RAPID EXPOSURE AND LOSS ESTIMATES FOR THE MAY 12, 2008 Mw 7.9 WENCHUAN EARTHQUAKE PROVIDED BY THE U.S. GEOLOGICAL SURVEY'S PAGER SYSTEM

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ABSTRACT :

One half-hour after the May 12th Mw 7.9 Wenchuan, China earthquake, the U.S. Geological Survey's Prompt Assessment of Global Earthquakes for Response (PAGER) system distributed an automatically generated alert stating that 1.2 million people were exposed to severe-to-extreme shaking (Modified Mercalli Intensity VIII or greater). It was immediately clear that a large-scale disaster had occurred. These alerts were widely distributed and referenced by the major media outlets and used by governments, scientific, and relief agencies to guide their responses. The PAGER alerts and Web pages included predictive ShakeMaps showing estimates of ground shaking, maps of population density, and a list of estimated intensities at impacted cities. Manual, revised alerts were issued in the following hours that included the dimensions of the fault rupture. Within a half-day, PAGER's estimates of the population exposed to strong shaking levels stabilized at 5.2 million people. A coordinated research effort is underway to extend PAGER's capability to include estimates of the number of casualties. We are pursuing loss models that will allow PAGER the flexibility to use detailed inventory and engineering results in regions where these data are available while also calculating loss estimates in regions where little is known about the type and strength of the built infrastructure. Prototype PAGER fatality estimates are currently implemented and can be manually triggered. In the hours following the Wenchuan earthquake, these models predicted fatalities in the tens of thousands.

KEY WORDS: Wenchuan Earthquake, rapid response, PAGER, ShakeMap, earthquake loss estimation

1. INTRODUCTION

It can take days to determine the scope of an earthquake disaster. Six hours after the May 12th, 2008 Wenchuan, China earthquake disaster, major news agencies were reporting 6 confirmed deaths. Over the next 10 days the media's reported casualty numbers steadily grew to nearly 70,000 dead and 18,000 missing. Only considering these media fatality reports for earthquake response would delay the humanitarian response, prolong suffering, and possibly increase the death toll. Rapid estimates of an earthquake's impact, and supporting products can inform decisions by governments, insurance agencies, and relief organizations to release aid funds, prioritize regions for closer reconnaissance, and mobilize rescue teams.

To help inform these decisions, the USGS operates an automated system to quickly estimate the number of people exposed to severe shaking for earthquakes worldwide. The system, called Prompt Assessment of Global Earthquakes for Response (PAGER), estimates the number of people exposed to potentially damaging shaking and distributes alerts and associated maps to users via wireless devices, e-mail, and the Internet. The currently operating exposure-based PAGER system realizes the first step towards a system that provides quantitative estimates of fatalities, injuries, displaced population, and economic loss in the minutes following damaging earthquakes worldwide. In this paper, we will provide a short overview of the PAGER system and products and discuss the system's performance during the Wenchuan, China earthquake disaster.

2. PAGER PROCESS

PAGER results are built on a suite of systems and products developed and run by multiple institutions primarily under the umbrella of the Advanced National Seismic System (ANSS) (Benz et al., 2000). The process begins for each new event with the determination of the earthquake source parameters (hypocenter, magnitude, and mechanism). Once the source parameters are known, maps of the predicted ground shaking are calculated and used to estimate the population exposed to potentially damaging shaking. PAGER products are generated for all earthquakes of magnitude 5.5 and greater globally and for lower magnitudes of about 3.5-4.0 within the contiguous US, Hawaii, and a region surrounding Anchorage, Alaska.

The NEIC and ANSS regional seismic networks provide the estimates of hypocenter and magnitude used by ShakeMap and PAGER. Within dense ANSS regional networks, these parameters are generally available within 5 minutes and in other more sparely instrumented regions throughout the world, source parameters are generally available within 20 minutes. The hypocentral and magnitude solution triggers secondary systems that produce source mechanisms and seismic-moment estimates using body- and surface-wave moment-tensor inversions. For large earthquakes, these latter estimates in turn inform finite-fault waveform inversions, which currently provide source-rupture models within several hours. In the interim, source dimensions are inferred from aftershock distributions, if possible. All available source parameters become constraints for the ShakeMap system.

