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Uncertainties in Teleseismic Earthquake Locations: Implications for Real-Time Loss Estimates

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Abstract For estimating fatalities and injured within minutes after an earthquake worldwide, we rely on real-time teleseismic determinations of epicenters. To estimate the teleseismic location errors, we computed the difference between the local epicenters of the dense seismograph networks of Japan, Italy, and Taiwan with those given by the PDE, those distributed in real time by the U.S. Geological Survey (USGS), and the European Mediterranean Seismological Center (EMSC). The average difference is 16 and 8 km between PDE teleseismic epicenters and those by the local networks for Japan/Taiwan and Italy, respectively. For EMSC epicenters, the average difference is 13 km for Italy. The average difference between real-time USGS parameters and those listed in the PDE is 12 km (median 9 km) for 30 earthquakes in Japan. Comparisons of real-time USGS epicenters and the Japan Meterological Agency (JMA) locations yield an average difference of 31 km (median 26 km). Estimates indicate that the epicenter errors in the local catalogs are typically 1 and 3 km for Japan/Italy and Taiwan, respectively. Assuming that the differences in earthquake locations are mostly due to teleseiseismic errors, we conclude that the mean errors in real-time epicenter solutions are in the range of 25 to 35 km. This implies that for earthquakes of $M \approx 6.7$ in the vicinity of a medium-sized city (80,000), the fatality estimates using QLARM in real time have to range from near 0 to 10,000 in the developing world and from 0 to 500 in an industrialized country. These results were verified by comparison with observed numbers of fatalities in the cases of the 2003 M 6.7 Bam, Iran, and the 2008 M 6.9 Iwate–Miyagi, Japan, earthquakes.

Introduction

The World Agency for Planetary Monitoring and Earthquake Risk Reduction (WAPMERR) has estimated losses (mean damage to buildings, fatalities, and number of injured) after strong earthquakes worldwide in real time over the last seven years (see the Data and Resources section). The reliability of these estimates depends on the accuracy of the source parameters supplied in real time by one or several of the agencies capable to estimate them worldwide. We use the expression real time as meaning within minutes of the occurrence of an earthquake. We have based our loss estimates exclusively on reviewed source parameters because we felt that, until now, uncertainties in automatic teleseismic solutions were too large to base estimates of fatalities on them. In this paper, we investigate the approximate errors of reviewed teleseismic epicenter determinations in real time and their influence on loss estimates.

In most countries, operators of regional and local seismograph networks do not supply the international community with earthquake source parameters in real time. This is especially true for the developing world, which is the focus of our efforts. Consequently, we have to rely on source parameters derived from teleseismic data. Seismological centers of most industrialized countries calculate approximate source parameters for strong earthquakes worldwide, but these epicenters have errors of typically hundreds of kilometers because of the small dimensions of the seismograph networks used.

The only institutions that have distributed reviewed teleseismic source parameters derived from worldwide seismograph networks during the last seven years in real time and which later make their catalogs available for analysis are the U.S. Geological Survey (USGS) and the European Mediterranean Seismological Center (EMSC). These data are of great use to us in estimating losses due to earthquakes, and these centers perform a service to the seismological community. When we analyze the accuracy of their data, it is not meant as a criticism. The spatial distribution of teleseismic seismograph stations that transmit their data in real time impose constraints that cannot be overcome. Our analysis only intends to show how real-time estimates of casualties are dependent on possible epicenter errors and how different these consequences are in developing and industrialized countries.

The purpose of our loss estimates in real time is to enable rescuers, governments, and disaster managers to decide on the extent of the response necessary, based on quantitative information. Given the numerous error sources that affect loss estimates, in addition to uncertainty in epicenter location, we can only hope to estimate the order of magnitude of the losses. Most importantly, we should be able to distinguish major disasters from inconsequential events. We define major disasters as those cases where we estimate that more than 1000 people were injured and about 400 may have died. In such cases, we telephone subscribers who wish to be called; for all other earthquakes with $M \geq 6$ and the potential for losses, we send e-mails to subscribers of this free service.

The number of e-mail alerts we have distributed over the last seven years is about 580, which amounts to a frequency of 1.6 per week. The median delay of our alerts is about 30 min after the earthquake (Wyss and Zibzibadze, 2009). We use approximately 10 min for calculating losses and for considering the possible range due to likely errors; it takes about 20 min for the fastest reviewed source parameters to reach us (those by the USGS).

For large earthquakes with source dimensions of more than 50 km (approximately M 7+), the uncertainty of the epicenter has less influence than the uncertainty of where along the rupture plane the greatest energy release(s) was located. This information does not become available within minutes, although it would be possible by waveform inversion. Generally, the distribution of energy release along the rupture becomes available only days after the event, too late for our purposes of guiding rescuers so they have a chance to save lives. However, large and very large earthquakes ($M > 7.5$) affect so many settlements (up to 3000) that the sum total of the estimated fatalities does not depend much on the chosen point of energy release, only on the distribution among the settlements. For earthquakes with $M < 7$, the direction of rupture away from the epicenter can influence the observed fatalities strongly, depending on whether it ruptures toward or away from a population center. This is a difficulty in real-time loss estimation that could be addressed by analysis of propagation direction in real time, but it is not the subject of this study.

