Impact-Based Earthquake Alerts with the U.S. Geological Survey's PAGER System: What's Next?

D. J. Wald, K. S. Jaiswal, K. D. Marano, D. Garcia, E. So[*] & M. Hearne
U. S. Geological Survey, Golden, Colorado, USA
[*] *Now at Cambridge University, U.K.*

SUMMARY:
In September 2010, the USGS began publicly releasing earthquake alerts for significant earthquakes around the globe based on estimates of potential casualties and economic losses with its Prompt Assessment of Global Earthquakes for Response (PAGER) system. These estimates significantly enhanced the utility of the USGS PAGER system which had been, since 2006, providing estimated population exposures to specific shaking intensities. Quantifying earthquake impacts and communicating estimated losses (and their uncertainties) to the public, the media, humanitarian, and response communities required a new protocol—necessitating the development of an Earthquake Impact Scale—described herein and now deployed with the PAGER system. After two years of PAGER-based impact alerting, we now review operations, hazard calculations, loss models, alerting protocols, and our success rate for recent (2010-2011) events. This review prompts analyses of the strengths, limitations, opportunities, and pressures, allowing clearer definition of future research and development priorities for the PAGER system.

Keywords: PAGER, ShakeMap, earthquake damage, earthquake losses

1. INTRODUCTION

Development of the USGS PAGER system began in 2005 after the 2004 Great (M9.1) Sumatra tsunami earthquake. In 2006, we began issuing PAGER exposure results for all significant global earthquakes, providing both estimated intensities as well as estimates of populations exposed to each shaking level. Finally, in 2010, the PAGER system began publicly releasing impact-based alerts following significant earthquakes around the globe based on estimates of ranges of likely casualties and economic losses shortly after the introduction of an Earthquake Alert Scale (Wald et al., 2010). The PAGER system is now at the point where re-evaluation of the fundamental goals and implementation strategies are in order. Recent experience with operations, hazard calculations, loss models, alerting protocols, analysis of our success rate for recent events, as well as direct interactions with many users allows us to review the current status of PAGER and set priorities for further research and development.

2. CURRENT PAGER HAZARD ESTIMATES, LOSS MODELS, AND OPERTATIONS

Estimated human and economic impacts are controlled primarily by the distribution and severity of shaking, the population exposed within the built environment, and the vulnerability of the built environment at each intensity level (which is dominated by the degree of seismic resistance of the building stock). PAGER divides impact assessment into four primary modules: earthquake source characterization, shaking hazard estimation (via ShakeMap), exposure and loss estimation, and lastly, communicating uncertain hazard and impact information rapidly, robustly, and coherently. These four PAGER modules have been developed in an open environment. Data, models, and outputs are all documented online, via peer-reviewed publications, and/or USGS Open-File Reports. In addition, valued intermediate and final data and products used in creating each PAGER loss estimate, including the ShakeMap hazard grid, are also publically shared and are accessible in near-real time. A comprehensive list of PAGER-related publications is available online (see http://earthquake.usgs.gov/pager/). The current status of, and recent updates to, these fundamental PAGER components and their operational context are outlined below.

2.1. Earthquake Source and Shaking Hazards

The PAGER system takes a ShakeMap as the primary hazard input. ShakeMaps are generated by the USGS automatically from these parameters within 30 minutes of any magnitude 5.5 or larger event globally, and for any ShakeMap generated in the U.S. by regional seismic networks (M>3.5). ShakeMaps produced by regional seismic networks, several country-wide systems running the ShakeMap software, and the Global ShakeMap (GSM) system run at the USGS National Earthquake Information Center (NEIC) all generate specific input grids (XML formatted).

To calibrate the PAGER loss models, USGS developed a systematic suite of ShakeMaps, an Atlas of approximately 6,000 events (Allen et al., 2009a) for significant global earthquakes that occurred from 1973-2007. The calibration of loss methodologies relied on this Atlas and on fatality and damage data collected by the NEIC (Jaiswal et al., 2009; Jaiswal and Wald, 2010, 2012b). As detailed by Garcia et al. (2012a), a significant revision of this Atlas (Version 2) is underway. The updated ShakeMap Atlas is a compilation of nearly 8,000 ShakeMaps of significant global earthquakes between 1973 and 2011. This revision includes several important recent improvements in the ShakeMap process. First, Atlas 2.0 uses a considerably modified version of the software (V3.5; Worden *et al.*, 2010) that, among other advancements, improves data utilization and computes spatially-varying uncertainty estimates. The new software combines prediction equations with observations, wherever available, to compute maps for two sets of layers: macroseismic intensity and peak ground motions. The macroseismic grid layer defaults to the Modified Mercalli Intensity (MMI) scale. Ground-motion layers grids and maps are produced for five different parameters: peak ground acceleration (PGA), peak ground velocity (PGV), and pseudo-acceleration response spectrum (PSA) at three different periods (0.3, 1.0, and 3.0 s). Uncertainty grids are computed for each parameter. One key addition in this software version is the natural and rigorous inclusion of macroseismic data, which competes against recorded and estimated peak ground motions through a weighted-average approach in the ShakeMap computations that considers their uncertainties.