Once triggered, Regional and Global ShakeMap systems (Wald et al., 2006) incorporate all available pertinent information and produce 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., 2008a; Wald et al., 2008b).
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 Modified Mercalli Intensity (MMI) using the global LandScan2006 (e.g., Bhaduri, 2002) database and the estimated MMI at selected settlements using the Geonames (http://www.geonames.org) database. These exposure estimates constitute the publicly distributed PAGER summary notifications and provide the input for PAGER's prototype fatality estimates.

3. PAGER OUTPUT

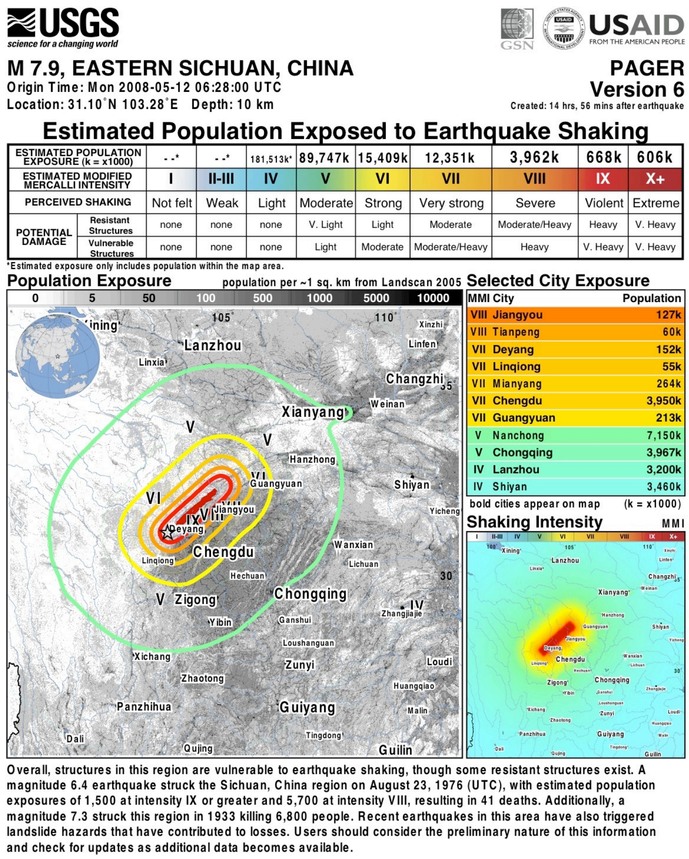
PAGER's signature product is a concise one-page summary report referred to as the "onePAGER". The maps and tables in this report provide a quick assessment of the possible impact of an earthquake. OnePAGERs are distributed by e-mail and are available on the USGS Earthquake Program webpages (http://earthquake.usgs.gov/pager/). Figure 1 shows an example onePAGER for the magnitude 7.9 Wenchuan, China earthquake of May 12th, 2008. The different sections of the onePAGER are described in a companion single-page summary available online.

The header of the onePAGER summarizes the basic earthquake parameters including origin time, magnitude, hypocenter, and the name of the region where the earthquake took place. The header also provides the version of the PAGER alert and the time it was created. New versions are generated when the location and/or magnitude are updated or when shaking maps are further constrained, for example, by the inclusion of ground shaking observations or estimates of rupture geometry. Recipients of PAGER alerts should check the PAGER website for the most recent changes in the hours following an earthquake, because not all versions of the alerts are e-mailed.

The onePAGER's most indicative information about the potential impact of an earthquake is displayed in table format just below the header information. This table shows the total number of people within the map boundary estimated to have experienced each MMI level from I (not felt) to X (extreme). The table also contains a rough guide to possible building damage at different MMI levels for resistant and vulnerable structures.