In this paper, we estimate the influence of the epicenter errors on loss calculations for the most frequent type of earthquake that causes severe losses: A strong earthquake ($M \approx 6.7$) in the vicinity of a medium-sized city (population $\approx$80,000). To illustrate the contrast between earthquake resistant and poorly constructed buildings, we use the Iwate–Miyagi, Japan, and the Bam, Iran, earthquakes (Table 1).

Data for Epicenters and Depths Listed in Catalogs

We selected earthquakes that are listed in the PDE of the USGS and by three national networks (Table 2) that are very dense, resulting in local errors of less than 3 km. In the Japan Meterological Agency (JMA) catalog, 60% and 90% of the epicenters have errors less than 0.1 and 0.25 s, respectively (H. Ueno, personal commun., 2010), which indicates that the epicentral location error is typically about 1 km. For Italian epicenters, Chiarabba *et al.* (2005) estimate the errors to be smaller than 1 and 2 km for 60% and 83%, respectively, for shallow earthquakes in their figure 3. After relocating epicenters with a 3D model for Taiwan (Wu *et al.*, 2008), these authors estimate that the errors are about 3 km (Y. M. Wu, personal commun., 2010).

Table 1
Source Parameters for the Two Earthquakes Used for Estimating Fatalities as a Function of Distance*

Name	Date (yyyy/mm/dd)	Hr	Longitude (°)	Latitude (°)	Depth (km)	M	Fatalities (Observed)	Fatalities (%)	Epicenter Distance to Population (km)
Iwate–Miyagi	2008/06/13	22	140.88	39.03	8	6.9	13	0.01	46
Bam	2003/12/26	1	58.35	29.10	4	6.7	26,271	32	1

*The hypocenters are from JMA and Wyss *et al.* (2006), respectively; magnitudes and fatality numbers are from the USGS significant earthquake list. The distance from the largest city is given in the last column.

Table 2
Average Differences between PDE Epicenter (and Depth) Estimates and Locations Based on Dense National Networks

Country	Region	Period	Number*	M_{min}	Epicenter Difference (km)	Standard (Epicenter; km)†	Depth Difference (km)	Standard (Depth; km)†	Source
Taiwan	All	1997–2005	216 (80)	4.5	18	11	9	9.0	IES
Japan	All	1999–2007	355 (349)	4.5	14.3	7.3	8.4	9.0	JMA
Italy	All	1997–2004	99	4.5	8	5	5	5.0	INGV

*Numbers of events used to estimate depth errors are given in parentheses (events with the default of 33 km were not used).
†Standard deviations of the averages.

Table 3
Average Differences between EMSC Epicenter (and Depth) Estimates and Local Locations in Italy

Country	Period	Number	M_{min}	Epicenter Difference (km)	Standard (Epicenter) (km)	Depth Difference (km)	Standard (Depth) (km)
Italy	1997–2004	82	4	13	8	14	15

We implemented three restrictions: The event must be located within the local network, beneath land, and shallower than 50 km.

Differences for the EMSC data could only be calculated for Italy (Table 3) because the rest of the world is inadequately covered by this dataset. The periods of data used in all sets were limited by the availability of local data.

Data for Real-Time Epicenters

We used the real-time, reviewed source parameters that become available within 15 to 30 min for estimating losses. These parameters are later revised by the USGS, as more data become available, so an improved location is finally listed in the PDE. Because we are interested in errors in real time, we must consider this difference. Table 4 lists the differences between reviewed epicenters and depths supplied by the USGS in real time and the parameters by the JMA for those 30 earthquakes for which we have calculated losses in real time in Japan.

In addition, we have computed the differences between real-time USGS locations and those given in the PDE for all events throughout the world for which we have issued real-time loss estimates. The period covered is November 2003 through November 2009. This set of 460 events includes all great earthquakes ($M > 8$) that occurred during these years; 90% of the events in the data set have magnitudes larger than six. These events covered all of the strongly seismogenic regions of the world and are thus a good sample

Table 4
Differences in Epicenters and Depths for Earthquakes in Japan between the USGS (Real-Time and PDE) and the JMA Locations*

