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ADVANCEMENTS IN CASUALITY MODELING FACILITATED BY THE USGS PROMPT ASSESSMENT OF GLOBAL EARTHQUAKES FOR RESPONSE (PAGER) SYSTEM

D.J. Wald[1] , K. Jaiswal[2], K. Marano[1], P. Earle[1], and T. I. Allen[3]

[1] *Geophysicist, National Earthquake Information Center,* U. S. Geological Survey, Golden, CO 80401, *USA*
[2] *Civil Engineer, National Earthquake Information Center,* U. S. Geological Survey, Golden, CO 80401, *USA*
[3] *Geophysicist, Geoscience Australia,* Canberra ACT 2601, Australia
Email: wald@usgs.gov

ABSTRACT

The advent of the U.S. Geological Survey (USGS) Prompt Assessment of Global Earthquakes for Response (PAGER) system, in conjunction with several recent advances and trends in related data sources and research efforts, bring to light new opportunities within the overlapping realms of earthquake hazard, earthquake engineering, and earthquake epidemiological studies. While casualty modeling has admittedly often suffered from the lack of epidemiological rigor on the part of earth scientists and engineers, comparable laxity is also evident in some analyzes of related hazard complexities on the part of social scientists. These limitations have often been due to insufficient oversight or interaction, or more commonly, insufficient data availability. Thanks to improved data sets, modeling approaches, and collaborations, there are now fewer obstacles to performing comprehensive casualty estimation, though formidable challenges remain. Under the auspices of the PAGER system, a global set of ShakeMaps has been produced for all significant earthquakes in the past 34 years (1973-2007). These event-specific ShakeMaps, constrained by any available data, are then combined with new global population data sets to develop systematic hazard and loss analyses. These and other important advancements, as well as their limitations, and their potential for contributing to casualty modeling are discussed. Example studies and applications are presented.

1. INTRODUCTION

One of the primary correlatives for building damage, and thus casualties, is the site-specific shaking hazard. Rather than shaking intensity (whether characterized by macroseismic intensity, peak ground motion or response spectral values), magnitude has commonly been used as a proxy (e.g., Alexander, 1996; Nichols and Beavers, 2003; Eriksson, 2006), oftentimes without consideration of earthquake source distance or event depth. Compounding these simplifications, often inconsistent tabulations of earthquake magnitude and fatalities as well as inaccurate source characteristics are used where more rigorous analyses of the hazard component of the problem are required. A potential remedy for these types of simplifications comes in the form of a systematic, openly-available, catalog of historical earthquakes, including their associated parameters and casualties (here referred to as PAGER-CAT). An associated catalog of ShakeMaps, developed primarily for the PAGER system, of all significant earthquakes over the past thirty-four years, and referred to as the ShakeMap Atlas compliments PAGER-CAT by providing the systematic estimates of the spatial distribution of shaking for each event. The ShakeMap Atlas is online and is freely and openly available for researchers in several formats.

A second, but often underutilized, correlative for casualties is the population exposure. Whilst seemingly obvious, this factor is also often overlooked while exploring explanatory variables. For example, the expectation that greater fatalities occur at night (the “time-of-day” factor) can only be proved i) with specific examples of two events, which sample day and night, occur in the same region, and have similar exposure levels as a function of intensity; or ii) with statistical analyses of multiple events spread out over time in a particular region, but again, correcting for the relative exposure of the population to various shaking levels. By analogy, one cannot shed significant light on patterns of earthquake damage to structures without an independent indication of the shaking level and its variations with respect to mapped damage extents. Here too, help is on the way, primarily from the recent arrival of global population datasets (e.g., Landscan; Bhaduri et al., 2002) which allow exposure levels to be computed (albeit, approximately) and considered as a normalizing factor. In turn, the spatial distribution of global population, combined with the ShakeMap Atlas allows one to constrain—with varying levels of accuracy—both the local shaking intensity as well as the population exposed to that level of shaking. This combination is provided in PAGER's Exposure Catalog (EXPO-CAT), tabulated for each of the ShakeMap Atlas earthquakes.

