Improving PAGER's Real-time Earthquake Casualty and Loss Estimation Toolkit: Challenges

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SUMMARY:
We describe the on-going developments of PAGER's loss estimation models, and discuss value-added web content that can be generated related to exposure, damage and loss outputs for a variety of PAGER users. These developments include identifying vulnerable building types in any given area, estimating earthquake-induced damage and loss statistics by building type, and developing visualization aids that help locate areas of concern for improving post-earthquake response efforts. While detailed exposure and damage information is highly useful and desirable, significant improvements are still necessary in order to improve underlying building stock and vulnerability data at a global scale. Existing efforts with the GEM's GED4GEM and GVC consortia will help achieve some of these objectives. This will benefit PAGER especially in regions where PAGER's empirical model is less-well constrained; there, the semi-empirical and analytical models will provide robust estimates of damage and losses. Finally, we outline some of the challenges associated with rapid casualty and loss estimation that we experienced while responding to recent large earthquakes worldwide.

Keywords: Earthquake Response, Casualty, Damage, Economic Loss, PAGER

1. INTRODUCTION

Prompt Assessment of Global Earthquakes for Response (PAGER) system operated by the U.S. Geological Survey at Golden Colorado, began publicly estimating casualty and loss-based impact alerts since September 2010 (Wald et al., 2011).

PAGER's main objective is to quickly identify the earthquakes that may require response and humanitarian attention, amongst the hundreds of other sizable earthquakes that the National Earthquake Information Center (NEIC) records in a given year. PAGER accomplished this main objective, for the most part, during the alert-based operational period of late 2010 through 2011. Since these estimates are available well in advance of ground-truth observations or news accounts, they can play a primary alerting role for domestic as well as international earthquake disasters.

PAGER's operational system currently relies on empirically based earthquake casualty and economic loss models to estimate the earthquake's likely impact and corresponding alerts. Empirical models currently being used tend to work best in places where sizable historical damage and loss data exist to constrain them. PAGER's engineering-based, semi-empirical and analytical models were also producing loss estimates during this time, although not publicly. Although engineering-based loss models are robust in their design and implementation and tend to work better at places where underlying inventory and vulnerability data exist, several challenges still remained to be addressed. This article discusses some of on-going developments and the challenges related to PAGER databases and loss model development efforts.

2. PAGER LOSS MODELING OVERVIEW

Many factors influence the estimation of earthquake ground shaking characteristics and its subsequent impact in terms of casualties and losses in a given built environment. Among these, some of the key factors are: a) basic earthquake parameters such as magnitude, location, depth, and source mechanism of an earthquake, b) site conditions, c) spatial variation of ground shaking intensity, d) structural characteristics of building and infrastructure stock exposed, and e) how vulnerable the population is to building/infrastructure damage, and the resiliency of the affected population. While each of these factors can be understood better or can be modelled uniquely in an isolated circumstance or environment, their collective influence determines the overall consequences and impact of an earthquake.

Often the unique characteristics of these factors associated with any given earthquake, or sometimes their complex interdependencies with a given built environment, are hard to fathom, which makes the near real-time damage and casualty estimation problem much more difficult. Nonetheless the need to quickly gauge the impact of worldwide earthquakes is critical, given the dreadful consequences of delays or inaction in rescue and response phase. The direction of PAGER development is guided not only by the advancement of the science and engineering knowledge but also the need to make progress in developing a range of products and toolkits that can inform decision-makers.

PAGER currently operates three parallel loss models, empirical, semi-empirical, and analytical, for estimation of earthquake fatalities. However, PAGER's public alerts are currently produced through PAGER's empirical loss models. The following subsections describe each of these models in brief and refer to relevant literature for additional details.