The revised ShakeMap Atlas (V2.0), spanning 1973 to mid 2011, results in a broader catalogue containing nearly 8,000+ events. In addition, most of the relevant earthquakes that took place in the second half of 2010 and 2011, such as those in Darfield and Christchurch (New Zealand), Tohoku (Japan), Lorca (Spain), and Virginia (USA), are available in this new version. Further, vastly more finite-fault models, macroseismic intensity and ground-motion data from regional agencies, and for some key events, USGS intensity assignments have been added to the Atlas dataset.

We have also developed and now employ a highly refined discrimination strategy to select appropriate prediction and conversion equations based on a detailed global seismotectonic regionalization scheme (García *et al.*, 2012b). The approach makes use of a wealth of global and regional seismotectonic information, including plate boundaries, hotspots, topography and bathymetry data, stable continental regions, slab models (Hayes et al., 2012), global seismicity catalogues, and additional studies for some complex areas (García *et al.*, 2012b). All these changes make the new Atlas a self-consistent, calibrated ShakeMap catalogue that constitutes an invaluable resource for investigating near-source strong ground-motion, as well as for seismic hazard, scenario, risk, and loss-modelling analyses.

The revised Atlas not only provides the base hazard layer for PAGER loss re-calibration but also for the Earthquake Consequences Database (GEMECD) within the GEM initiative. Of the 8,000+ events, 80+ have been selected to populate the GEMECD based on specific attributions, primarily their societal impact and the geospatial quality and availability of the loss data and ShakeMap constraints (e.g., finite faults, strong motion and intensity data). Given their importance for vulnerability function development and loss-model calibration, these select events will receive extra scrutiny and quality control and we invite earthquake experts to contribute data or provide critique on any of these ShakeMaps. In addition to the 80+ GEMECD events, the PAGER team has selected approximately 30 or so "case history" events that will be vital for calibrating landslide and liquefaction triggering and probability models. These, too, were selected based on quality of the ground deformation data and the nature of the hazards constraints, but we have relaxed the 40-year time span of the Atlas to include older notable landslide and liquefaction case history events. As with the entire ShakeMap Atlas 2.0, the landslide and liquefaction subset of ShakeMaps will be openly and freely available via USGS web pages (http://earthquake.usgs.gov/earthquakes/shakemap/atlas.php).

Critically, all the ShakeMap improvements that went into enhancing the Atlas events, including the automatic prediction equation selector and the use of ShakeMap Version 3.5 have also been deployed in parallel into NEIC's operational ShakeMap and PAGER primary and backup systems. These updates are also being deployed to other regional and country-wide seismic networks around the world. As for the ShakeMap Atlas, the real-time Global ShakeMap (GSM) system utilizes site-specific ground-motion amplifications based on Vs30 estimates (Wald and Allen, 2007) which are now being enhanced (Thompson and Wald, 2012). For data constraints, GSM opportunistically ingests recorded ground motions where reported, reported intensities via the internet (e.g., "Did You Feel It?", Wald et al., 2011), and estimated intensities when and where they become available.

For earthquakes of magnitude 6.0 and larger, a more accurate representation of the shaking pattern requires an approximate delineation of the fault plane rupture extent. Predictive shaking equations used in ShakeMap require the fault distance to be specified or additional uncertainty in the estimated shaking must be considered. For such large events, the USGS NEIC produces automatic moment-tensor solutions, providing source orientation (also used automatically in selecting proper GMPE equations and mechanism coefficients) and a robust moment magnitude. NEIC has also implemented rapid finite-fault inversion methodologies (e.g., Hayes et al., 2011). Fast finite-fault modelling requires manual review and expert guidance as does incorporating the fault model into ShakeMap.

2.2. Exposure and Loss Modelling

After establishing the hazard base layers (ShakeMap grids containing PGA, PGV, PSA, and intensity, as well as their uncertainties) we can estimate losses. Population exposure is estimated on a 1 km x 1 km global grid based on the LandScan worldwide population database (Bhaduri et al., 2002); we resample our ShakeMap grid to the same size as LandScan to get estimates of both population and shaking metrics at each cell. The current operational PAGER system relies on empirically-based loss models that account for estimated shaking hazard and population exposure, and employs country-specific fatality and economic loss functions derived using analyses of losses due to recent and past earthquakes (Jaiswal et al., 2009, 2012a). In some countries, our empirical loss models are informed in part by PAGER's semi-empirical and analytical loss models (Wald et al., 2008), particularly their building exposure and vulnerability data sets, both of which are being developed in parallel to the empirical loss-estimation approach (Jaiswal et al., 2010; Jaiswal and Wald, 2012b).

