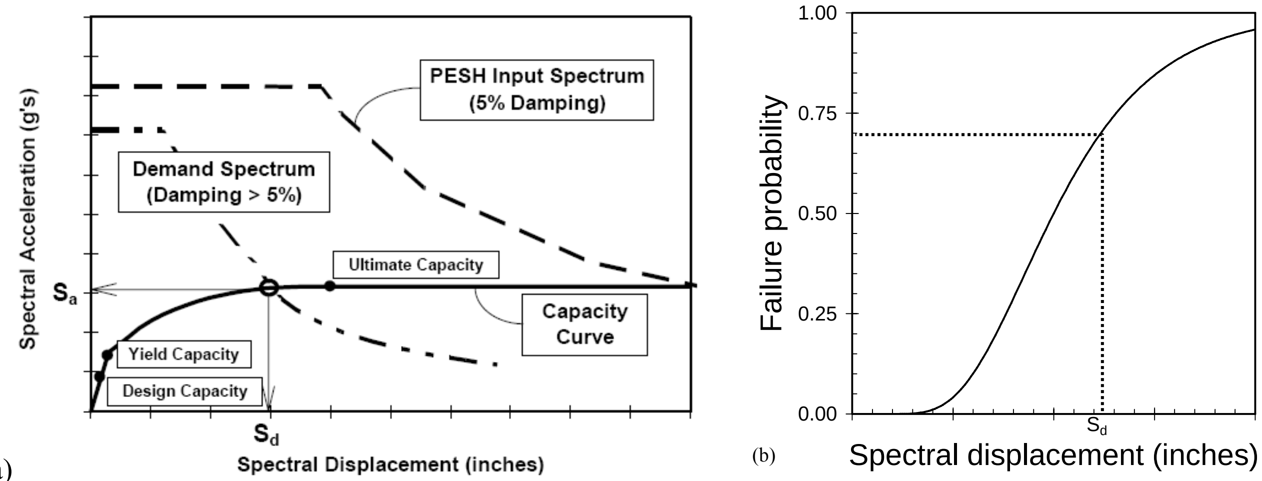
6. WHE COLLABORATION ON ANALYTICAL SEISMIC VULNERABILITY FUNCTIONS

A third approach to developing fatality-rate vulnerability functions employs an approach based on HAZUS-MH (NIBS and FEMA 2003). Before discussing the collaboration, it is first useful to summarize the methodology. The interested reader is referred to Porter et al. (2008) for mathematical details. First, each building type of interested is idealized by a single-degree-of-freedom nonlinear damped harmonic oscillator, and its structural response to various levels of shaking calculated using the capacity spectrum method (Figure 5a). The parameters of the structural model are derived, in general, from laboratory testing, forced vibration tests, or both. The index spectrum is idealized in four parts: zero-period acceleration, a constant-acceleration portion parameterized by S_a(0.3 sec, 5%), a constant-velocity portion parameterized by S_a(1.0 sec, 5%), and a constant-displacement portion parameterized by peak ground displacement.

The pushover curve is discretized in small increments, and the damping ratio and period at each point calculated. The period is calculated and compared with the period at the intersection of the constant-acceleration and constant-velocity portions of the response spectrum with damping ratio matching that of the performance point. This comparison determines which segment of the spectrum the performance point lies on, and one can calculate the values of $S_a(0.3, \beta_{eff})$ and $S_a(1.0, \beta_{eff})$, where β_{eff} denotes effective damping (low-amplitude viscous damping plus hysteretic damping). From the performance point one can infer S_a(0.3, 5%) and S_a(1.0, 5%). (This approach avoids iteration to determine structural response, but nonetheless honors all aspects of the HAZUS methodology.)

Then, just as in HAZUS-MH, the spectral displacement at the performance point is entered into fragility functions (e.g., Figure 5b) to determine the probability of various structural damage states at the performance point. Each damage state is associated with a deterministic indoor fatality rate, and the theorem of total probability is employed to estimate the indoor fatality rate at the performance point. The fatality rate is then related back to S_a(0.3 sec, 5%) and S_a(1.0 sec, 5%). The process is repeated for every point on the pushover curve. Since the shape of the index spectrum depends on magnitude, distance, seismic domain, and site class, the process is repeated for every combination of M = 5, 6, 7, or 8; R = 10, 20, 40, or 80 km, and site class = A, B, C, D, or E.