Two maps on the onePAGER provide an indication of the geographic extent of the shaking and distribution of the affected population. One map plots estimated MMI color contours over a gray-scale of population per

~1km^2. The regions of integer MMI values are labeled with Roman numerals and separated by the thick contour lines. The epicenter is shown as a black star and marks the surface projection of the earthquake rupture initiation. It is important not to over emphasize this location because the area above the entire ruptured fault will have the highest intensities rather than just the area near the epicenter. A complementary map shows shaking intensity as a continuous color gradient.



USGS science for a changing world

USAID FROM THE AMERICAN PEOPLE

M 7.9, EASTERN SICHUAN, CHINA
Origin Time: Mon 2008-05-12 06:28:00 UTC
Location: 31.10˚N 103.28˚E Depth: 10 km

PAGER
Version 6
Created: 14 hrs, 56 mins after earthquake

Estimated Population Exposed to Earthquake Shaking

ESTIMATED POPULATION EXPOSURE (k = x1000)		- -*	- -*	181,513k*	89,747k	15,409k	12,351k	3,962k	668k	606k
ESTIMATED MODIFIED MERCALLI INTENSITY		I	II-III	IV	V	VI	VII	VIII	IX	X+
PERCEIVED SHAKING		Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	Resistant Structures	none	none	none	V. Light	Light	Moderate	Moderate/Heavy	Heavy	V. Heavy
	Vulnerable Structures	none	none	none	Light	Moderate	Moderate/Heavy	Heavy	V. Heavy	V. Heavy

*Estimated exposure only includes population within the map area.

Population Exposure population per ~1 sq. km from Landscan 2005

Selected City Exposure

MMI	City	Population
VIII	Jiangyou	127k
VIII	Tianpeng	60k
VII	Deyang	152k
VII	Linqiong	55k
VII	Mianyang	264k
VII	Chengdu	3,950k
VII	Guangyuan	213k
V	Nanchong	7,150k
V	Chongqing	3,967k
IV	Lanzhou	3,200k
IV	Shiyan	3,460k

bold cities appear on map (k = x1000)

Shaking Intensity MMI

Overall, structures in this region are vulnerable to earthquake shaking, though some resistant structures exist. A magnitude 6.4 earthquake struck the Sichuan, China region on August 23, 1976 (UTC), with estimated population exposures of 1,500 at intensity IX or greater and 5,700 at intensity VIII, resulting in 41 deaths. Additionally, a magnitude 7.3 struck this region in 1933 killing 6,800 people. Recent earthquakes in this area have also triggered landslide hazards that have contributed to losses. Users should consider the preliminary nature of this information and check for updates as additional data becomes available.

Figure 1. The onePAGER summary report generated 15 hours after the May 12th Wenchuan, China earthquake. This was the sixth update following the earthquake. Subsequent updates had no significant changes in shaking distribution or population exposure estimates. This was the first version to include fault dimensions inferred from a finite-fault waveform inversion. See text for details.

The table to the right of the population exposure map provides a list of up to eleven settlements that fall within the map boundaries and their corresponding population and estimated MMI. The table preferentially contains country capitals and the six settlements with the highest estimated intensity. The remaining settlements listed are the ones with the highest population that fall within the map boundaries. The listed cities are often part of a larger connected urban area so the total exposed population in the region surrounding the city can be significantly larger than that stated for the city it self.

The damage caused by an earthquake greatly depends on the vulnerability of the shaken buildings. Earthquakes in the world's most vulnerable regions can result in a fatality rate roughly 5,000 times higher than in the most resistant regions. To help the user assess the possible impact of a newly alerted earthquake, a regionally specific comment is provided below the maps. The comment describes the vulnerability of the buildings in the affected country and, when available, gives example population exposures and reported fatalities from previous nearby earthquakes. If previous earthquakes triggered landslides, tsunami, or fire, the comment notes that these secondary effects may contributed to losses. These data are drawn from databases specifically compiled as part of the PAGER project (Jaiswal et al., 2008a, Allen et al., 2008b).