PAGER's parallel loss systems, running in the background, are engineering-based loss estimation models which require detailed building inventory, population, and economic exposure datasets of requisite quality at a global scale. Efforts have been made to improve such datasets through in-house research over several years, as well as through the Earthquake Engineering Research Institute (EERI) World-Housing Encyclopedia-PAGER initiative. PAGER's building inventory, and population exposure schemes now also serve as fundamental input into GEM's Global Exposure Database (GED4GEM) project. GED4GEM's goal is to treat diverse subnational inventory data of varying quality through a globally consistent approach. In addition, PAGER's three-tiered loss estimation procedure, consisting of empirical, analytical, and semi-empirical (expert opinion based) approaches was key in guiding GEM's seismic vulnerability estimation strategy. 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.

2.3. Loss-Based Alerting Protocols: An Earthquake Impact Scale

In order to facilitate rapid and appropriate earthquake responses based on our probable (and uncertain) loss estimates, in early 2010 we proposed a four-level Earthquake Impact Scale (EIS; Wald et al., 2010). Instead of simply issuing median estimates for losses—which can be easily misunderstood and misused—this scale provides ranges of losses from which potential responders can gauge expected overall impact from strong shaking. EIS is based on two complementary criteria: the estimated cost of damage, which is most suitable for U.S. domestic events; and estimated ranges of fatalities, which are generally more appropriate for global events, particularly in earthquake-vulnerable countries. Summary Alerts are determined as the larger of either the economic- or fatality-based color code. Alert levels are characterized by alerts of green (little or no impact), yellow (regional impact and response), orange (national-scale impact and response), and red (international response). Corresponding fatality thresholds for yellow, orange, and red alert levels are 1, 100, and 1000, respectively. For damage impact, yellow, orange, and red thresholds are triggered when estimated US dollar losses reach 1 million, 100 million, and 1 billion+ levels, respectively.

PAGER notification protocols now support EIS-based alerts. Critical users receive PAGER alerts based on the EIS-based alert level, in addition to or as an alternative to magnitude and population/intensity exposure-based alerts, and optionally, for only user-selected regions of the world. As developed, EIS is not specific to PAGER; it could be used by any system providing human and financial loss estimates. We have instituted a review process for PAGER alerting whereby initially "green" and "yellow" alerts run through the system and alert automatically but the rare "orange" or "red" alerts are initially embargoed (up to about 20 min) until source parameters stabilize to the comfort level of the seismic expert on call. This review step for critical alerts was instituted to ensure stability of the magnitude, epicenter, and depth and the associated choice of ground motion prediction equations (e.g., Garcia et al., 2012b). The review process can delay the initial alert message, but we have found that a minor delay for very critical events outweighs the increased potential for sending out a premature, erroneous alert based on preliminary source parameters. While any such alert is pending, a "pending" message goes to all critical users and on the web pages that signals a "heads up"—that a potentially significant earthquake occurred and is currently under manual review. As revised earthquake source information become available or new seismic or intensity data are acquired, PAGER alerts are updated online and are re-alerted under specific conditions that warrant updates from the users' perspectives. The online PAGER content is always the latest, up-to-date version.

In Fig. 1 we provide an example of PAGER's "onePAGER" summary and EIS for destructive M8.8, 27 Feb 2010, central Chile earthquake, which killed nearly 400 people. This earthquake reached an orange alert level based on projected fatalities and a red alert in terms of economic losses (thus a red summary alert was issued). On the PAGER one-pager summary, each individual alert level is based on the median loss estimate; uncertainty in the alert level can be gauged by the histogram showing the likelihood that adjacent alert levels (or loss/fatality ranges) occur. Accompanying text clarifies the nature of the alert based on experience from past earthquakes and provides context on the total economic losses in terms the fraction of the Gross Domestic Product (GDP) of the country affected. The summary also provides regionally-specific information concerning the potential for secondary hazards, such as earthquake-induced landslides, tsunami and liquefaction. Users of PAGER should be aware of the inherent uncertainty in shaking (Worden et al., 2010) and loss estimations (e.g., Wald et al., 2008) and always seek the most current PAGER release on the USGS website for any earthquake.

3. EVALUATING ALERTING ACCURACY

After one and a half years of alerting, we now provide a summary of the performance of PAGER's impact-based alerting for a subset of the events. A complex system such as this requires constant examination, reanalysis, and updating. The PAGER team has analyzed 746 earthquakes from September 2010 through the end of June 2011 for potential losses, 70 of which warranted alerting PAGER email recipients. Of these, 39 had Earthquake Shaking Alerts of "yellow" or greater, indicating an estimated economic loss of $1 Million USD or higher and/or estimated fatalities of one or more. During this same time period, there were 25 earthquakes with known fatalities or economic losses. Graphs of initial and final PAGER predicted fatalities versus reported fatalities for the 25 loss events are shown in Fig 2. Colored squares indicate ranges for each alert level. Data points above the colored squares indicate over-predictions, and vice-versa for points below. During this period, 707 "green" alerts were generated, and in many cases these "no concern" alerts were also incredibly valuable for decision-makers, often avoiding unwarranted attention despite, in often cases, large magnitudes.