2.1. Empirical Model

The PAGER empirical model estimates earthquake fatalities or economic losses (referred to here as expected losses $E(L)$ in general) at each level of shaking intensity s by using the exposure (which can be total population exposed, or total economic exposure, i.e., the monetary value of all the exposed physical assets) and the *Loss Ratio* (which can be fatality rate ν or economic loss ratio r as defined subsequently) corresponding to each level of modified Mercalli (MM) intensity directly obtained from ShakeMap (http://earthquake.usgs.gov/shakemap/). Total losses are made by summing the losses from different intensities to estimate total losses for a given earthquake j:

$$E\left(L_j\right) = \sum_s \left(Exposure\right)_{s,\ j} \times \left(Loss\ \ Ratio\right)_{s,\ j} \tag{1}$$

2.1.1. Empirical Fatality Model

In order to estimate total fatalities in any given earthquake, the key challenge is to estimate both population and fatality rate at each intensity level. PAGER's employs ShakeMap's hazard input and the LandScan population database (Bhaduri et al., 2002), so in near real-time we can estimate population exposure (total number of people) at each level of shaking intensity by simply overlaying the shaking intensity map on top of a gridded population map and then summing the population in each intensity bin.

The fatality rate is expressed as the number of fatalities divided by the total population exposed at each level of shaking intensity. Estimating the fatality rate at each level of shaking intensity for all regions of the world is a difficult task. In order to estimate this rate for a given earthquake, we would need to know the total population and also the number of fatalities at each intensity level. Casualty survey data generally do not provide geospatial fatality statistics; only aggregated statistics either at the city level are available, or more usually, only an earthquake total.

Instead of collating data on fatality occurrences at each intensity level and then estimating the fatality rates, Jaiswal et al. (2009) proposed a new approach. The authors suggested that the fatality rate ν could be expressed in terms of two-parameter lognormal cumulative distribution function of shaking intensity *s* and it could be written as:

$$\nu = \Phi\left[\frac{1}{\beta}\ln\left(\frac{s}{\theta}\right)\right] \tag{2}$$

where Φ is the standard normal cumulative distribution function. Thus, for a given country with a number of earthquakes with known total losses, one can solve for these two parameters, without knowledge of the loss rates geospatially. In the present application, the shaking intensity *s* ranges from 5.0 to 9.0 (i.e., V to IX defined in terms of MM intensity scale), where total exposure at MM intensity IX and above is aggregated and assigned to IX. The terms θ and β are the two unknown parameters of the distribution. Once the two parameters of this functional form are known, one can determine the fatality rate ν at each intensity level *s*. Refer to Jaiswal and Wald (2010) for more details and the global application of this procedure.

2.1.1. Empirical Economic Model

Following the empirical fatality model, Jaiswal and Wald (2011) extended the approach to estimate economic losses for PAGER alert estimation purposes. In principle, the economic loss ratio, r, which is defined as the total direct economic loss (that includes structural, non-structural and content losses) normalized by the total economic exposure is similar to the fatality rate ν defined earlier. The total economic exposure at each level of shaking intensity can be approximated in terms of the total GDP exposed (which is estimated as total population exposed times per capita GDP of the region) and the country- or region-specific exposure correction factor α as shown below:

$$Eco.\ Exposure_s = \alpha_{region} \times Total\ \ GDP_{region,\ s} \tag{3}$$

The procedure to calculate exposure correction factor α and subsequently the model parameters θ and β is described in Jaiswal and Wald (2011). In the operational PAGER system, we use the most recent population and GDP datasets to estimate earthquake alerts based on fatalities and economic losses.

Following a sizable earthquake (with minimum threshold of M3.5 within USA, and M5.5 worldwide) the arrival of a ShakeMap automatically triggers the PAGER system to produce impact alerts. For example, within the first hour of the M7.1 October 23, 2011 Van, Eastern Turkey earthquake, the operational PAGER automatically estimated a ‘red alert’ for economic losses as shown in figure 1. The estimate indicated a high likelihood that the shaking-related economic impact could amount to more than a billion dollars of direct economic loss.

