DEVELOPMENT OF THE U.S. GEOLOGICAL SURVEY'S PAGER SYSTEM (PROMPT ASSESSMENT OF GLOBAL EARTHQUAKES FOR RESPONSE)

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ABSTRACT:

The Prompt Assessment of Global Earthquakes for Response (PAGER) System plays a primary alerting role for global earthquake disasters as part of the U.S. Geological Survey's (USGS) response protocol. We provide an overview of the PAGER system, both of its current capabilities and our ongoing research and development. PAGER monitors the USGS's near real-time U.S. and global earthquake origins and automatically identifies events that are of societal importance, well in advance of ground-truth or news accounts. Current PAGER notifications and Web pages estimate the population exposed to each seismic intensity level. In addition to being a useful indicator of potential impact, PAGER's intensity/exposure display provides a new standard in the dissemination of rapid earthquake information. We are currently developing and testing a more comprehensive alert system that will include casualty estimates. This is motivated by the idea that an estimated range of possible number of deaths will aid in decisions regarding humanitarian response. Underlying the PAGER exposure and loss models are global earthquake ShakeMap shaking estimates, constrained as quickly as possible by finite-fault modeling and observed ground motions and intensities, when available. Loss modeling is being developed comprehensively with a suite of candidate models that range from fully empirical to largely analytical approaches. Which of these models is most appropriate for use in a particular earthquake depends on how much is known about local building stocks and their vulnerabilities. A first-order country-specific global building inventory has been developed, as have corresponding vulnerability functions. For calibrating PAGER loss models, we have systematically generated an Atlas of 5,000 ShakeMaps for significant global earthquakes during the last 36 years. For many of these, auxiliary earthquake source and shaking intensity data are also available. Refinements to the loss models are ongoing. Fundamental to such an alert system, we are also developing computational and communications infrastructure for rapid and robust operations and worldwide notifications. PAGER's methodologies and datasets are being developed in an open environment to support other loss estimation efforts and provide avenues for outside collaboration and critique.

1. INTRODUCTION

As World Data Center for Seismology, Denver, the mission of the USGS National Earthquake Information Center (NEIC) has long been to rapidly determine the location and size of all destructive earthquakes worldwide and to immediately disseminate information about earthquake severity to concerned national and international emergency management agencies, scientists, and the general public. The PAGER project is a natural extension of this role, improving global earthquake information and response by rapidly quantifying the impact of all significant events. The NEIC produces automated earthquake solutions. These solutions are human reviewed and disseminated nearly instantaneously by on-site seismic analysts 24x7. In addition, near real-time earthquake source analyses have been rapidly evolving at NEIC, as have technological tools for disseminating new earthquake information and products. These elements, developed in-house, provide essential input and tools that form much of the backbone of the PAGER system. Yet, PAGER requires specific tuning of these earthquake source analysis tools and further development of new elements, mainly pertaining to estimating shaking intensity and losses.

While the primary purpose of PAGER is rapid dissemination of earthquake impact assessments for decision-making purposes, the intermediate PAGER data, databases, and by-products are also useful tools and sources of earthquake and impact information. For example, in the research and development of PAGER, we have, and will make openly available, databases on earthquake occurrence and their associated population exposures and losses, Vs30 soil site-

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condition maps for the world, and an Atlas of approximately 5,000 ShakeMaps for 36 years of significant earthquakes around the globe (see Table 1 for a current summary). Furthermore, we now provide macroseismic intensity observations, global predictive ShakeMaps, and alerts for population exposure and shaking levels at any specific site around the world in near-real time. Despite being a developmental system, a wide range of users has already recognized beneficial by-products from PAGER. For example, they are currently used by government agencies, the re/insurance industry, national and foreign aid organizations, the military, rapid response groups, and by the media.

This report provides a brief overview of the PAGER system, its operations and status, intermediate products and databases, and ongoing developments. Related USGS developments in progress under the auspices of the PAGER Project not specifically addressed in this short article include rapid finite-fault modeling, global ShakeMap enhancements, ground motion and loss uncertainty analyses, and more informative ways to portray casualty and loss information (as well as their uncertainties); these projects are addressed in depth in related articles.