For the 16 EIS Alert Yellow+ PAGER runs in this period, the initial Summary Alert level was correct six times, an over-prediction five times, and an under-prediction five times. The final Summary Alert level was correct nine times, an over-prediction six times, and an under-prediction one time. Even when under- and over-predicting, results were within the neighboring alert level. This illustrates the importance of the alert level histogram, since neighboring alert levels often have similar probabilities (see Fig. 1). During that time, PAGER's operational system relied on empirically-based earthquake casualty and economic loss models to estimate the likely earthquake impact. Empirical models 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; we do not analyze those results as they are not yet globally applicable.

Judging the accuracy of PAGER's alert levels is fraught with difficulties in that the system produces not one, but potentially several, evolving alerts for each event. Likewise, since alerts have explicit quantifiable uncertainties, what level of overlap of alert levels can one declare success (that is, when is a "high" yellow alert sufficiently close to an "low" orange alert)? Compounding this complexity, the built-in logic with PAGER also entails short-term embargo of orange and red alerts until release by a system expert. In this context, a delayed but more accurate alert would logically be deemed more useful than an immediate, yet inaccurate one.

One notable initial overestimation of losses by PAGER was triggered by the 2011 M7.2 Van, Turkey, earthquake. PAGER's initial alert (at 27 min) was "red" for both fatalities and economic losses. A day later, revised hazard inputs resulted in orange and red alerts for fatalities and economic losses, consistent with eventual losses. In contrast, initial rapid estimates in-country (Kamer et al., 2012) proved more accurate, suggesting that their better source information, prediction equations and inventory data at a sub-country scale could indeed improve our more general country-wide PAGER models. Seismic and engineering efforts expended in Turkey are nearly unique due to the combination of expertise, data collection, and openness in the process of risk assessment there. Developing comparable data sets in other countries will take a long time.

Analysis of the most inaccurate PAGER alerts in the past few years reveals some commonalities. The main factors, in approximate order of detriment are: inadequate GMPE selection; initial poorly-constrained depths, particularly when trying to distinguish between upper crustal or subduction-zone interface events; inaccurate epicentral locations for on-land events near population centers; and initial magnitude overestimates. Several of these we hope are partially remedied: for example, switching to the Garcia et al. (2012b) prediction-equation selector will improve initial ground motion estimates. Other issues await further scientific and technical developments, and some of these may be a long time coming. We have learned that initial errors on the side of under-prediction are preferable since a low magnitude will result in an under-prediction and may not alert many recipients initially; minutes later a upwardly-revised magnitude could up the alert level, resulting in correct initial alerts to many recipients who are normally no-worse off for a slightly delayed notification. On the other hand, initial high-level alerts which are later revised downward can potential initiate organizational response in the absence of non-collaborating information or revised PAGER alerts. We are considering ways to increase conservatism in the initial alerting of losses without systematically under-predicting losses.