2.2. Semi-Empirical Model

As discussed in previous section, the empirical vulnerability models directly rely upon the relationship between population exposure and earthquake fatality rates at each level of shaking intensity to estimate total fatalities. What is added in the semi-empirical model is the detailed data on building types, their collapse vulnerability and the fatality rate associated with structural collapses. Thus, the key to the semi-empirical approach is relying upon the ground shaking intensity-damage relationships and using structure-specific casualty/fatality rate (obtained from observations during past earthquakes). In the current implementation, we focus primarily on estimating structural collapse, which usually is the dominant cause of earthquake fatalities. The quantitative model incorporates shaking hazard via the ShakeMap system, population exposure by building type within a given country, fragility of building type expressed in terms of probability of collapse at each intensity, and earthquake fatality rate given building collapse. Building inventory and vulnerability data have been compiled at the country level. For each country, the inventory database provides the population distribution according to different structure types for two-occupancy types (residential and non-residential) and two population density types (urban and rural). Details about inventory database development are discussed in Jaiswal and Wald (2008). At the grid cell (approx. 1 km x 1km) level, we have total population count, urban/rural categorization of that cell, and the shaking intensity estimate. We use three time intervals to define time of day (day, night and transit). For each earthquake's time of day, we estimate the total indoor population among three broad occupancy categories, i.e., residential, non-residential and outdoor population, using a global work-force database (Jaiswal and Wald, 2010). Similarly, for vulnerability assessment, we collated the data specific to collapse probability by construction classes from different countries, using both empirical data as well as expert judgment surveys, and then developed a set of collapse probability functions (Jaiswal et al., 2011). By combining HAZUS level 4 injury rates for the complete damage state with collapse (NIBS and FEMA, 2009) and the fatality rates by structure type for D5 damage grade proposed by Spence for the European LessLoss study (Spence, 2007), we developed fatality rates specific to PAGER structure types (PAGER-STR, Jaiswal and Wald, 2008). Loss computations are performed at the grid-level in which the grid-specific population count, and shaking estimates forms the key modelling input for damage and loss analyses. The population exposure, inventory and vulnerability data are used to estimate total casualties and thus account for spatially varying shaking intensity and exposure between different grid cells as discussed in Jaiswal and Wald (2010).

2.3. Analytical Model

In the analytical approach, the building inventory and occupancy-related databases derived for the semi-empirical approach are used, however, the structural collapse rates are determined from HAZUS capacity-spectrum methodology that estimates the response of a structure from spectrum demand and spectral-capacity curves (NIBS-FEMA, 2009). In principle, 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 hysteretic energy dissipation through an iterative procedure. The spectral displacement S_d associated with the performance point forms an input to fragility functions that give 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 are the same as in the semi-empirical approach. The mean-collapse fragilities are derived primarily for HAZUS Model Building Types (MBTs) using the HAZUS capacity and fragility parameters. For non-US building types, the basic MBTs were mapped to PAGER-STR types using a preliminary mapping scheme. In general, the structural capacities are quite different between the basic MBTs and corresponding PAGER-STR as discussed in D’Ayala et al (2010).

In order to understand and evaluate the differences between structural capacity and fragility parameters and to propose procedures for estimating collapse vulnerability of non-US building types, a parallel effort is underway under the umbrella of WHE-PAGER project (Phase IV). Early analyses suggest that there could be significant differences in estimated structural capacities of RC types depending upon the modelling assumption or methodology adopted for inelastic analyses for given structure types. The differences could be larger in case of the ultimate displacement S_{du}, which is challenging to estimate (given the structural model-specific assumptions involved) during inelastic analysis. Nonetheless, significant progress has been made in compiling the requisite data of non-US building types to be used within the operational PAGER system.