2. THE PAGER SYSTEM

An overview of the conceptual, computational, and developmental framework of the PAGER system is provided in Figure 1. Arrows connecting the four subsystems in Figure 1 indicate the exchange of intermediate products or information that become rapidly, publically available using standard protocols, particularly via Extensible Markup Language (XML) files and Really Simple Syndication (RSS) feeds. The subsystems themselves consist of four basic PAGER elements.

2.1 Earthquake Source

Fundamental, rapid earthquake information necessary to inform and trigger the PAGER system is produced at the NEIC within 20 min of significant earthquakes worldwide (within 5 min domestically). Hypocentral and magnitude estimates then trigger secondary systems that produce source mechanisms and seismic-moment estimates using body- and surface-wave moment-tensor inversions. These latter estimates in turn inform finite-fault waveform inversions which currently provide source-rupture models within several hours. In the interim time period, source dimensions are inferred from aftershock distributions, if possible. All available source parameters become constraints for the Global ShakeMap system (GSM).

2.2 Shaking Distribution

Once triggered, Global ShakeMap (Allen et al., 2008c; Wald et al., 2006) incorporates all available pertinent information and produces the full suite of ShakeMap products (Wald et al., 2005) within about a minute. While only hypocenter and magnitude parameters are required, shaking uncertainty is significantly reduced by additional constraints, particularly rapid USGS “Did You Feel It?” macroseismic intensity data, seismic station peak-ground motions where available, and fault dimensions (Allen et al., 2008c; Wald et al, 2008).

2.3 Loss Modeling

ShakeMap produces (among other products) a grid of shaking parameters, including intensity. PAGER takes these grid values and computes the population exposed to each level of intensity using the global LandScan2006 (e.g., Bhaduri, 2002) database. Currently, these exposure estimates constitute the PAGER summary notifications. However, the primary goal for the PAGER is to rapidly estimate potential fatalities from any earthquake worldwide. Given the complexity of this challenge, we have adopted a comprehensive three-tiered approach to fatality estimation. Figure 2 provides a visual description for the motivation of a multi-model approach to fatality estimation.

In regions that have experienced numerous earthquakes with high fatalities historically, typically in developing countries with dense populations living in vulnerable structures, enough data exist to calibrate fatalities from the historical earthquake record alone (Jaiswal et al, 2008a). In such regions, building inventories are typically lacking, as are systematic analyses of their vulnerabilities; hence, analytical tools are inadequate for loss estimation.