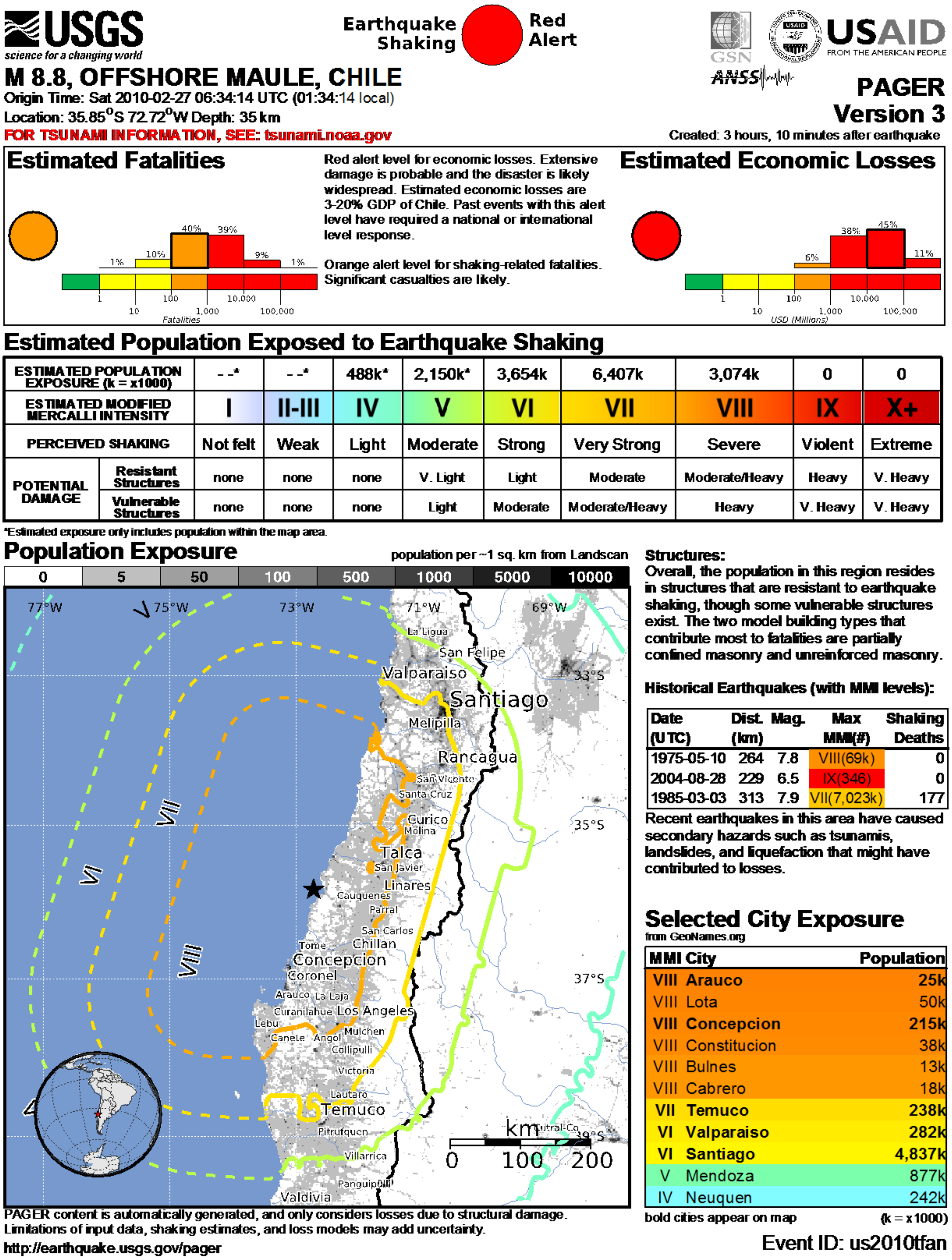

Figure 1. Example PAGER summary figure for the M8.8 Chile earthquake of 2010 showing population density, contoured intensity level (lower left), population exposed per color-coded intensity level (middle), selected cities with population and intensity level (lower right), vulnerable structures, relevant historical earthquakes (middle right), and color-coded impact scale indicating the alert level.

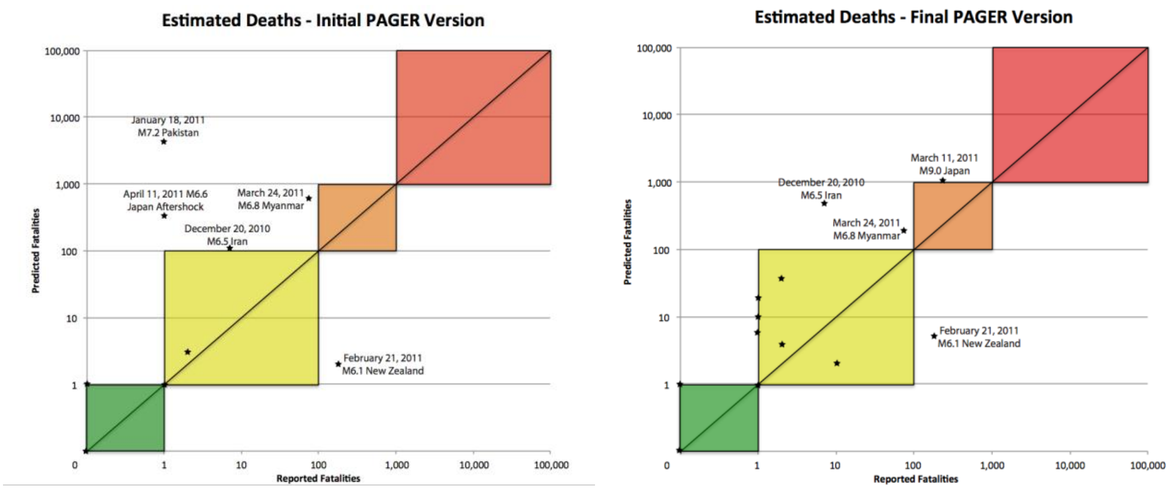

Figure 2. Initial (Left) and final (Right) PAGER predicted fatalities versus reported fatalities. Colored squares indicate ranges for each alert level. Data points above the colored squares indicate over-predictions, and vice-versa for points below.

4. PAGER RESEARCH AND DEVELOPMENT PRIORITIES

With an understanding of the current status of the PAGER system, its operations, and current and potential users and uses, it becomes clearer where to focus future efforts. In its current state, PAGER is an extremely useful tool for users to quickly understand the scope of a potential disaster and to develop the best response in the minutes and hours after an earthquake. Yet, PAGER is a work in progress, and while there are still some technical and data-related challenges, there are also many opportunities to improve PAGER's capabilities so that it remains an essential tool in the realm of early impact estimation, long-term mitigation, and general and scientific hazard and risk understanding.