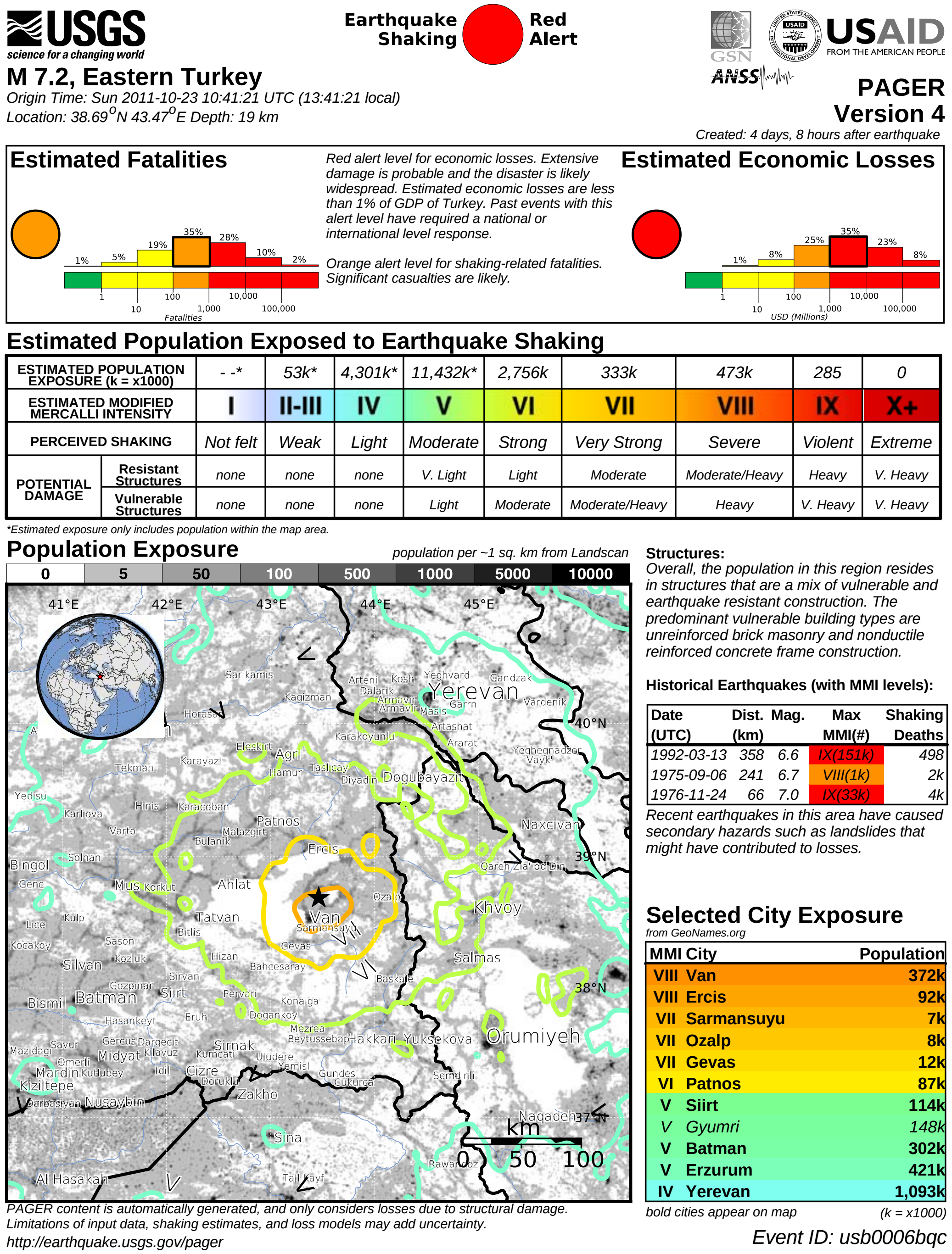

Figure 1. An automated PAGER impact estimate following the M7.1 Van, Eastern Turkey earthquake. In the first version of PAGER that was produced 27 minutes following the earthquake, we estimated a 'Red alert' for both fatalities as well as economic losses. With better constraint on magnitude (which was revised to M7.1), location, and shaking, the PAGER estimates were subsequently revised as shown here.