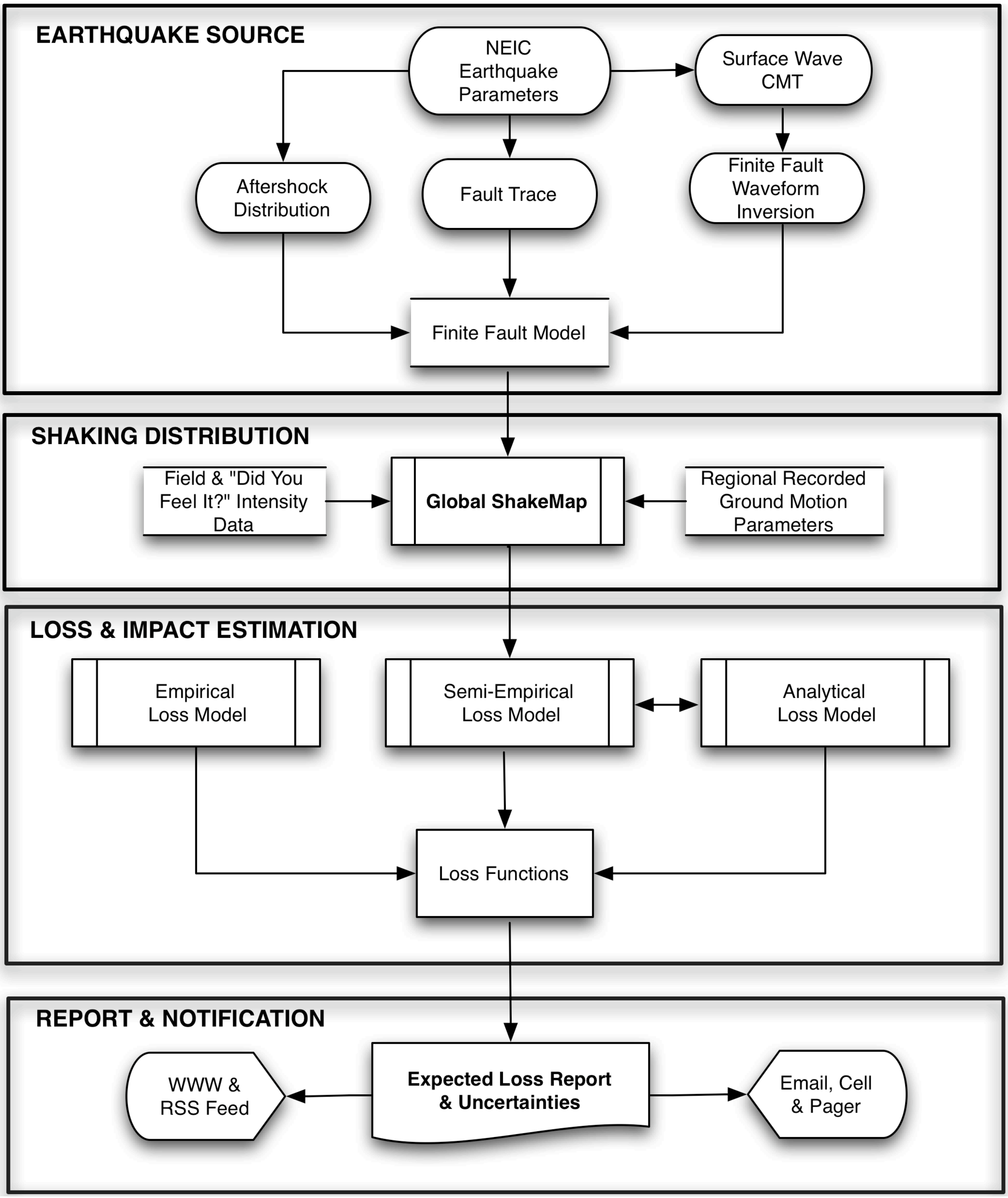

Figure 1. Basic PAGER flowchart for operations, calibration, and loss-estimation.

In contrast, in the most highly developed countries, particularly those with substantive building code implementation, structural responses are more easily characterized analytically and their distributions and occupancy are more readily available (e.g., HAZUS; FEMA, 2006). Due to the success of such building codes, for the purpose of fatality loss modeling, this category of country typically has had relatively few fatal earthquakes, making it difficult to use empirical calibration from past events alone. In such cases, fatality estimates are largely informed from analytically-derived collapse rates and inferred fatality ratio given a structural collapse.

TABLE 1. Databases, Products, Tools, and Services associated with the development of PAGER.