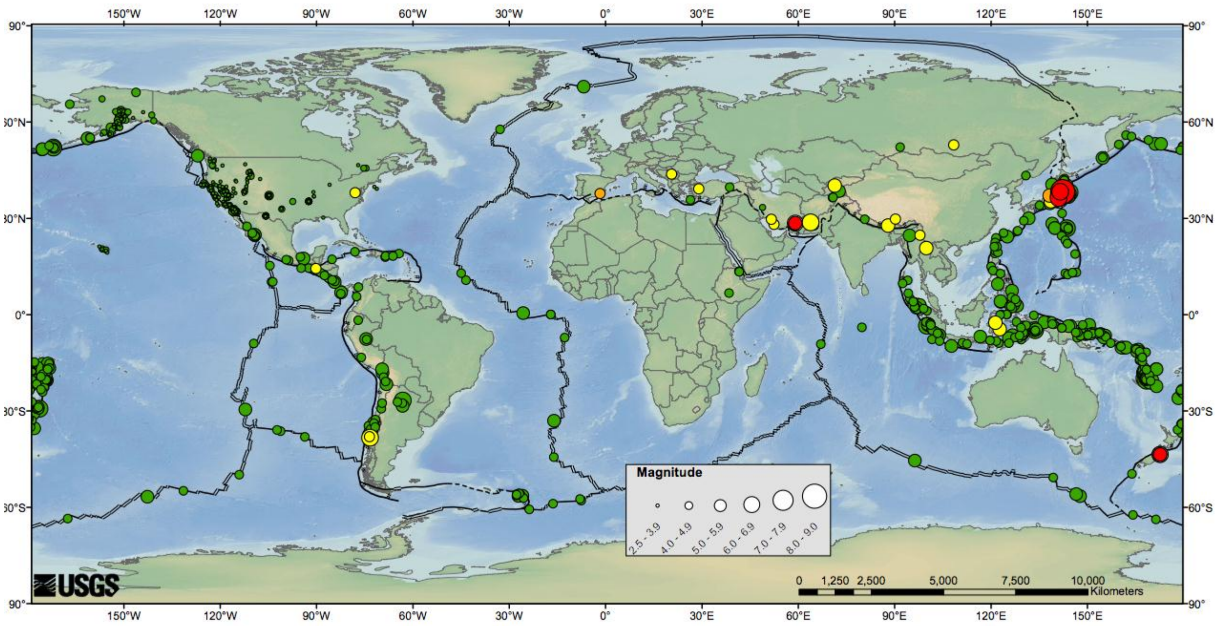

Figure 3. Map of fatality-based alert levels triggered for 2010-2011. Earthquakes (circles) are color-coded to alert levels and scale in size to magnitude (see legend).

4.1. Hazard Estimates

There are several continuing developments under the auspices of the PAGER project. Refined strategies for global-scale estimates of patterns of site amplification characterization are being realized through better approaches that infer Vs30 by combining observations with geologic and topographic constraints (Thompson and Wald, 2012) and will allow multi-scale site maps. Thus, for regions where more detailed site condition maps are available, GSM will be able to incorporate them. The aforementioned ShakeMap enhancements continue including the automatic selection of regionally- and tectonically-suitable prediction and intensity-ground motion conversion equations, updated equations, more rigorous calculations of ground-motion uncertainty and combining estimated and predicted ground motion and intensity observations. However, improved spatially-varying uncertainty computations, per intensity metric (Worden et al., 2010), require further analyses particularly as related to the spatial correlation of reported and assigned macroseismic intensities, functions not available in the literature. Automated finite-fault estimation continues to warrant attention (e.g., Hayes et al., 2011), for example, incorporating realistic 3-D source geometries for finite rupture model determinations has been shown to increase the slip resolution over simple moment-tensor based geometries (e.g., Hayes et al., 2009). Additional efforts here involve incorporating remotely-sensed optical and InSAR data, and geodetic data in near-real time to compliment the current seismic-waveform based strategies.

4.2. Inventory, Vulnerability, and Loss Functions

USGS is improving the PAGER system to include more comprehensive loss-estimate methodologies that take into account more detailed building inventories representing sub-country level regional variations, more complete population demographics (including time of day population shifts) and better tools to compute building damage. Such data sets are very difficult and time consuming to acquire, and are often unavailable in many areas of the globe. Continuing efforts with GEM’s global components will help bring the underlying building inventory and vulnerability data and models to the level where parallel—and hopefully more robust—damage and loss estimates can be made for areas of the world where PAGER’s empirical model is less-well constrained. However, experience with our own sub-country building inventory acquisition and development, as well as knowledge gained working as part of GED4GEM makes it clear that there is no quick solution to developing suitable sub-country inventories, and that expectations for a much improved global inventory will not be realized anytime soon. In fact, PAGER's current domestic (U.S.) empirical loss-models are not yet fully calibrated since so few events have been deadly nor produced significant economic losses, particularly in the eastern expanse of the country. Further work is also needed before we can rely on the inventory-based semi-empirical and analytical models in the U.S.

One significant limitation of most lost-estimation approaches that can now be rectified is the failure to explicitly account for spatially-varying uncertainties of the hazard input. With improvements by Worden et al. (2010) in the ShakeMap uncertainty calculations, it will be more accurate and straightforward to propagate these uncertainties through to loss estimates. Luco and Karaka (2007) and Lin and Wald (2012) show how these can be propagated into improved loss estimates that explicitly account for the spatially-varying uncertainty of the pertinent hazard input intensity measure. While it is difficult to add spatially-varying intensity uncertainty to the PAGER empirical model since it aggregates hazard intensity levels, carrying hazard uncertainties will be a natural extension to the calculations for both the semi-empirical and analytic PAGER loss models.