3. IMPROVING GLOBAL INVENTORY AND VULNERABILITY DATA

PAGER's semi-empirical and analytical loss estimation systems require detailed building inventory, population, and economic exposure datasets of requisite quality at a global scale. Efforts have been made to compile such datasets through in-house research over several years, as well as through the World-Housing Encyclopedia (WHE)-PAGER initiative. However, current implementation of grid-level loss computation still relies on broad country-level statistical data on dwelling-type distribution, and creative mapping schemes in order to approximately distribute indoor population occupancy among different buildings types in a given country.

PAGER's building inventory, and population exposure schemes now also serve as fundamental input into the Global Earthquake Model (GEM)'s GED4GEM (Global Exposure Database for Global Earthquake Model) project. However, at a global scale, the level of detail and the resolution necessary to perform detailed structural vulnerability and risk computations are difficult to achieve. GED4GEM's goal is to treat diverse subnational inventory data of varying quality through a globally consistent approach and produce a grid-level global physical building exposure database. As a part of GED4GEM consortium, the PAGER team is working closely with consortia partners in order to develop the methodology and structural and occupancy-mapping framework for estimating grid-based building counts, structure types and occupancy details, and economic exposure characteristics.

In addition, PAGER's three-tiered loss estimation strategy, consisting of empirical, analytical, and semi-empirical (expert-opinion-based) approaches, was key in guiding the GEM's seismic vulnerability estimation protocols. Moreover, as an open, global system, PAGER continues to contribute to the GEM's Global Vulnerability Consortium (GVC) effort by providing global vulnerability data and models, as well as supplementing these with PAGER's global hazard and loss calibration capabilities.

4. PAGER PRODUCTS AND VISUALIZATION TOOLS

The primary objective of ongoing development of the PAGER system is to digest readily available scientific data on specific earthquakes and then create information products that help communicate an earthquake's hazards and potential impacts to a wide array of users. Although PAGER provides fatality and economic impact-based alerts immediately following any significant earthquake, the media, general public and responders have ever-increasing expectations for information. This is especially true given the severe consequences of recent large earthquakes, e.g., the 2008 Wenchuan, China, 2009 L'Aquila, Italy, and 2010 Haiti earthquakes. Responders want to, first and foremost, know whether a given earthquake could become a crisis situation, but also to then identify potential zones of impact, understand dominant vulnerable constructions (or "culprits"), and the scope of a potential humanitarian needs, e.g., injuries, displaced persons, shelter, food. Clearly, the list of such demands can be long and challenging compared to limited resources that are being put forward to address them at a global scale. In this context, we highlight some of the additional tools and capabilities that PAGER can offer to aid decision-makers and responders.

4.1. Portraying Population Exposure

Given the significance of spatial variability of ground shaking and its impact on the built environment, it is necessary to highlight the population exposure that is subjected to high levels of shaking and hence the most likely areas of concentrated damage and loss. The exposure maps currently produced by the operational PAGER system are unable to provide functionality such as zooming in and out or distinguishing areas of high exposure, infrastructure or zones of importance given the spatial distribution of shaking, which are critical in near real-time response environments.

By rendering ShakeMap and the LandScan population database in a Keyhole Markup Language (KML) format, it is now possible to depict the relative population impacted by different levels of shaking in applications like Google Earth (Jaiswal et al., 2011). Fig. 2 shows a snapshot of a Google Earth window showing a 3D color-coded bar chart for the 2010 Haiti earthquake. The bar height indicates the affected population and the color indicates the ShakeMap estimated shaking intensity shown using the standard ShakeMap color palette. To avoid a user's misinterpretation of vertical bars as buildings, an appropriate legend is provided to explain the distinction. Aggregate estimates of total population at integer intensity levels (V, VI, VII, and so on) are also produced for the extent of the ShakeMap as shown separately in the panel to the left of the map and as a part of the legend shown in Fig. 2.