Database/Product	Description	Use	Reference
Earthquake Source			
Fast Finite Faults	Rapid slip models for major earthquakes	Compute shaking; tsunami, stress change	Ji et al (2004); Hayes & Wald (2008)
PAGER-Cat	Quality earthquake catalog (1900-2006)_	Input for ShakeMap Atlas; ExposureCat	Allen et al (2008a)
Shaking Distribution			
Global Slope Data	Topographic slope	Landslides, Vs30	Verdin et al (2007)
Global Vs30 Server	Vs30 values for the globe	Estimating site amplification	Allen & Wald (2008); Wald & Allen (2008)
Global "Did You Feel It" Intensities	Rapid intensities from Internet users	Constrains Shake-Map & event bias	Wald et al (2006b); Wald et al (2008b)
Ground Motion/ Intensity Relations	New relations relating ground motion & intensity	Relate MMI to peak motions	Gerstenberger et al (2009)
ShakeMap Uncertainty	Quantitative & Qualitative shaking values	Computing loss uncertainty	Wald et al (2008b)
ShakeMap Atlas	ShakeMaps for global earthquakes (1970-on)	Scenarios, planning, hazard calculations	Allen et al (2008c)
Rapid Global ShakeMaps (GSM)	Estimated ShakeMaps for all global earthquakes (M>5.5)	Shaking input for loss estimation, decision making	Wald et al (2006a)
Loss & Impact Estimation			
Deadly Earthquake List	Online resource list (1900-2006)	General Reference	On Wikipedia: see "List of Deadly Earthquakes"
Exposure-Cat	Population exposed per intensity for each Atlas ShakeMap	Fatality rates calculations	Allen et al. (2008a)
Global Building Inventory	Country-based data on buildings & collapse rates	Country-specific loss estimation	Jaiswal & Wald (2008b); Porter et al (2008a)
Empirical Loss Model	Country-specific fatality rates	Fatality estimates given exposure	Porter et al (2008a) Jaiswal et al (2008a)
Semi-Empirical Loss Model	Country-specific, building vulnerability	Fatality estimates based on structures	Jaiswal et al (2008b)
Analytical Loss Model	HAZUS vulnerability functions	Structure dependent loss computations	Porter (2008); Porter et al (2008a)
Reporting & Notifications			
OnePAGER	Population Exposure Notifications	Post-earthquake decision making	Earle & Wald (2007)

Finally, we further consider an intermediate approach, the semi-empirical model, which, for each country, requires a basic description of building inventory and distribution, their occupancy at the time of the earthquake, and their vulnerability (in the form of collapse rates) as function of shaking intensity (see Jaiswal and Wald, 2008a,b). This approach also requires estimates of fatalities for each structure type given collapse.

As the empirical model does not require knowledge of the building inventory, it cannot be employed directly for impact assessments beyond fatalities—the data used in its calibration. Alternatively, both the semi-empirical and analytical approaches, which require at least basic building inventories and estimates of the number of structural collapses, thus allow for the computation of other losses, including injuries, homelessness, and financial impact. In the following subsections we briefly describe the empirical, semi-empirical, and analytical model approaches for PAGER loss computations using a consistent nomenclature. Jaiswal et al. (2008a), Jaiswal and Wald (2008b), and Porter et al. (2008a,b) provide more comprehensive descriptions of the loss-modeling approaches.