	JMA			USGS	GSreal-JMA	PDE-JMA	GSreal-PDE	GSreal-JMA	GSreal-PDE
Date (yyyy/mm/dd)	Longitude (°)	Latitude (°)	Depth (km)	M	Epicenter Diff (km)	Epicenter Diff (km)	Epicenter Corr (km)	Depth Diff (km)	Depth Corr (km)
2003/05/26	141.65	38.82	72	7.0	19	9	9	19	−15
2003/07/25	141.17	38.4	12	6.1	19	19	2	−3	9
2003/09/25	144.08	41.78	45	8.3	34	19	16	12	6
2003/09/25	143.7	41.71	21	7	24	14	10	−12	0
2003/11/12	137.06	33.17	398	6.4	48	1	48	7	7
2003/12/29	144.76	42.42	39	5.6	26	16	20	29	−23
2004/03/26	144.37	41.76	37	5.5	35	21	14	−2	17
2004/04/11	144.99	42.83	47	6.1	21	19	2	7	−1
2004/09/05	136.8	33.03	38	7.2	52	20	51	18	6
2004/09/05	137.14	33.14	44	7.1	11	9	5	34	0
2004/09/06	137.29	33.21	41	6.3	9	7	5	16	15
2004/10/23	138.87	37.29	13	6.6	12	12	5	−3	0
2004/11/11	144.49	42.08	39	6.1	37	18	29	19	−12
2004/11/28	145.28	42.95	48	7	22	19	3	4	5
2004/12/06	145.34	42.85	46	6.8	16	13	3	10	1
2004/12/21	145.51	42.93	45	5.6	11	11	4	11	−3
2005/02/26	142.6	40.69	45	6.1	148	25	140	12	−35
2005/03/20	130.18	33.74	9	6.6	25	9	17	−1	0
2005/04/10	140.62	35.73	52	6	34	28	8	15	−6
2005/06/19	140.69	35.73	51	6.1	30	27	3	2	1
2005/08/16	142.28	38.15	42	7.2	35	30	6	−11	17
2005/10/19	141.04	36.38	48	6.3	21	22	2	4	12
2005/11/14	144.94	38.03	45	7.0	18	10	9	21	13
2006/06/11	131.44	33.14	145	6.3	33	32	18	−10	15
2007/01/15	138.89	34.94	175	5.9	25	28	3	12	−7
2007/02/17	143.72	41.73	40	6.0	35	20	16	5	4
2007/03/25	136.69	37.22	11	6.7	45	17	28	−22	25
2007/07/16	138.61	37.56	17	6.6	25	18	9	−32	37
2007/07/16	135.1	36.87	374	6.8	29	28	3	58	−34
2008/06/13	140.88	39.03	8	6.9	31	24	8	−2	0

*GSreal, Geological Survey real time; Diff, difference; Corr, corrected for estimating the improvements found in the PDE compared with the original real-time locations. The improvement is on average 12 km and in the median 9 km.

Data for Building Properties

The built environment is modeled in the database of QLARM by distributing buildings and population into vulnerability classes (A to E) of the European Macroseismic Scale (EMS; Gruenthal, 1998) differently for three classes of city size (Trendafiloski *et al.*, 2011). For a medium-sized city in Iran, such as Bam, the building type distributions (Fig. 1a) are constructed using the PAGER database (Jaiswal and Wald, 2008). The collapse rates (Fig. 1b) we use for Bam are those for southern Asia provided by the World Housing Encyclopedia (see the Data and Resources section). The damage and number of casualties at Bam have been reported by Kuwata *et al.* (2005).

The model for cities in the vicinity of the Iwate–Miyagi earthquake (Fig. 2a) does not contain buildings of the two weakest classes, A and B, which dominate in Bam. We use this type of distribution of buildings and people, as well as the collapse rate (Fig. 2b) for cities larger than 20,000 in Japan (World Housing Encyclopedia, see the Data and Resources; Porter *et al.*, 2008).

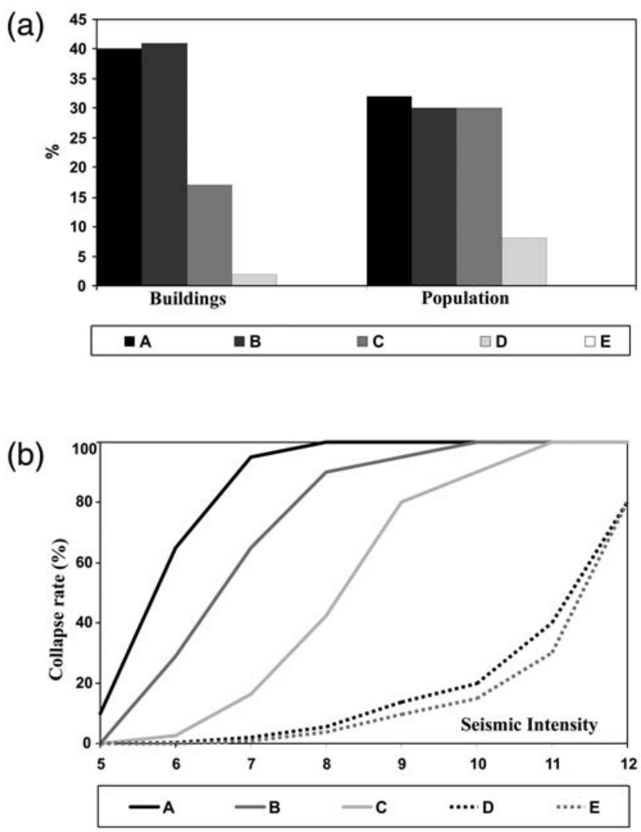


Figure 1. (a) Bam building and population distributions into vulnerability classes, with A the weakest in resisting ground shaking. (b) Collapse rates for Bam for the vulnerability classes, as a function of intensity EMS.