Opportunities abound for combining remotely-sensed data for inventory development and for ground-truth losses after significant earthquakes, though currently data latency is still problematic for PAGER purposes. Nonetheless, the PAGER team is collaborating with Caltech/JPL efforts involving post-earthquake spatial analyses (optical and radar decorrelation) used as a proxy for ground deformation and, potentially, building damage under the auspices of the Advanced Rapid Image for Analysis (ARIA) Center for Natural Hazards. This promising, developing arena entails significant challenges in rapidly and automatically updating model-based loss estimates with observationally-based assessments of damage. Likewise, rapidly-developing approaches for crowd-sourced post-earthquake impact content continue to improve.

4.3 Estimating Secondary Losses

PAGER currently provides qualitative advisory statements pertaining to the likelihood of secondary perils for each earthquake alerted. For example, every event is checked against the database of losses for the country of interest, and if landslides, liquefaction, fire following, or tsunami losses were common historically, PAGER's messaging lists those perils as potential additional contributions to losses not directly accounted for in PAGER's shaking-based estimates. Moving forward, we are using the ShakeMap hazard layer to more quantitatively assess both the likelihood and spatial distribution of secondary hazards. Estimating both liquefaction and landslide probabilities are feasible yet they are not yet applicable on a global scale in practice. Ongoing calibrations are being performed with the greatly improved subset of recent landslide and liquefaction calibration case-history events provided by the ShakeMap Atlas 2.0 (Garcia et al., 2012a).

4.4 Communicating, Tools, and Products

Requests for new information products come from the many users who desire to not only determine whether or not a given earthquake might be disastrous, but also to then identify potential zones of impact, understand dominant vulnerable construction, and provide estimates of the scale of potential humanitarian needs, e.g., the number of injuries, internally displaced persons, and potential food and sheltering requirements. Though in demand, such derivative products need to be based on loss models with geospatial loss estimates commensurate in detail with the level of accuracy needed for the specific information product. While such information is highly useful and is much desirable, significant improvements in the demographic and building inventories are still necessary to confidently depict, for example, dominant structure types that lead to collapse in sub-regions for many specific countries.

We aim to avoid unrealistic expectations from our user base. For near-real time applications, users tend to understand the uncertainties implied by the color-coded logarithmic loss-based alert scale. Yet, an increasingly common request for ShakeMap/PAGER scenarios warrants consideration of where such scenarios are valid and what spatial scale is appropriate for their portrayal. The expectations for uncertain, real-time loss estimations are lower than those for urban or regional-scale scenario earthquake loss calculations meant for careful planning or mitigation deliberations.

Yet, new geospatial products are indeed warranted in many instances, and Jaiswal and Wald (2012b) describe some of the possible value-added web content and information products that may benefit a variety of PAGER users. These developments include automatically 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. More attention will be paid to the generation and delivery of scenarios with not only standard ShakeMap and PAGER outputs, but also additional products. We are prototyping ways to include population demographics and the nature of the building inventory and its vulnerability. Other region-specific details could be included, for example, the potential for landslides and liquefaction.

In its current state, PAGER is an extremely useful tool for users to quickly understand the scope of a potential disaster and to develop the best response in the minutes and hours after an earthquake. PAGER is a work in progress, and while there are still some technical and data-related challenges, there are also many avenues to improve PAGER’s capabilities so that it remains an essential tool in the realm of early impact estimation. Opportunities abound!

ACKNOWLEDGMENTS

On going advice from D Bausch, M Blanpied, and D Applegate has been vital. PAGER development and maintenance is supported by the USGS, with additional funding and guidance from the U.S. Agency for International Development/Office of Foreign Disaster Assistance (USAID/OFDA). Collaboration with the GEM Foundation continues to contribute to on-going PAGER improvements. Data from Oak Ridge National Lab, Munich Reinsurance, EM-DAT, and NOAA were vital for developing and calibrating PAGER loss models.

REFERENCES

Allen, T.I., Wald, D.J. and C.B. Worden (2012). Prediction of macroseismic intensities for global active crustal earthquakes, *Journal of Seismology*, in press.

Allen, T.I., Wald, D. J., Earle, P. S., Marano, K. D., A. J. Hotovec, Lin, K, and Hearne, M. G. (2009a). An Atlas of ShakeMaps and population exposure catalog for earthquake loss modeling, *Bull. Eq. Eng.*, **7**:701-718.

Allen, T.I., Marano, K.D., Earle, P.S., Wald, D.J. (2009b) PAGER-CAT: a composite earthquake catalog for calibrating global fatality models. *Seismol. Res. Lett.* 80(1):57–62.

Bhaduri, B., Bright, E., Coleman, P., Dobson, J. (2002). LandScan, *Geoinformatics* 5(2):34–37.