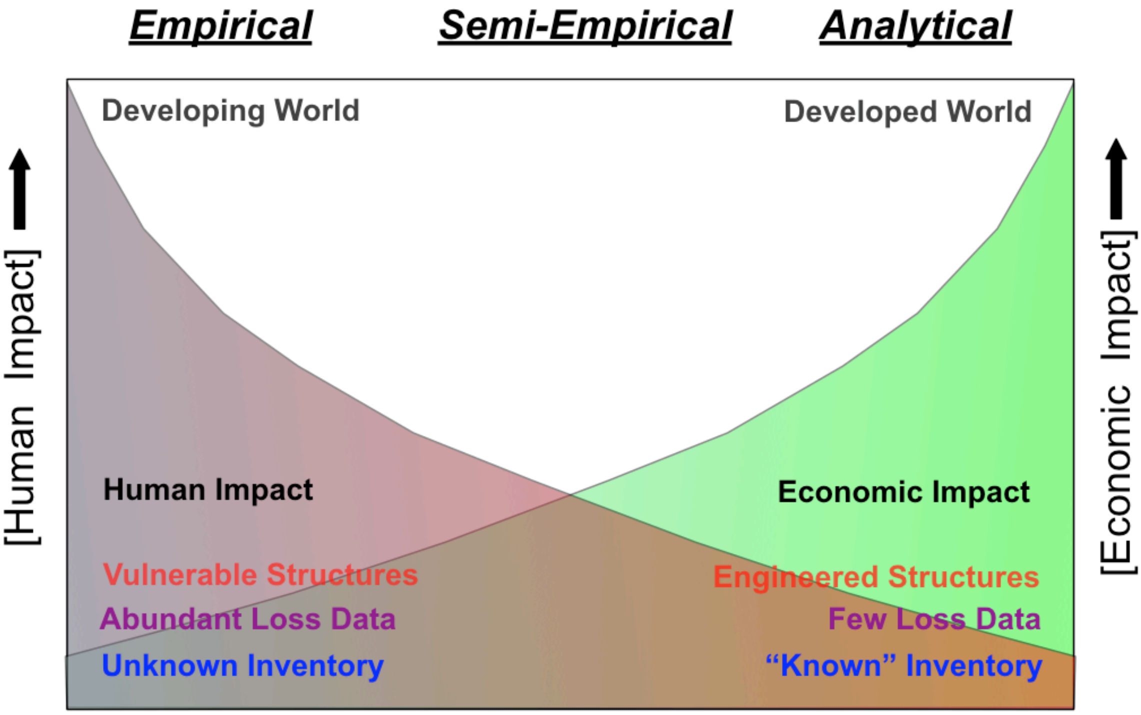

Figure 2. PAGER Loss estimation approaches. Empirical losses are computed where sufficient loss data exist yet inventories are sparse or poorly constrained. Analytical tools (HAZUS-like capacity-spectral approach; FEMA, 2006) are applicable where inventory is known and seismic response can be computed. The semi-empirical approach bridges the gap where inventory and vulnerability is either available or can be estimated via expert opinion. See text and other references on loss modeling for details.

2.3.1 Empirical

In the empirical approach, the building stock distribution and its relative vulnerability are not modeled explicitly; the effective fatality rate defined in terms of persons killed per number exposed at each intensity level (MMI VI—IX), directly incorporates these variations at a country level. For each country *k,* the estimated total number of fatalities can be computed for earthquake *j* by summing the population exposed at each intensity level and then multiplying by the fatality rate for that intensity level:

$$E_j = \sum_{i=1}^{n} v_{i,j} y_k(s_i) \varepsilon_k \qquad (2.1)$$

Here, *v* is the population exposure at grid cell *i*, *s* is the intensity in grid cell *i, y* is the fatality rate for intensity *s,* and

ε_k is a residual error obtained for each country by hindcasting their past earthquake losses. For each country, values of *y* are determined by solving for the best mean and standard deviation values (beta, theta) for a lognormal cumulative distribution of fatality rate as a function of Modified Mercalli intensity (Jaiswal et al, 2008a). We minimize a combined L2 and logarithmic norm between the observed and estimated earthquake fatalities. In the forward calculation the fatality rates are given at each ½ intensity unit and are applied to the population exposed to intensity *s* (±1/4 intensity unit) that experiences that intensity range. Countries lacking historical earthquake loss data are assigned fatality rates from an analogous country using expert judgment (for details, see Jaiswal et al., 2008a).

2.3.2 Semi-Empirical

In the semi-empirical approach, building inventories are considered along with each structure type's occupancy (derived from distributing the population per grid cell), intensity-based vulnerability (here, collapse rates), and fatality rate (given a collapse of that type of structure). In a forward sense, for each country *k,* the fatalities can be estimated for each grid cell first, by distributing the grid cell population in different structure types (as a function of local time of the earthquake) using knowledge of building inventory distributions and their occupancy pattern, and by then analyzing the structure-specific vulnerability to compute earthquake fatalities. Vulnerability analysis consists of computing the number of collapsed structures for each structure type exposed to the intensity in that cell, and multiplying by the fatality rate for collapse of that structure type. The estimated total number of fatalities for earthquake *j* in country *k* is then:

$$E_j = \sum_{i=1}^{n} \sum_{t=1}^{m} v_{i,j,t}\, c_t(s_i) f_t\, \varepsilon_k , \qquad (2.2)$$