Since two earthquakes with similar population exposure in the same region will likely produce similar damage, the comment provides a rough guide to the possible impact of a newly alerted quake. However, the user should expect variation especially for small fatality earthquakes since these deaths often result from isolated collapse of anomalously weak buildings. The initial comment is generated automatically but is sometimes manually updated.

PAGER exposure estimates and maps are also presented in an expanded form on the USGS Earthquake Hazards Program website (http://earthquake.usgs.gov/pager/). The PAGER web pages also contain an overview of the system and an archive of PAGER results for all earthquakes processed since the system was publicly released in October 2007. The web-pages are the best source for the most recent PAGER results.

PAGER e-mail alerts are available in two formats, a short version suitable for a mobile device and an extended text format with the optional onePAGER PDF (Adobe System's Portable Document Format) attachment. Alerts are sent when a user's personally specified minimum MMI or magnitude threshold is exceeded. Using an intensity-based threshold reduces the number of alerts a user receives, because only earthquakes that affect people are sent. People or organizations interested in receiving PAGER alerts should contact the authors.

4. PAGER RESULTS FOR THE WENCHUAN, CHINA EARTHQUAKE

The May 12th Wenchuan, China earthquake was the largest earthquake disaster since the public release of the PAGER system in October, 2007. The system performed well. Thirty-one minutes after the earthquake PAGER distributed exposure estimates and associated maps which indicated a large-scale disaster had occurred to critical users including the World Bank, United Nations, U.S. Agency for International Development, U.S. State Department and Reuters. In addition, the combination of USGS's Earthquake Notification Service (ENS, Wald et al., 2008c) and Earthquake Program Web pages (http://earthquake.usgs.gov), directed millions of additional seekers to the PAGER and related earthquake information pages. In all, these pages served over ½ billion hits within a week of the Wenchuan event.

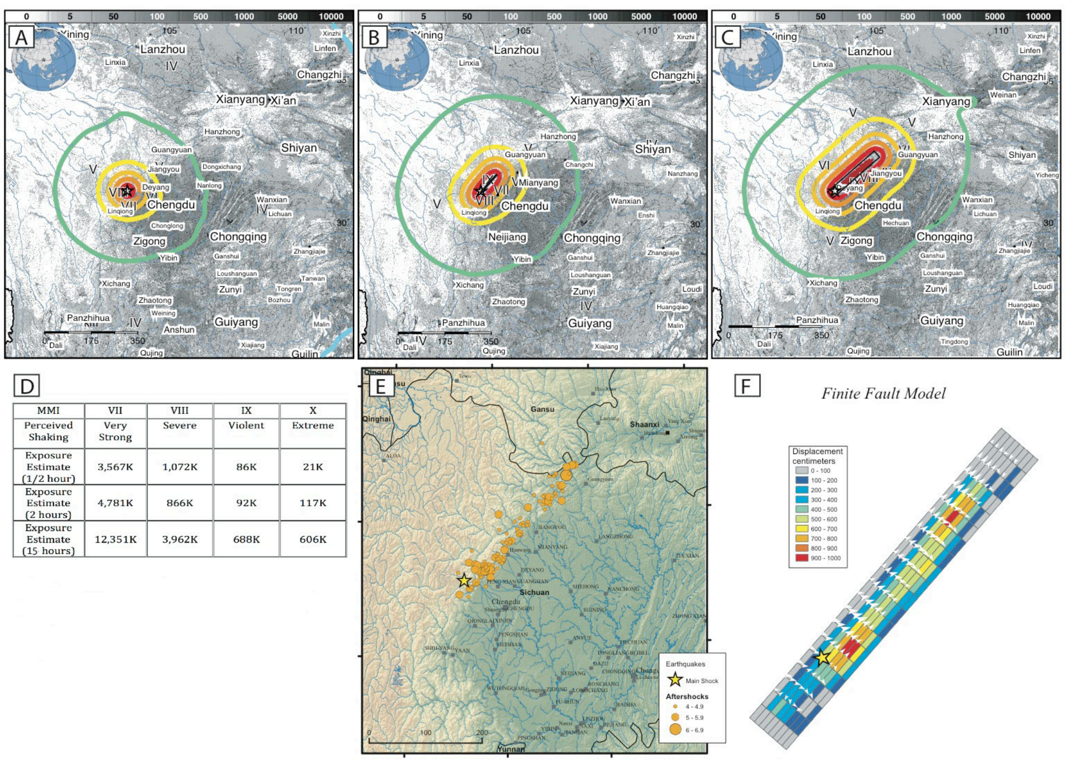
The first PAGER alert was automatically generated and predicted 1.2 million people were exposed to MMI VIII or greater shaking. Exposure estimates this high in a region with vulnerable infrastructure is a clear indication of a disaster. A full-scale response by the NEIC staff ensued to improve initial magnitude and location estimates and determine details of the rupture using aftershock locations and finite-fault waveform inversion. Eleven PAGER updates were produced in the following hours. The most significant improvements were obtained by including estimates of the fault's length and geometry in ShakeMap's ground-motion calculations.