4.2. Building Stock Inventory Characterization

To characterize the most vulnerable country-specific building stock in any given earthquake, we are working in collaboration with Earthquake Engineering Research Institute's (EERI)'s World Housing Encyclopedia (WHE) team, to develop a country-specific, building-type library, taking existing information from WHE's housing prototype and extending the coverage further by adding more countries. This library serves multiple purposes but its primary benefits are to: 1) list the building types that are prevalent in a given country, 2) describe certain key aspects of these structure types in terms of their construction or their vulnerability to past earthquakes, 3) identify the types that potentially could dominate the risk of major losses in a given country, e.g., to help create awareness for long term mitigation, and 4) identify structure types that could pose challenges during post-earthquake rescue and response. Delivery of content from the library for pre-earthquake mitigation, planning, and education will take the form of country-specific building descriptions and photos, both contributed by USGS/PAGER and EERI/WHE (Fig. 3). The library not only helps to document the general features of construction practices in different countries but also to communicate overall risk: a combination of vulnerability and occupancy. Prototype webpages have been created for 42 countries via the USGS PAGER and Earthquake Program web pages which are also linked through the EERI/WHE web pages.

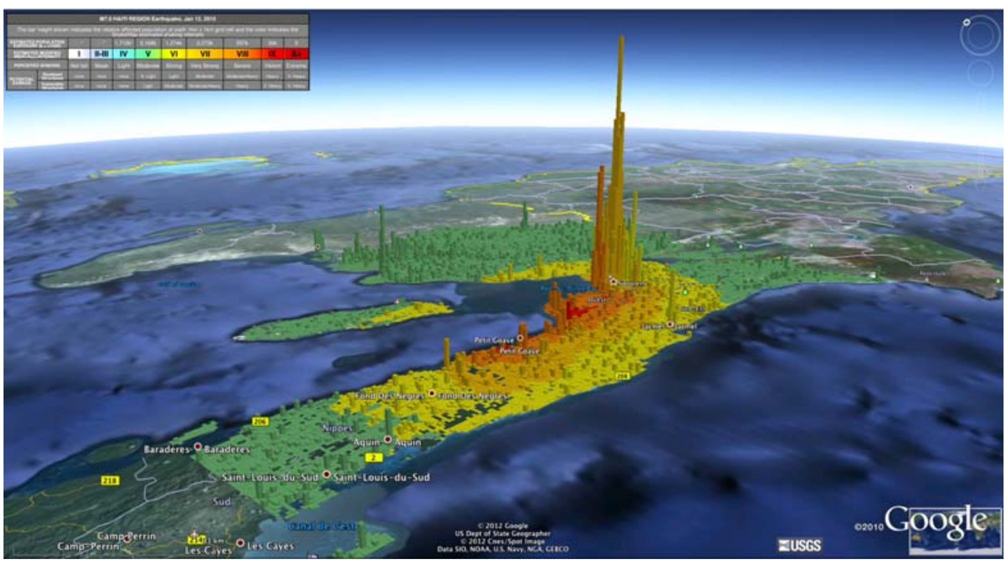

Figure 2. PAGER Exposure estimate and its overlay on the LandScan population database in Google Earth for 2010 Haiti earthquake. The bar height indicates the affected population and the color indicates the ShakeMap estimated shaking intensity

4.3. Damage/Loss Characterization

In order to understand the demands related to shelter requirements, one needs to estimate the total dwellings that might have been severely damaged or collapsed during an earthquake. While the engineering-based damage and loss estimates were not made public from an operational perspective since they are not equally suitable in all countries, the PAGER system is producing a suite of outputs related to fatality and damage estimates from the semi-empirical model. Fig. 4 shows one such output automatically produced following the M7.1 Van, Eastern Turkey earthquake on

October 23, 2011. Fig. 4 shows that most of the fatalities are expected from the collapse of unreinforced brick masonry bearing wall, adobe and nonductile reinforced concrete frame constructions. The earthquake resulted in 604 fatalities, 4,152 injuries and at least 33,016 buildings that sustained serious damage or collapsed (http://www.eeri.org/wp-content/uploads/Van_Turkey_eq-report.pdf). Early reports indicated that most fatalities were caused due to the collapse of nonductile concrete frame and bearing wall construction as indicated by the semi-empirical model, however it is still unclear what was the actual distribution among concrete frame, masonry and adobe construction. In order to present the building types that are at risk in a hierarchical order, for each earthquake and for each country, the PAGER team will need to further improve the PAGER building inventory and vulnerability models for those structures. At present, such tools can help in creating awareness about potentially vulnerable buildings in a given area, for planning for mitigation exercises, and in aiding response decision-making, including assessment of rescue equipment likely to be required by USAR teams, and comprehension of potential search and rescue challenges within certain geographic areas.