One missing ingredient needed in formal analyses of earthquake losses is comprised of building-specific damage and casualty observations. Gradually, these data sets are being gathered, and critically, are being made publically available (for example, see the Cambridge University Earthquake Damage Database, or CUEDD). A second ingredient for casualty modeling must come from social science contributions that help understand and thus constrain casualty outcomes. From cohort and other post-event interviews and evaluations, we can further constrain the numerous variables related to human response, an important component in casualty modeling, that mitigate or increase casualties. These societally-dependent variables include personal protection actions, building egress rates, as well as rescue and emergency medical capabilities. In conjunction with the hazard ingredients mentioned above, there is hope for rapid advancement in the ability to estimate and understand these additional contributions of earthquake casualties on a global basis.

Initially, we discuss the data and contributions made under the efforts of the USGS PAGER system towards lowering some of the hurdles that limit casualty modeling. We then provide several example applications and demonstrate opportunities afforded by these new data sets and tools. Finally, we discuss caveats of the current approaches and other limitations that must be addressed to continue making progress, particularly as applied to rapid fatality estimation, which is at the core of the PAGER system.

2. PAGER'S CONTRIBUTIONS TO LOSS MODELING

The PAGER system now plays a primary alerting role for global earthquake disasters as part of the U.S. Geological Survey's (USGS) response protocol. PAGER builds on ShakeMap, "Did You Feel It?" and other rapid earthquake information systems. Currently, PAGER automatically reports the number of people, and the names of cities exposed to severe shaking caused by an earthquake anywhere in the world, thus informing emergency responders, government agencies, and the media of a potential disaster within 20 minutes of the earthquake's occurrence. This information is available 24x7 via e-mail, text message, and the Internet.

In addition to near real-time applications, there are specific contributions developed under the auspices of PAGER that have broader benefits for the loss-modeling community. Near real-time information from PAGER, as well as all related applications, data sets, and tools, with corresponding online reference) can be found at http://earthquake.usgs.gov/pager/ and http://earthquake.usgs.gov/pager/prodandref/index.php, respectively.

2.1 Hazard Contributions

Hazard-related products include: i) databases on earthquake occurrence including event and casualty information, ii) approximate V_S^{30} soil site-condition maps for the world, iii) an Atlas of approximately 5,600 ShakeMaps of significant global earthquakes over the past 34 years, and iv) a catalog estimating event-associated population exposures for each Atlas ShakeMap.

2.1.1 PAGER-CAT. A primary concern for hazard calculations is starting with the best composite earthquake catalog of earthquake source parameters and loss data. Although unpublished, proprietary catalogs exist within the loss modeling community, we found no publicly available catalog containing both comprehensive earthquake source parameters and fatality information. The necessary information is spread throughout numerous earthquake catalogs, reports, and online databases. Earthquake catalogs are created for different purposes, and consequently they excel in different areas. Some catalogs provide high-quality hypocenter information while others contain carefully researched damage and casualty reports.

This led us to develop a systematic approach to produce PAGER-CAT (Allen et al., 2009a), and to make it widely available. PAGER-CAT provides accurate earthquake source (e.g., hypocenter, magnitude, focal mechanism) information necessary to compute reliable ShakeMaps in the Atlas. It also contributes loss information (i.e., number of deaths and injuries) from historical events and characterizes the deaths as due to shaking or other (secondary) causes. The first release of PAGER-CAT contains more than 140 fields specific to each earthquake, covering source and impact information and currently includes events from 1900 through December 2007, (with emphasis on earthquakes since 1973).

2.1.2 Global V_S^{30} Server. In order to produce ShakeMaps nationally and globally, it was necessary to develop a procedure for deriving uniform shear-wave velocity (Vs30) estimates from data available on a global basis. V_S^{30}, or the average shear velocity to 30 m depth, serves as a well-established proxy for ground motion site amplification and is used in building codes as well. To this end, Wald and Allen (2007) presented a method for deriving uniform global seismic site conditions from Shuttle Radar Topography Mission (SRTM) 30 arc second (approximately 1 km resolution) digital elevation data. More specifically, this method is based on simple correlations between measured V_S^{30} values and topographic gradient. Based on numerous requests for the V_S^{30}estimates for other hazard and loss analyses around the globe, we produced a V_S^{30} Online Server, allowing for online access and V_S^{30}grid file downloads for the most of the globe.