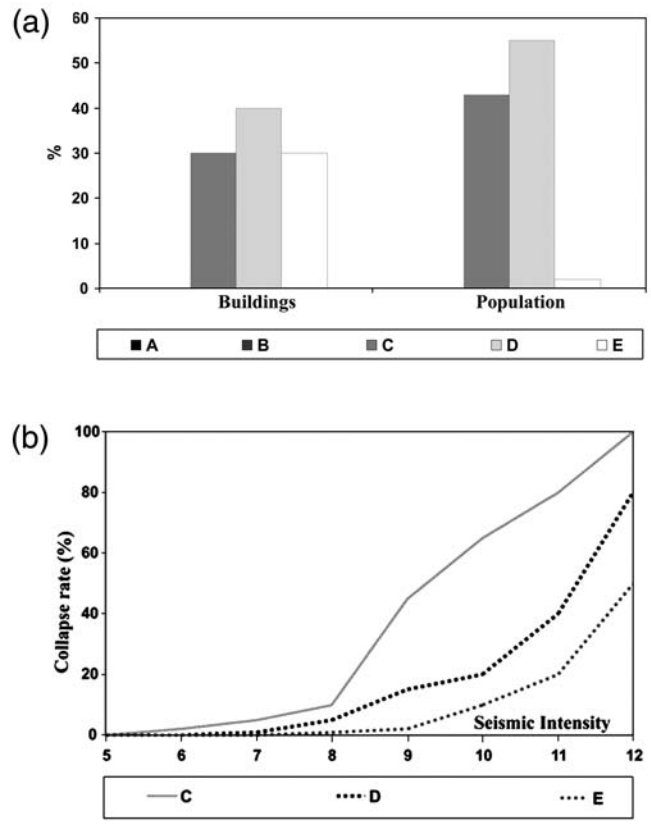


Figure 2. (a) Japan building and population distributions into vulnerability classes, with A the weakest in resisting ground shaking. (b) Collapse rates for settlements with more than 20,000 inhabitants in Japan for the three vulnerability classes, as a function of intensity.

Method

The locations of earthquakes are not accurately known, so we have to use the best estimates available. The epicenters determined by the dense local seismograph networks of Japan, Taiwan, and Italy have errors that do not exceed 1 to 3 km (Chiarabba *et al.*, 2005; H. Ueno, personal commun., 2010; Y. M. Wu, personal commun., 2010). In this paper, we take the locally estimated origin to be the preferred location. Consequently, we can take the difference, DELT(epi), between local epicenter positions [EPI(loc)] and the teleseismic estimate [EPI(tel)] as our estimate of the error of ERR(tel). The teleseismic uncertainties are about an order of magnitude larger than those from dense local networks. We keep in mind that this is not quite correct, because in this way we assign zero error to the EPI(loc).

$$\mathrm{ERR(tel)} \approx \mathrm{DELT(epi)} = \mathrm{EPI(tel)} - \mathrm{EPI(loc)}. \quad (1)$$

Estimating the differences in losses as a function of epicenter errors, we have generated curves of fatalities expected as a function of distance to major cities for $M \approx 6.7$ earthquakes, using our loss estimating tool, QLARM (Trendafiloski *et al.*, 2009; Trendafiloski *et al.*, 2011). In this tool, we have calibrated the estimates of fatalities in the two countries considered here, by evaluating each of the parameters other than hypocenter and magnitude that affect this calculation. The parameters considered in the calibration are: wave attenuation, classification of buildings into vulnerability classes, distribution of people into vulnerability classes, collapse rates by vulnerability class, and the casualty matrix (Trendafiloski *et al.*, 2008). As a result, the numbers of fatalities calculated for both cases approximate the observed numbers when we use the best estimates of the hypocenters and magnitudes. We assume that the theoretically calculated numbers of fatalities approximate the numbers that would have been observed, if the earthquake had taken place at that distance from the settlement.

The attenuation relationship of intensity with distance we used (Shebalin, 1968) with standard parameters has given correct estimates of observed intensities in several earthquakes in both countries of the earthquakes studied and was therefore not changed. For our purpose of estimating the order of magnitude of errors in fatality estimates, it is appropriate to use an average attenuation function and to assume that soil conditions throughout the settlements near the earthquake vary and cancel on average in calculating the sum of all losses. Transmission properties in different parts of the world and for specific earthquake-settlement combinations can modify the results we present here.

For city types, we have used two examples: one with predominantly structurally weak buildings and one with earthquake-resistant buildings. This was done to illustrate the difference in consequences depending on the properties of the built environment. Using as an approximate measure of resistance to shaking of buildings the ratio of injured to fatalities, we have found that Japan has worldwide one of the best built environments and rural Iran one of the worst (Wyss and Trendafiloski, 2011).

Loss Estimates as a Function of Location Uncertainties

The average difference between PDE and Japanese/Taiwanese epicenters is 16 km. The average differences for Italy are 13 and 8 km by the EMSC and USGS, respectively. The median and average differences between the real-time, teleseismic USGS and the JMA hypocenters for the 30 earthquakes listed in Table 4 are 26 and 31 km, respectively (Table 5). The changes in the median and average, resulting from revision of the hypocenter estimate by the USGS going from GS real-time solutions to PDE results are 8 and 17 km, respectively.