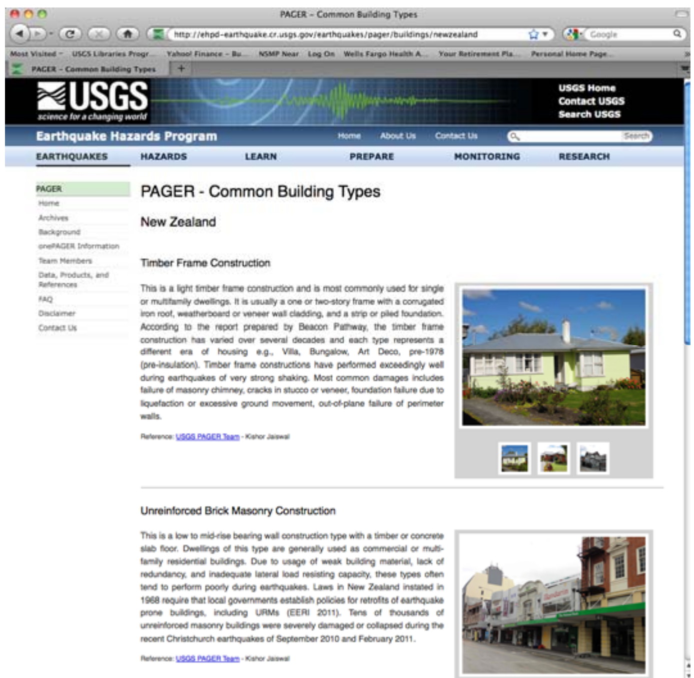

Figure 3. Country-specific description of common building typology library for PAGER response.

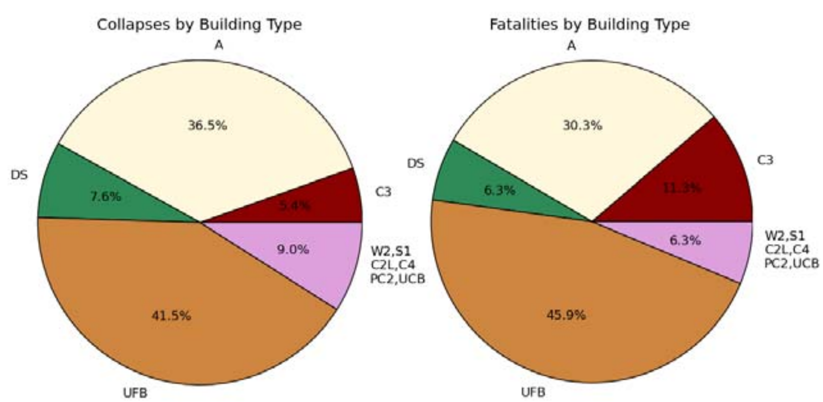

Figure 4. Estimated collapse (left) and fatality (right) distribution according to PAGER-STR building typologies (see, Jaiswal and Wald, 2008 for description of PAGER-STR) produced by the semi-empirical model following the M7.1 Van earthquake on October 23, 2011.