2.1.3 ShakeMap Atlas. Utilizing the PAGER-CAT and the global V_S^{30} grid, and using the standardized ShakeMap approach of combining observations and ground motion estimates (Wald et al., 2005), we produced ShakeMaps for over 5,600 earthquakes which occurred from January 1973 through December 2007. Almost 540 of these maps were constrained in part by instrumental ground motions, macroseismic intensity data, community internet intensity observations, and published earthquake faulting rupture models. For each of the Atlas ShakeMaps, uncertainty maps are also provided. The uncertainty values (Wald et al., 2008b) can be used for computing uncertainties associated with the hazard component in loss modeling. In addition to its primary purpose—allowing for loss calibration—the Atlas is useful for earthquake planning, earthquake studies, loss modeling, and other hazard and risk analyses (for example, see UNISRD, 2009).

2.1.4 Exposure-Cat (EXPO-CAT). A catalog of human exposures at each shaking intensity level was derived using current PAGER methodologies (e.g., Wald et al, 2008a). EXPO-CAT is derived from two key datasets: the PAGER-CAT earthquake catalog (Allen *et al.*, 2009a) and the Atlas of ShakeMaps (Allen *et al.,* 2008). Exposure to discrete levels of shaking intensity is obtained by merging Atlas ShakeMaps with a global population database (LandScan2006; Bhaduri, 2002) and hindcasting population with negative growth rates to estimate population exposure at the time of the earthquake. Combining this population exposure dataset with historical earthquake loss data provides a critical resource for calibrating loss methodologies against a systematically-derived set of ShakeMap hazard outputs. In addition, these population/exposure levels for all significant earthquakes in the past 34 years allow comprehensive statistical analyses to be made that account for relative exposure within events and among events for correlation with other factors (for example, see “time-of-day” correction, below).

2.2 Loss and Risk Contributions

On the impact assessment front, PAGER-related studies and tools include extensive databases on: i) country-based global building inventories (developed in collaboration with the Earthquake Engineering Research Institute’s World Housing Encyclopedia project, WHE), and ii) empirical, semi-empirical and analytical fatality and building damage functions. The global building inventory is discussed in detail in Jaiswal and Wald (2008); the three PAGER loss models are described in Jaiswal et al. (2009), Porter et al. (2008), and Wald et al. (2008a).

PAGER’s use of multiple fatality loss models (Wald et al., 2008), stems from the wide, global variability in the built environment and uncertainty associated with inventory and structural vulnerability data, as well as the knowledge about past casualties in different countries. 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 models that rely on knowledge of complex datasets including building inventories, time-dependent population distributions within specific building types, the vulnerability of regional building stocks, and casualty rates given structural collapse. The semi-empirical model uses expert judgment to define the probability of collapse as a function of shaking intensity, whereas the structural vulnerability functions adopted in the analytical model are derived using the HAZUS capacity-spectrum method and thus requires spectral acceleration as the hazard input. Both the semi-empirical and analytical approaches rely heavily on published or reported casualty rates, and thus it is of the utmost importance to the PAGER system to further refine building collapse and related fatality rate functions.

For the purposes of this discussion, we note that the PAGER empirical model can be derived directly from the data sets described above. In that sense, best-fit parameters can be obtained to best hind-cast fatalities from past events (Jaiswal et al., 2009). However, both the semi-empirical and analytical model approaches require forward calculations which contain interdependent variables that can only be constrained by improved data on time-dependent building occupancy patterns, spatial building distribution, building collapse functions, and lethality ratios as well as social aspects, primarily on human response (e.g., building egress) and emergency and medical response (post-collapse mortality). Since separating these variables in the fatality estimates is extremely difficult in terms of an inverse problem, particularly with severely limited data constraints, improvements in the semi-empirical and analytical loss models will come only as separate event-specific loss computations are performed to better constrain these important variables.

PAGER efforts now focus primarily on further refining each of three separate loss methodologies and from them, producing alerts with fatality estimates (as well as uncertainties) for the wide variety of global risk environments. Currently, both the empirical and semi-empirical models are complete and are allowing USGS to produce global fatality estimates in near real-time. These data, tools, and models are valuable for other engineering and seismological studies and are also open and freely available. In addition to the primary audience of response users, beneficiaries from PAGER's open-access environment include, for example, loss-modelers (global V_S^{30}, ShakeMaps, inventories, vulnerabilities), reinsurers (catastrophe bonds), and non-governmental agencies (risk analyses).