Figure 2 shows the three most significant improvements in PAGER's exposure estimates for the Wenchuan earthquake. The initial ShakeMap ground-shaking estimate considered the average rupture length for the earthquake's magnitude (Wald et al., 2008b) but contained no information about the specific fault geometry. This average-fault approximation produced the bulls-eye MMI contours seen in Figure 2a. The deviation of the contours from concentric circles results from local site amplification estimated using topographic slope (Wald and Allen, 2007).

Figure 2b shows the third PAGER alert issued for the Wenchuan quake. Generated 2¼ hours after the quake, it was the first version to incorporate an estimate of the rupture-length and geometry. We inferred that the rupture propagated 110 km from the hypocenter to the northeast based on initial aftershocks, fault-length versus magnitude relations (Wells and Coppersmith, 1994), and regional topography. The fault was approximated by a line source (black line Figure 2b). The use of an extended linear fault for estimating shaking produces contours of concentric ovals (Figure 2b). The total estimated population exposure to the highest intensities did not significantly change from PAGER's first estimate but this version provided a better estimate of the area affected by the highest levels of shaking.

Care must be taken when using early aftershocks to define the rupture zone because it can take several hours or days for the extent of the rupture zone to be well delineated. Additionally, large earthquakes often trigger aftershocks far removed from the causative fault. In hindsight, for the Wenchuan earthquake, our initial estimate of fault length based on the initial aftershock distribution was an underestimate. However, the locations of the aftershocks (Figure 2e) in the days following the event were a good indicator of the extent of the main rupture zone.

The last significant update to the PAGER results occurred 15 hours after the event (Figure 2c). For this version, the estimated rupture width as well as its length was included. The rupture length was extended further to the northeast primarily based on seismic waveform modeling of the rupture's extent (Figure 2f) (Ji and Hayes, 2008) and the locations of additional aftershocks. This more accurate representation of the earthquake's rupture resulted in a increase in PAGER's exposure estimate to about 5.2 million people exposed to MMI VIII or greater (about 4.3 times our original estimate). These results are based on inferred shaking levels based on seismological inferences and ground motion prediction equations. Definitive results await the release of recorded ground motion data.