5. ONGOING CHALLENGES IN RAPID LOSS ESTIMATION

5.1. Evolving Estimates of Earthquake Magnitude, Depth and Location

Measuring and disseminating the key earthquake parameters such as location, depth, and magnitude are fundamental to NEIC 24/7 responses to all significant global earthquakes. Yet these estimates, particularly for the largest earthquakes, evolve in time. For instance, Hayes et al. 2011 provides a detailed timeline associated with the NEIC operational response process following the M9.0 Tohoku Japan earthquake in 2011. The key earthquake parameters that form the basis for creation and distribution of a suite of NEIC's real-time earthquake information products, in particular, the ShakeMap and PAGER systems evolved in a relatively short time period (first few hours). The first version of PAGER estimated a "Yellow" alert based on M7.9 (produced 23 minutes after the earthquake) which was revised to "Red" alert in the second version (at 42 minutes) with a revised magnitude of M8.8, which stabilized in subsequent versions at M9.0. Similarly, the October 23 Van, Eastern Turkey earthquake was estimated to be M7.3 and was located in the proximity of the city of Van (population 367,419 in 2010). In part due to proximity to the city with sizable population exposure, PAGER overestimated earthquake losses by a factor of two to three in its first version. The magnitude was subsequently revised to 7.1, and importantly, it was then estimated to be 19 km north-northeast of the city, which resulted in more accurate loss estimates.

5.2. ShakeMap Shaking Estimates

Ground shaking estimates produced within the ShakeMap system are crucial in the early hours of a large earthquake. Selecting the appropriate ground motion prediction equations is complicated, yet significant progress is being made in this area as documented by Garcia et al. (2012). The existing prediction equation selection scheme within the ShakeMap system is being revised by carefully considering factors such as tectonic regimes and seismotectonic domain, focal mechanism , hypocentral depth, and fault types (Garcia et al., 2012). Logic-based selection of the most appropriate prediction equations is not only vital in real-time applications, but it is also important for developing the ShakeMap Atlas of events used for calibrating loss models.

5.3. Stability of the PAGER Loss Model Parameters

The operational PAGER loss models are revised periodically using the newer earthquake damage and casualty data. The revision cycle vary from six months to a year depending upon availability of reliable casualty data for the entire observation period.

Such revisions are extremely important for regions or countries with little contemporary loss experience. For example, during the 2010 Haiti earthquake, the PAGER system (its *beta* version) was operated internally for testing purposes. The beta PAGER system estimated a "Red" alert (indicating over 1,000 fatalities) but the median fatality estimate was much lower, almost a factor of 10 lower than the actual estimate. In the absence of an historical earthquake that produced fatalities, the Haiti fatality model v1.0 was based on a regional model with data from neighbouring countries with much lower vulnerability than was the case for the Haitian building stock. The fatality model is now calibrated to reflect the (uncertain) reported losses for the 2010 earthquake. Nonetheless, other loss-data limited countries may pose an important and on-going modelling challenge and could be significantly influential in PAGER's accuracy and its operational capability.

One of the possibilities that PAGER models offer beyond real-time loss estimation is the ability to generate a range of scenario earthquakes in different parts of the world (Wald et al. 2012). This allows us to perform *a-priori* studies to understand the potential influence of local building inventories and vulnerability characteristics using engineering-based loss models, in conjunction with estimates produced by the operational empirical loss models.

6. SUMMARY AND CONCLUSIONS

Rapid earthquake loss estimation tools like PAGER provide an estimate of likelihood of building and infrastructure damage, deaths and financial losses, and help responders to understand the scale of a disaster and determine potential humanitarian needs in the aftermath. PAGER's early assessment capability for potential earthquake impacts is a much-needed advancement to NEIC's global earthquake information delivery repertoire. While the availability of large and fatal historical earthquakes serves as a backbone for the PAGER's empirical model, it also provides a useful benchmark for modelling earthquake losses using both semi-empirical and analytical approaches.

PAGER developers are now closely working with various GEM risk estimation-related projects. Through its network of international consortia of organizations and experts, it is possible to develop protocols for collection of critical dataset, to compile global exposure datasets, and to prepare guidelines on development of global seismic vulnerability functions. It is envisioned that the newly compiled data, models and protocols through GEM efforts will help encourage more researchers worldwide to contribute data through an open-source environment. This will also help PAGER to improve its global earthquake vulnerability modelling capabilities.

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