3. EXAMPLE APPLICATIONS

The PAGER data sets are contributing to PAGER-related as well as parallel hazard and loss modeling analyses. For example, Trendafiloski (2009), take advantage of the Global Vs30 server for comparing losses computed for large cities based on varying spatial scales for hazard, site condition, and building inventories. Their efforts contribute to developing QLARM, a rapid, global loss estimation project. Similarly, CUEDD points to the ShakeMap Atlas to provide shaking intensity estimates for each earthquake and at each location for which they provide detailed accounting of building losses. Below we provide two sample studies recently completed which also were made possible with these new data sets.

3.1 Geospatial Analysis of Casualties due to Secondary Hazards

One example of the utility of PAGER-CAT is shown in Figure 1, where Marano et al. (2009) separate out secondary causes of fatalities for earthquakes over the past 34 years. This work was pursued to answer questions about how and, critically, where to prioritize research and modeling efforts to augment PAGER's capability to estimate shaking related deaths. As shown in Figure 2, Marano et al.'s analyses show that landslide hazards require the most attention (not counting the rather unique 2004 Sumatra tsunami disaster), and that each of the secondary hazards has particular and perhaps predictable geospatial concentrations around the globe. While tsunami obviously require near-oceanic earthquake sources, landslides are a significant contributor to fatalities in predictable, high-slope areas of the globe. Similarly, post-secondary fires are a major concern for casualties, primarily in Japan and the United States.

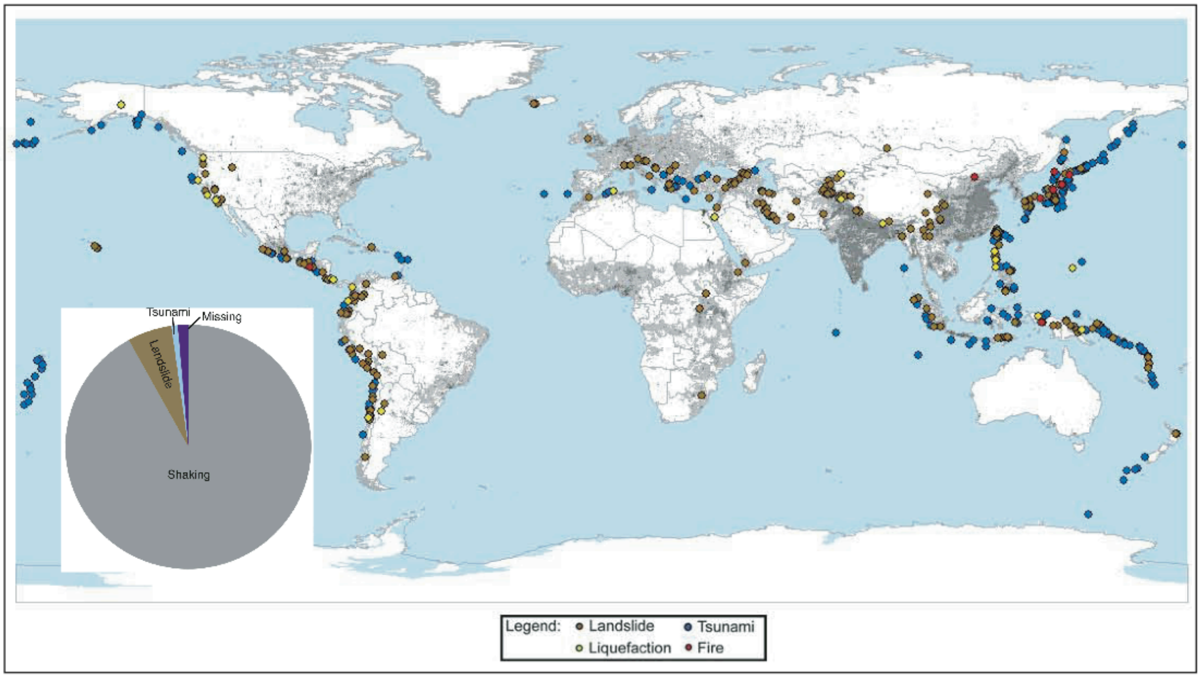

Figure 1. Epicenters of earthquake-induced landslides (brown), liquefaction (yellow), tsunami (blue), and fire (red). Inset shows fatality causes for all deadly earthquakes between September 1968 and June 2008, which is dominated by shaking-related deaths. (From Marano et al., 2009; see that manuscript for more details.)