García, D., Mah, R.T. Johnson, K.L., Hearne, M.G., Marano, K.D., Lin K.W., Wald, D.J. Worden, C.B., & So, E. (2012a). ShakeMap Atlas 2.0: An Improved Suite of Recent Historical Earthquake ShakeMaps for Global Hazard Analyses and Loss Models, *Proc. 15th World Conf. on Eq. Eng.*, Lisbon, 10p.

Garcia, D., Wald, D. J. & Hearne, M. G. (2012b). A Global Earthquake Discrimination Scheme to Optimize Ground-Motion Prediction Equation Selection, *Bull Seism. Soc. Am.*, **102**, 185-203.

Hayes, G. P., D. J. Wald, and R. L. Johnson (2012), Slab1.0: A three-dimensional model of global subduction zone geometries, *J. Geophys. Res.*, 117.

Hayes, G., Earle, P., Benz, H., Wald, D. J., Briggs, R., and the USGS/NEIC Earthquake Response Team (2011). 88 hours: The U.S. Geological Survey National Earthquake Information Center response to the March 11, 2011 Mw 9.0 Tohoku earthquake, *Seism. Res. Lett.*, **82 (4)**: 481-494.

Jaiswal, K.S., and Wald, D.J. (2012a). Improving PAGER's Real-time Earthquake Casualty and Loss Estimation Toolkit: A Continuing Challenge, *Proc. 15th World Conf. on Eq. Eng.*, Lisbon, 10p.

Jaiswal, K., and D. J. Wald (2012b). Estimating Economic Loss from Earthquakes Using an Empirical Approach, *Earthquake Spectra*, in press, 16 pp,

Jaiswal, K., Wald, D. J., and Porter, K. (2010). Creating Global building inventory for earthquake loss estimation and risk management, *Earthquake* Spectra, **26 (3)**: 731-748.

Jaiswal, K., Wald, D. J., Earle, P., Porter, K, and M. Hearne (2010). Earthquake Casualty Models Within The USGS Prompt Assessment Of Global Earthquakes For Response (PAGER) System, in *Human Casualties in Earthquakes: Progress in Modelling and Mitigation*, R. Spence, E. So, and C. Scawthorn, eds., Springer.

Jaiswal, K.S., Wald, D.J., & Hearne, M., (2009). Estimating casualties for large earthquakes worldwide using an empirical approach: U.*S Geological Survey Open-File Report*, **2009-1136**, 78 p.

Kamer, A., Zulfikar, C. Demircioglu, M.B., Tuzun, C. Sesetyan, K. & Erdik, E. (2012). Post-Earthquake Rapid Loss Estimation for the October 23, 2011 Van Earthquake, *Proc. 15th World Conf. on Eq. Eng.*, Lisbon.

Lin, K. & Wald, D.J. (2012). Developing Statistical Fragility Analysis Framework for the USGS ShakeCast System for Rapid Post-Earthquake Assessment, *Proc. 15th World Conf. on Eq. Eng.*, Lisbon.

Luco, N., & Karaca, E. (2007). Extending the USGS National Seismic Hazard Maps and ShakeMaps to probabilistic building damage and risk maps, *Proceedings of the 10th Int'l Conf. on Applications of Statistics and Probability in Civil Engineering, Tokyo, 8 pp.*

Thompson, E, & Wald, D.J. (2012). Developing Vs30 Site-Condition Maps By Combining Observations With Geologic And Topographic Constraints, *Proc. 15th World Conf. on Eq. Eng.*, Lisbon, 9 pp.

Wald, D.J., Quitoriano, V., Worden, C. B., Hopper, M. & Dewey, J. W. (2011). USGS "Did You Feel It?" Internet-based Macroseismic Intensity Maps, *Annals of Geophysics*, 39 pp., 688-709.

Wald, D. J., Jaiswal, K., Marano, K. D. & Bausch, D. (2010). An Earthquake Impact Scale, *Natural Hazards Review*, **12**: 125-139, doi:10.1061/(ASCE)NH.1527-6996.0000040.

Wald, D. J., Earle, P.S., Porter, K., Jaiswal, K., & Allen, T.I. (2008). Development of the U.S. Geological Survey's Prompt Assessment of Global Earthquakes for Response (PAGER) System, *Proc. 14th World Conf. Earth. Eng.*, Beijing. 10 pp.

Wald, D. J., Lin, K., Porter, K., & Turner, L. (2008). ShakeCast: Automating and Improving the Use of ShakeMap for Post-Earthquake Decision-Making and Response, *Earthquake Spectra*, 24:2, 533-553.

Worden, C.B., Gerstenberger, M.C., Rhoades, D.A., and Wald, D.J. (2012). Probabilistic relationships between ground-motion parameters & Modified Mercalli intensity in California. *Bull. Seism. Soc. Am.* **102**, 204-221.

Worden, C.B., Wald, D.J., Allen, T.I., Lin, K.W., García, D., & Cua, G. (2010). A revised ground-motion and intensity interpolation scheme for ShakeMap. *Bull. Seism. Soc. Am.* **100:6**, 3083-3096.