As a function of time, we cannot detect significant changes in the location accuracy (Fig. 3). The standard deviations of the means are much larger than the fluctuations observed. This suggests that the available worldwide seismograph network has not improved with time.

Depth errors are not the main topic of this paper, but they are listed in Tables 1 through 3 and averaged in Table 5. The PDE shows an average absolute depth difference from local data in Japan/Taiwan of 9 km. In Italy, the depth differences are 14 and 5 km for the EMSC and PDE data, respectively. The median and average differences of the depth given in real time in reviewed locations for Japan by the USGS compared with the JMA data are 12 and 14 km, respectively. We give the median values in order to reduce the influence of outliers.

Influence of Epicenter Errors on Fatality Estimates in Real Time

We use two medium-sized earthquakes to illustrate how epicenter errors can influence fatality estimates in real time. In the case of the earthquake in 2003, Bam–Baravat with 78,000 inhabitants is the only large city in the area and located above the major energy release (Fig. 4a). The calculated decrease of fatalities as a function of distance is unperturbed by the presence of other population centers. An analysis of InSAR images eventually furnished an unusually accurate location of the energy release (Wyss *et al.*, 2006), whereas near real-time estimates placed the epicenter at about 20 km from the city (Fig. 4a).

In the case of the Iwate–Miyagi earthquake, the accurate calculation by the JMA placed the earthquake into the uninhabited mountains, far from Yokote, with 92,000 inhabitants, the major population center in the area. Teleseismic real-time locations furnished epicenter estimates approximately 20 km closer to Yokote (Fig. 4b).

To illustrate the influence of epicenter position on loss estimates, we calculated fatalities for hypothetical positions of epicenters in a straight line from beneath the center of Yokote (worst case) to the epicenter reported by the JMA (most favorable case). The contribution of Yokote to the fatality count dominates contributions from smaller settlements such as Yuzawa (Fig. 5b). For the Bam case the

Table 5
Median and Average Epicenter and Depth Differences between Real-Time USGS and Final JMA Solutions for the 30 Earthquakes in Table 4

	Real-Time Epicenter Difference (km)			Real-Time Depth Difference (km)		
	GSreal-JMA	GSreal-PDE	PDE-JMA	GSreal-JMA	GSreal-PDE	PDE-JMA
Median	26	8	18	12	7	9
Average	31	17	18	14	11	12

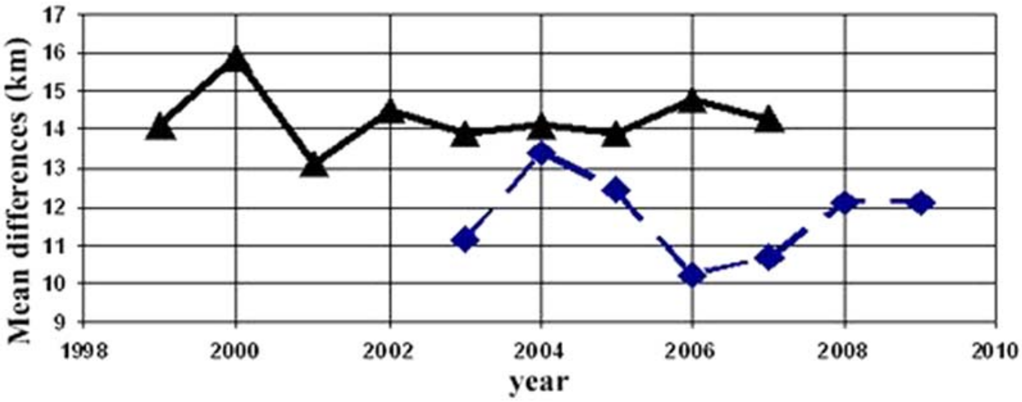


Figure 3. Annual mean of the difference between PDE and local JMA epicenter positions for 356 events (solid) and the difference between real-time USGS and the PDE locations for 490 events (dashed). The color version of this figure is available only in the electronic edition.

expected fatalities were calculated as a function of distance of the hypothetical epicenter from the center of Bam to the southwest (Fig. 5a).

The contrast between earthquake consequences in developing and industrialized countries is clearer when we use the same earthquake parameters and population numbers for both cases and eliminate the influence of settlements scattered in the area (Fig. 6). The size of the population center and the magnitude is the same as that in the Bam case.

The error in the estimate of fatalities can be read from Figure 6 as a function of an assumed error in epicenter location, with the hypocentral depth as a parameter. If the true epicenter is at zero distance from the settlement, then the correct number of fatalities is given on the ordinate at a distance equal to zero. The incorrect estimate resulting with epicenter errors that may be selected on the abscissa can then be read from the curves. The difference between the correct and incorrect fatality estimate is the error of the fatality estimate in real time. Suppose the true location is at a distance of 20 km from the settlement, then the correct number of fatalities can be read from the curves at a distance 20 km. If the teleseismic location is afflicted by an error of 20 km in the direction of the line connecting the true epicenter location and the center of the settlement, then the resulting incorrect fatality estimate can be read from the curves in Figure 6 at zero distance and at 40 km distance, respectively. The differences between these latter readings and the reading at the true distance are then the possible errors in fatality estimates.