3.2 Time-of-day Corrections for Casualties

As an example use of EXPO-CAT, Allen et al. (2009c) compared shaking-related deaths since 1973 at different times of day to examine the "time-of-day" effect on earthquake casualties. Essentially, a significant signal was expected (e.g., Scawthorn, 1978; Coburn and Spence, 2002) given the combined potential factors that would contribute to higher fatalities at night: for example, higher percent of the population in vulnerable structures, fewer people escaping collapsed buildings, and community and emergency response (including lack of lighting due to power loss). However, once corrected for earthquake occurrence—more specifically, the population exposed to intensity VIII and higher—Allen et al. found little quantitative evidence to suggest that time-of-day is a consistent, significant factor in earthquake mortality (see Figure 2). Moreover, earthquake mortality appears to be more systematically linked to the population exposed to severe ground shaking (MMI VIII+), an observation made possible only with the EXPO-CAT database.

One can imagine a number of analogous studies that could be made with these data sets. For example, structural damage as a function of building type can be examined for a particular earthquake using a ShakeMap, population, and building inventory databases publically available via the USGS PAGER website. However, without a reasonable map of the shaking distribution, little can be quantified in terms of relative vulnerability; again, as with the time-of-day analysis, the actual or estimated exposure to different shaking levels must be taken into account.

4. LIMITATIONS AND ONGOING NEEDS

All of the data sets described above have inherent as well as resource-related limitations that result in inaccuracies. PAGER-CAT source parameters are derived quantities; some earthquakes were better recorded than others, and they have differing data vintages. ShakeMaps constituting the Atlas are a combination of shaking recordings, macroseismic observations, and shaking estimates; each of these carries a wide range of uncertainties depending on region- and event-specific circumstances (e.g., Wald et al., 2008a). Likewise, once a ShakeMap of intensity distribution is produced, EXPO-CAT, made by combining the spatial intensity and population distributions, carries new uncertainties, in that the population itself is approximate (Bhaduri et al., 2002) and we further correct for the change in population over time, as far back as 1973. In some cases this may not be too bad, but one can imagine regions where country-wide growth curves do not adequately capture essential migration and inconsistent growth patterns. Lastly, while the definition of an earthquake related death is less (but not completely) ambiguous, the numbers associated with "injured" in the PAGER-CAT database are poorly established for most events. While in some cases this is quite understandable given the disaster at hand, more recent collections show the importance of high resolution and quality casualty data sets (e.g., Peek-Asa et al., 2003). Significant efforts are needed in this domain.

These uncertainties can, in part, be reduced with more careful analyses at finer temporal and spatial scales, and with more data for individual events. It is hoped by the PAGER team that any deficient or erroneous aspects of any of the catalogs be brought to light with heavy use of these data sets. As with open-source software, our open data policy will undoubtedly allow more experts from individual countries to examine our data and sources. We anticipate updating these data sets as new, additional, or improved data or models come to light. For example, we will be regenerating the entire PAGER-CAT data set in the near future to incorporate the latest ground motion prediction equations (e.g., Stewart et al., 2008). After evaluation, for example by Allen and Wald (2009b), a new suite of ground motion prediction equations will be employed to recompute the entire ShakeMap Atlas. These revised intensities, in turn, require regeneration of exposures for EXPO-CAT. We hope that with country-wide earthquake data assemblages, individual or event-specific errors will tend to be minimal in, for example, the PAGER empirical loss model coefficients. However, reduced uncertainties and the best possible hazard models are of upmost importance for the PAGER system, so this process will continue. In addition, we will provide routine bi-annual updates with recent earthquake data.