MMI	VII	VIII	IX	X
Perceived Shaking	Very Strong	Severe	Violent	Extreme
Exposure Estimate (1/2 hour)	3,567K	1,072K	86K	21K
Exposure Estimate (2 hours)	4,781K	866K	92K	117K
Exposure Estimate (15 hours)	12,351K	3,962K	688K	606K

Figure 2: Evolution of PAGER results for the Wenchuan, China earthquake. A, B, and C: Color MMI contours plotted over grayscale population per ~1km^2 for PAGER alerts released 30 minutes, 2¼ hours, and 15 hours after the event. D: Estimated population exposure for the three alerts E: Aftershocks recorded in the days following the earthquake. F: Finite-fault model used to estimate fault dimensions shown in panel C.

The increase in PAGER's population exposure estimates with time for the Wenchuan Earthquake is typical and expected for large earthquakes. Initial ShakeMaps calculated using the average-fault approximation (e.g., Figure 2a) predict a smaller geographic extent for the highest intensity shaking than do ShakeMaps calculated using a finite-fault representation (e.g., Figure 2c). This larger area will generally increase population exposure estimates. Recipients of PAGER alerts should be aware that for large earthquakes (magnitude > 7) the initial exposure estimates are likely a lower bound.

5. PAGER PROTOTYPE LOSS ESTIMATES

PAGER currently reports the population exposed to different levels of shaking intensity. This is a useful indicator of an earthquake's potential impact. However, estimates of the number of people killed, injured, and displaced would provide more actionable information for emergency response. To provide this information, a significant effort is underway to develop loss models and collect the required datasets on a global scale. Given the complexity of this challenge, we have adopted a comprehensive three-tiered approach to fatality estimation (*Wald et al., 2008a*).

In regions that have experienced numerous fatal earthquakes in the past, typically in developing countries with dense population living in vulnerable structures, enough data exist to empirically derive the earthquake fatality rates from the historical earthquake record alone (Jaiswal et al, 2008b). In such regions, information specific to building inventories, and population exposure are typically lacking, as are the systematic analyses of their vulnerabilities; hence, analytical tools are often inadequate for loss estimation.

In contrast, in the most highly developed countries, particularly those with substantive building code implementation for earthquake resistant design, structural responses are more easily characterized analytically and their distributions and occupancy are more readily available (e.g., HAZUS; FEMA, 2006). Due to more shake resistant construction practice and stricter enforcement of earthquake specific building codes, even the larger earthquakes in these countries result in fewer building collapses and hence less fatalities. Thus, despite high seismicity in such countries, it is difficult to calibrate empirical models from the few fatal earthquakes. In such cases, fatality estimates are largely informed from analytically-derived collapse rates and inferred fatality ratio given a structural collapse (e.g., Porter, 2008b).

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 a function of shaking intensity (*Jaiswal and Wald, 2008c*). 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, allow for the computation of other losses, including injuries, homelessness, and financial impact.

PAGER's loss models rely on extensive global databases that are being compiled as part of the project including, 1) a composite earthquake catalog containing the best available source parameters and reported losses (Allen et al., 2008c), 2) an Atlas of 5,000 ShakeMaps for earthquakes occurring since 1973 (Allen et al., 2008a), and 3) a global building inventory for loss assessment developed in cooperation with the Earthquake Engineering Research Institute (*Jaiswal et. al., 2008a, and Porter et. al. 2008a*). All PAGER's datasets and methodologies are being developed and distributed in an open environment to support other loss estimation efforts and provide avenues for outside collaboration and critique.

Prototype versions of the empirical and semi-empirical models were run in a manually triggered mode in the hours following the Wenchuan earthquake. Based on population exposure estimates for the well-constrained fault geometry determined 15 hours after the event, PAGER's empirical model predicted 50,000 deaths (Figure 3a) and the semi-empirical model predicted 30,000 deaths (Figure 3b).

The empirical model uses a two-parameter lognormal distribution for the fatality rate as a function of shaking intensity (Figure 3c). The coefficients of this model were determined by minimizing the residual error between recorded and estimated fatalities for historical earthquakes in China (Jaiswal et al., 2008b). For the semi-empirical model, the population exposure by building class is estimated using a broad country-level building inventory obtained from WHE-PAGER Phase 1 survey data for China (Jaiswal et al. 2008c). The collapse fragility functions were derived from expert judgment after collating survey data for 26 countries by building class (Figure 3d). The building-specific fatality rates implemented in the prototype system were directly adopted from HAZUS casualty rates (FEMA, 2006) by building type given complete structural damage with collapse.