The difference in resulting losses in the developing and the industrialized world is dramatic, as the comparison of Figure 6a with 6b shows. Establishing more stringent building codes and enforcing them could make a great deal of difference in protecting the population in developing countries.

Discussion of Teleseismic Epicenter Uncertainties

We found that the typical epicenter error in the teleseismic earthquake catalogs of the PDE is approximately 16 km for Japan/Taiwan (Table 2). We assume that the difference between teleseismic and local locations equals the error of the teleseismic estimates. For Italy, we found the average epicenter error of the PDE and EMSC catalogs to be approximately 8 and 13 km, respectively (Table 3).

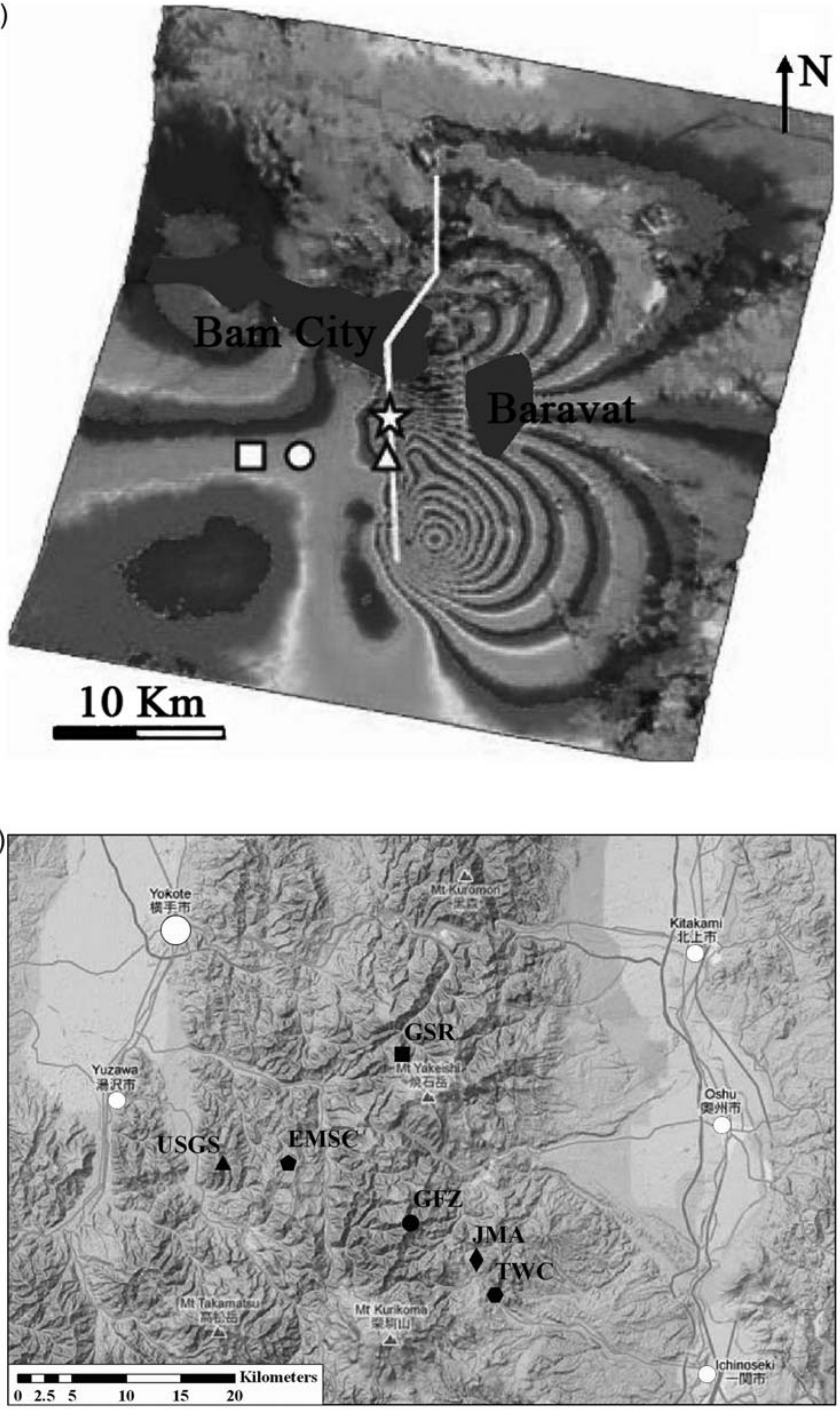
The average difference between real-time and the JMA locations is 31 km, and the average difference between those of the PDE and the JMA are 18 km for events on land in Japan (Table 5). Although the differences in Italy are smaller, we cannot avoid the conclusion that errors of real-time locations by the USGS are in the range of 20 to 30 km, even though they are the best available for the parts of the world where local real-time solutions are not distributed.