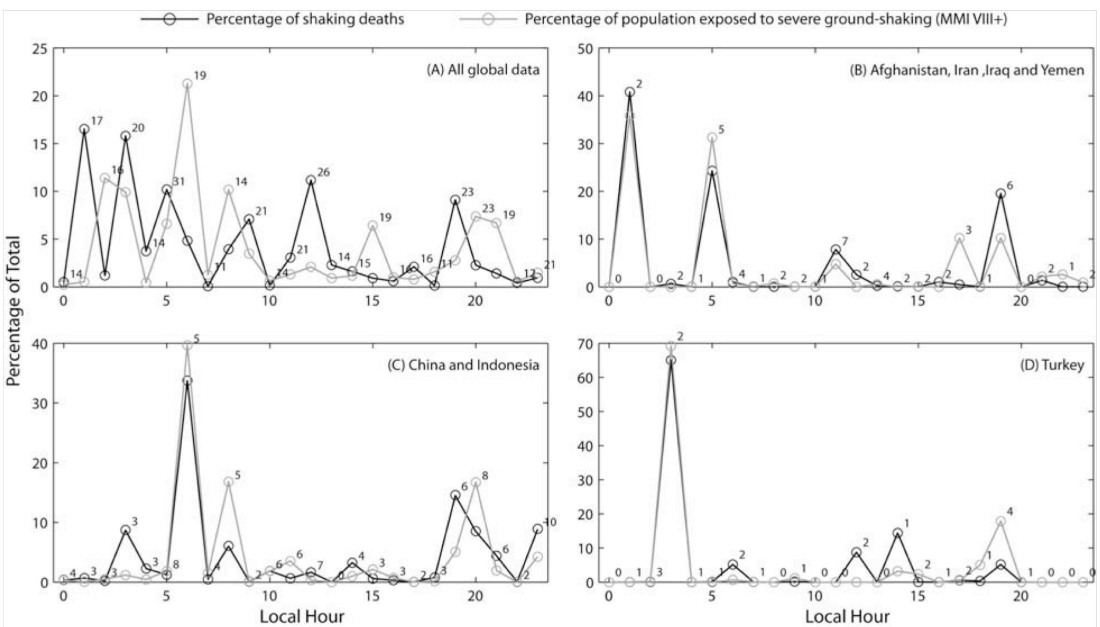

Figure 2. Percentage of shaking deaths to have occurred at each local hour, in addition to the estimated percentage of people exposed to MMI VIII or higher for; (1) all global earthquakes since 1973 with shaking fatalities; (b) the Middle East (Afghanistan, Iran, Iraq, and Yemen); (c) Eastern Asia (China and Indonesia) and; (4) Turkey. Numbers to the top-right of data points represent the number of events in that hour window. From Allen et al., 2009c; see that manuscript for more details.

5. DISCUSSION AND CONCLUSIONS

Proper casualty loss estimation requires assignment or knowledge of a number of interdependent variables. A number of recent contributions towards the improvement of casualty modeling have been discussed herein, in particular, those related to the developing PAGER project and with emphasis on the hazard component. Reducing the uncertainties associated with these variables is extremely important: for example, Peek-Asa et al., (2003) show the importance of rigorous incorporation of the variations in the shaking hazard when drawing conclusions about factors controlling casualties. For the 1994 Northridge, California earthquake, direct comparison of shaking levels derived from ShakeMap allowed Peek-Asa et al. to make credible conclusions concerning causal relations between casualties and ground motion levels, building damage, and inhabitants' locations. Of course, while the data for that event were highly detailed, the total number of fatalities was low, so these conclusions cannot be applied to more lethal areas of the global.

Fortunately, significant data sets, particularly suitable for comparing hazard and losses directly, have also been acquired for other recent earthquakes (e.g, CUEDD). Important studies of the 1995 Kobe, Japan, the 1999 Kocaeli, Turkey and Chi-Chi, Taiwan events also provide loss data for events with well-constrained ground motions from seismic recordings. There is hope that future release of strong motion and casualty data from the 2008 Sichuan, China earthquake will contribute improved models of that event for a country that has dominated earthquake fatalities historically.

These, and many other earthquake studies point to the potential to help constrain, for a range of varying built environments, time-dependent building occupancy, spatial building distribution, building collapse functions, injury distributions, and lethality ratios as well as social aspects, primarily on human response (e.g., building egress) and emergency response (post-collapse mortality). Yet, data sets to constrain many of these predictor variables are poorly constrained for most of the globe

Only by either gathering and by making openly available additional and better data in other parts of the world, or making improved estimates of the hazards (e.g., the ShakeMap Atlas), can we continue to expand the databases by which better fatality estimates can be made. The primary function of the ShakeMap Atlas and EXPO-CAT is to supplement and extend these event-specific loss studies, albeit to a lesser degree of accuracy, to many more events, and for many areas of the world, where fewer hazard and loss data are available. Done systematically, we hope this extrapolation will prove useful for applying loss models on a global scale.

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