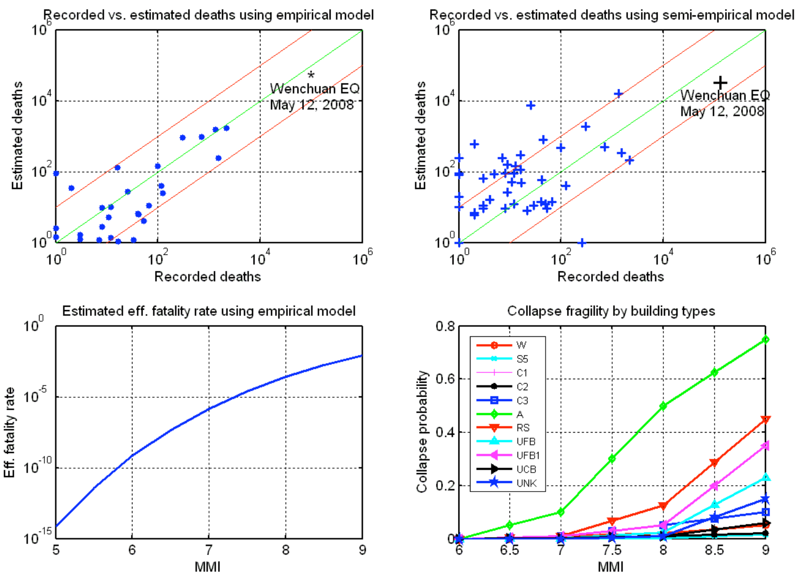


Figure 3. Fatality estimation using prototype empirical and semi-empirical models produced 15 hours after the Wenchuan earthquake of May 12, 2008. a) Empirically-estimated fatalities for historical and Wenchuan earthquakes and b) Estimated fatalities using semi-empirical method c) Empirically derived effective-fatality rate versus shaking intensity. d) Building-specific collapse fragility versus shaking intensity.

The results obtained from the prototype loss methodologies for both the models were generally consistent and useful in assessing the overall impact of the earthquake. At the time our estimates of 30,000 and 50,000 deaths were produced, major media outlets were reporting 9,000 fatalities. In weeks after the event, reports stabilized near 70,000 dead and 18,000 missing (UNICEF, 2008). The prototype version of the PAGER loss models are being updated with newly gathered data on population exposure and improved knowledge of country-specific building vulnerability and global fatality rates.

6. SUMMARY

After catastrophic earthquakes, it is difficult to rapidly assess the overall impact and the geographic extent of the disaster from first-hand accounts. Communications and physical access to the devastated areas are often disrupted resulting in a lack of reports from the most damaged regions. Additionally, effectively assimilating and assessing hundreds or thousands of individual reports is extremely challenging for local and national authorities during a crisis.

For the Wenchuan earthquake disaster, PAGER's exposure estimates provided a faster assessment of the overall situation than did the media. PAGER showed that the event was likely catastrophic within half an hour and an accurate estimate of the geographic extent of the severe shaking was distributed within 15 hours. PAGER's overall assessment preceded accurate fatality totals reported by major media outlets by several days. Six hours after the earthquake Reuters reported a total of 6 fatalities. Five days later these number had increased to 29,000, still far short of the ~70,000 killed and ~18,000 missing, presumed dead reported by UNICEF weeks after the earthquake.

The China earthquake provides a specific example of how PAGER alert content improves with time. Many enhancements to PAGER and its subsystems are underway that will improve PAGER's content, accuracy, and timeliness. When these enhancements are implemented stable estimates of the shaking extent and fatality estimates for large earthquakes will be available within 2 hours.

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