Uncertainties in depth have not been analyzed in detail because accurate teleseismic depths cannot be calculated for shallow earthquakes in real time without employing signal analysis. A large portion of the solutions have a default depth value of 10 or 33 km. Given that these depths are artificial, we use expert opinion for depths in loss estimates in real time. Most of these ad hoc depths are approximately correct, but in the case of Bam we assumed 20 km in real time, the typical value for Iranian quakes. The observation that the uncertainties in real-time estimates of depths are only about 13 km (GSreal-JMA in Table 5) is encouraging.

Discussion of Uncertainties in Fatality Estimates due to Epicenter Errors

The agreement of the calculated numbers of fatalities we present here with the observed ones is acceptable for rescue teams that need to know whether or not to mobilize. In the case of Bam, we underestimate the fatalities by about a factor of 2, and in Iwate–Miyagi our estimate is 11 fatalities fewer than reported (squares in Fig. 5). Thus, we are confident that we can expect the theoretically calculated numbers of fatalities to be correct within less than a factor of 5 in most cases where we have accurate information on the location and magnitude. For example, the observed fatalities in the L'Aquila, Italy, M 6.3 (2009) and the Wenchuan, China, M 8.0 (2008) earthquakes were within the bounds of

(a)



(b)

Figure 4. Epicenter maps of the two earthquakes analyzed in detail. (a) In the case of the Bam 2003 earthquake, the preferred location of energy release (star) was derived from a fault model based on InSAR (figure from Wyss *et al.*, 2006) and is compared with USGS locations that were distributed within 1.33 (automatic), 1.5 (manual), and 11 (revised) hours marked by a circle, square, and triangle, respectively. (b) In the case of the Iwate–Miyagi 2008 earthquake, the preferred location is that given by JMA (diamond). The epicenter estimates by GFZ and the Tsunami Warning Center were the first to become available (after 8 min) and are good approximations of the JMA solution. All other teleseismic solutions have errors of 20 km and more, including that by the Geophysical Survey of the Russian Academy of Sciences. The city of Yokote is the major population center for which we calculated losses in Figure 6.

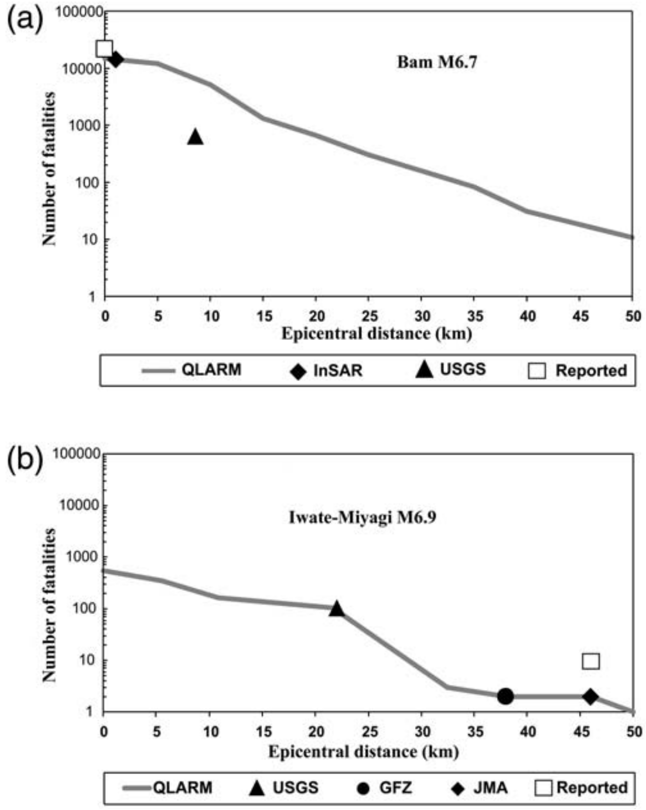


Figure 5. Estimated fatalities as a function of the epicenter distance away from a population center, (a) for the case of the Bam, and (b) of the Iwate–Miyagi earthquake (Table 1). The origin of the plot is placed beneath the largest cities in each area, as the worst case that could be assumed in real time, given the USGS epicenter and its average error. The estimates based on USGS and GFZ real-time source parameters are marked by triangles and a circle, respectively. The locations based on JMA and the InSAR method (Wyss *et al.*, 2006) are the most accurate ones available, in the respective cases, and shown as diamonds. Given the average error of USGS real-time epicenter estimates (approximately 30 km), the results that need to be considered in real time cover more than the entire plot (b) and out to 40 km distance in plot (a). Reported numbers of fatalities are shown by the squares.