NIBS and FEMA (2003) provides all the necessary parameters for most forms of US construction. The challenge addressed by the WHE collaboration was to derive the pushover curve and fragility function parameters for various non-US construction.



(a)

Figure 5. Two elements of the analytical seismic vulnerability: (a) structural analysis to relate response spectrum to structural response S_d (image: NIBS and FEMA 2003) (b) damage analysis to relate spectral displacement S_d to structural damage. Not shown is the last step: relating structural damage to indoor fatality rate

Calculation of indoor fatality rate considering all structural damage states requires a large number of parameters: at least 4 for the control points on the pushover curve (S_a and S_d at both yield and ultimate), 8 parameters of the structural fragility functions (median and logarithmic standard deviation for each of 4 damage states), 1 for collapse rate given complete structural damage, and 5 fatality rates: one for each damage state plus collapse. Furthermore, to honor the HAZUS methodology requires low-amplitude (elastic) viscous damping ratio plus 3 "κ" terms to account for hysteretic energy dissipation in short, medium, and long-duration shaking, for a total of at least 22 parameters. To reduce the problem to more-manageable dimensions, it was recognized that building collapse accounts for most shake-related fatalities, so lower damage states are ignored, and a single fragility function derived for the collapse damage state. This reduces the required fragility parameters from 9 to 2, and reduces the number of required fatality-rate parameters from 5 to 1. The total number of required parameters is thus reduced to 11: elastic damping ratio, 4 pushover parameters, 2 for collapse fragility, 3 κ values, and fatality rate given collapse. Generally, WHE experts provided pushover curves that were more complicated than the simple elastic, yielding, perfectly plastic assumption of HAZUS-MH. As of this writing, WHE experts have provided parameters and evidence supporting them for approximately 40 analytical fatality-rate vulnerability functions for non-US construction. The analytical vulnerability functions are currently in development.

7. CHALLENGES TO GLOBAL COLLABORATIVE EFFORT

Engaging numerous experts from around the world to participate in any project can be challenging. Consensus slowly developed from extensive discussion with WHE leaders about (1) the reasonableness of vulnerability functions that depend on simple scalar intensity measures such as MMI or PGA, as opposed to vectors of spectral response, duration, etc.; (2) whether experts could realistically judge collapse probability; and (3) that a useful global vulnerability model is practical without an effort on par with HAZUS. It helped to show that a simpler model (not discussed here) that depended on MMI already reasonably hindcast losses, so that the present effort would simply improve upon a working system. Ultimately, we agreed not to let the perfect be the enemy of the good. Other challenges were to identify qualified experts from around the world and to design a data-collection instrument that was clear but concise. Several revisions of the form were required.

8. CONCLUSIONS

In an ongoing collaborative effort between the US Geological Survey, the Earthquake Engineering Research Institute, and the World Housing Encyclopedia, experts from around the world have estimated the distribution of predominant buildings types in each of 26 countries, and provided by judgment or statistical survey collapse fragility functions for the predominant structure types in each country. Efforts have been first focused on constraining loss models for countries having substantial seismic risk, so this subset of countries constitutes those that will likely contribute a large percentage of losses in the near future. In many cases the inventory judgments are informed by local housing censuses and other public data sources. To complement or validate their estimates of the whole-building collapse fragility functions, WHE experts have provided parameters necessary to create analytical indoor fatality-rate vulnerability functions for more than 40 non-US structure types.

The resulting inventory and vulnerability estimates are intended as first-order approximations, not as a substitute for more-sophisticated modeling and analysis work taking place in some countries, although they may complement such efforts. No comparable database currently exists, in that this appears to be the first effort to create a publicly available, transparent, community-developed, global inventory of country-specific building stocks and their seismic vulnerability. Some possible applications of the new database include (1) estimating damage and loss from global earthquakes shortly after they occur, for humanitarian response purposes; (2) global seismic risk modeling (i.e., estimating the potential effects of future earthquakes); and (3) informing decisions about development needs for seismic risk reduction.

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