where $v_{i,j,t}$ is the population exposure for earthquake *j* in structure type *t* of grid cell *i*; $c_t(s_i)$ is the collapse rate for structure *t* and for intensity at grid cell *i;* f_t is the fatality rate for each structure given collapse of a particular structure type *t; n* and *m* are the number of cells and structures, respectively. The residual error term ε_k is obtained for each country by hindcasting past earthquake losses using the semi-empirical approach. The building distribution, collapse, and fatality rates are provided from models available in the literature and collected using expert judgment via the USGS PAGER/Earthquake Engineering Research Institute (EERI) World Housing Encyclopedia (WHE, http://www.world-housing.net/) collaborative effort (Porter et al., 2008a). For countries with a sufficient number of calibration earthquakes, we can improve the model's predictability by accurately deducing the collapse and fatality rates for the most common building types using past earthquake damage data (Jaiswal and Wald, 2008b). The modified collapse functions are propagated to comparable structures for countries that lack empirical calibration fatality data. Calibration to refine the collapse and fatality rates will be based on losses and associated intensities for events in the ShakeMap Atlas, from data now aggregated in the PAGER exposure catalog (Allen et al., 2008a).

2.3.3 Analytical

For the analytical method, the building inventory and occupancy databases derived for the semi-empirical approach are used. However, the collapse rates are now determined from basic engineering considerations (i.e., using openly-available versions of the HAZUS capacity-spectrum-based approach; Porter, 2008a; Porter et al., 2008a). Since the only differences from the semi-empirical model are the collapse functions, the forward model for the analytical approach can thus be formulated similarly to the semi-empirical model (Eqn. 2.2). In order to calibrate the analytical model against earthquake loss (fatality) data, the inverse problem is analogous to the semi-empirical approach. However, in this case, only the assumed fatality rates are modified since the analytic vulnerability functions were determined from basic principles and laboratory testing. Proper, relative weighting of the results of the three loss modeling approaches will require further investigation. Hindcasting past losses, and losses for events in recent years not used in the calibration process, will be used in countries for which there are sufficient loss data to do so. For other countries, consideration of the relative quality of constraints for each approach will be made by expert opinion, considering i) the assignment of empirical models to neighboring or analogous countries, ii) the quality of inventory and expert-based vulnerability functions, and iii) the applicability of existing or specially-developed analytical models to the country's building inventory structural types.

2.4 Notifications

Currently, the PAGER system alerts select users for any earthquake that has populations exposed to high (MMI>VI) intensities, though the alerting level is customizable. PAGER alerts can be sent to cell/pager or emailed, with information content commensurate with the delivery mechanism. Each summarizes the population exposed to each level of intensity, a good proxy for potential impact. The signature product is called the "OnePAGER" (Earle and Wald, 2007). These same summary files are available online with expanded content in near-real time at http://earthquake.usgs.gov/pager/.

We now produce in-house estimates of fatalities for the empirical and semi-empirical systems, but both are undergoing rigorous calibration and testing prior to public release. We are also trying to quantify uncertainty for both hazard (Wald et al., 2008b) and loss estimates. The PAGER products will be modified to provide intuitive descriptions of potential fatalities and their associated uncertainties. In addition, at that time, alerts will be available publicly and we will allow them to be selective, with customizable regions around the globe as well as by alert levels.

3. INTERMEDIATE AND DERIVATIVE PRODUCTS

Table 1 summarizes the current list of databases, products, and tools established in the process of developing PAGER. While the most visible outcome of the PAGER system are the notifications and alerts described above, it is anticipated that significant benefits to other global loss modeling, earthquake response, and mitigation efforts will come out of these intermediate and derivative tools and by-products. Some tools, for instance the Global Vs30 Server (Allen and Wald, 2007), are already in wide use, providing maps of estimated shallow shear-wave velocities for regions of the globe. Other tools listed in Table 1, including the fast finite-fault inversion system, are ongoing and comprehensive complements to the PAGER system and NEIC efforts in general. As such, while they are intended to provide immediate benefit in the short term, they will require long-term development and operational capabilities that will take time to fully implement.

The open availability of the tools and products listed in Table 1 is in notable contrast with analogous but proprietary systems or subsystems developed primarily for commercial use. Such proprietary models tend to be result-oriented, so their databases, intermediate results, and models are not openly available for use or assessment. It is hoped and anticipated that given the open nature of the PAGER data and models, interactive and collaborative efforts will facilitate more rapid hazard estimation updates, further exchange of real-time seismic data and more difficult to access loss data, and improved loss methodologies.

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