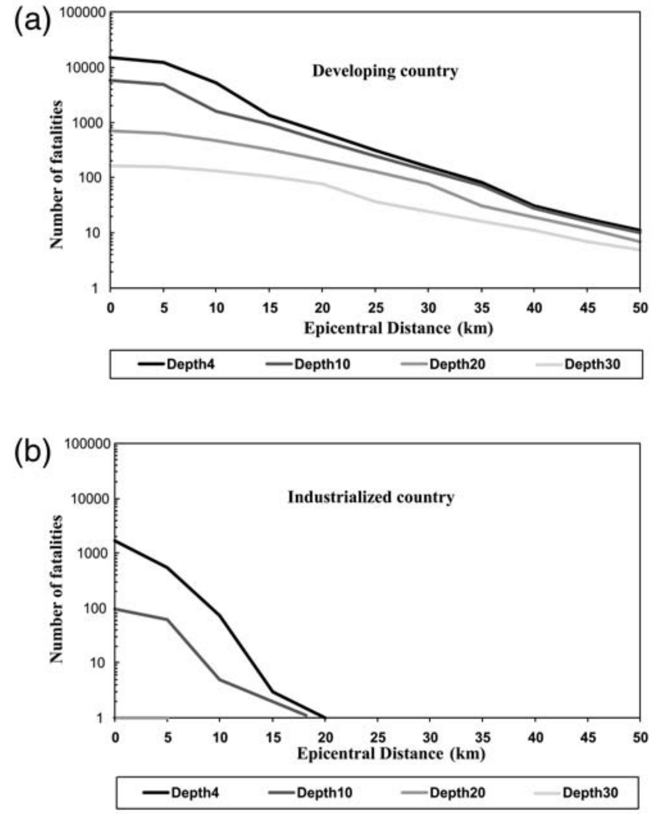


Figure 6. Calculated number of fatalities in the case of an *M* 6.7 earthquake, as a function of distance from a city of 78,000 inhabitants; (a) for building stock in a developing country (Fig. 1), (b) for building stock in an industrialized country (Fig. 2). Hypocentral depth is used as a parameter.

WAPMERR's real-time estimates (see the Data and Resources section). However, WAPMERR underestimated the fatalities in the Haiti earthquake, *M* 7.2 (2010) by a factor of 10, because the poor quality of the building stock had not been known well before this event.

The estimated numbers of fatalities decrease rapidly to very rapidly with the distance of shallow earthquakes from a major population center, although this is not immediately evident from Figures 5 and 6 because a semilogarithmic scale is used. For very shallow earthquakes in the industrialized world, decreases of 1 and 2 orders of magnitude are calculated at approximately 7 and 15 km (Fig. 6b). For the developing world a decrease by an order of magnitude is estimated at about 15 to 20 km for very shallow sources. For earthquakes in the lower crust, an order of magnitude reduction of fatalities is expected in the range of 35 to 45 km (Fig. 6b) for the developing world. In the industrialized world, no fatalities are expected, due to sources of *M* 6.7 in the lower crust.

The difference in the percentage of the population killed in the same size earthquake at the same depth and distance in developing and industrialized countries ranges from one to three orders of magnitude (Fig. 6). A way to characterize this difference is to say that the percentage of the population that is likely to be killed in developing countries is two orders of magnitude larger than in industrialized countries.

The influence of the 25 to 30 km uncertainty in real-time estimates on the fatalities is large. In order to appreciate the situation in real time, one has to consider the points marked by the solid triangles in Figure 5a,b. The real-time, reviewed location by the USGS placed the earthquake source at the respective distances from the population centers. Visualizing an error bar of 30 km in either direction from the triangles shows that the entire range is covered in Figure 5b, admitting fatality estimates of 0 to 500. In the case of Bam, the range of possible fatalities is from about 50 to 20,000.

In the worst predicted case scenario, the percentage of fatalities among the population in Bam was about 30%, which was also the real case. For Iwate–Miyagi we estimate that the worst case might have caused about 0.5% fatalities.

At 15 km distance from the epicenter, a more likely case in general, the expected fatality rate is about 1.3% in a case such as Bam; in Japan we estimate it as less than 0.002% for very shallow earthquakes.

The problem of large errors due to epicenter uncertainties applies only to medium magnitude earthquakes (approximately $6 < M < 7$) that occur near population centers. In the daily task to estimate human losses in real time for all populated areas of the globe, approximately 95% of the cases that require an estimate generate zero or negligibly few fatalities. This fact applies to the events listed in Table 4. Therefore, the errors in fatality estimates cannot be derived from these events, only the errors in location. How location errors map into errors in fatality estimates can only be calculated theoretically as done in Figures 5 and 6.

Conclusions

We found an average difference of 16 km between PDE teleseismic epicenters and those by the local networks for Japan/Taiwan. In Italy, the difference is 8 km. For EMSC epicenters, we found an average difference of 13 km from the local Italian epicenter. We assume that these numbers equal approximately the teleseismic errors because the local errors are an order of magnitude smaller. The average difference between real-time parameters and those listed in the PDE is 12 km (median 9 km) for 30 earthquakes in Japan. Comparisons of real-time USGS epicenters and JMA locations yield an average difference of 31 km (median 26 km). We conclude that the mean errors in real-time epicenter solutions are in the range of 25 to 35 km.

This result implies that for earthquakes of $M \approx 6.7$ in the vicinity of a medium-sized city (80,000), the fatality estimates in real time may have to range from near 0 to 10,000 in the developing world and from 0 to 500 in an industrialized country, in the worst case. These findings were verified by comparison with observed numbers of fatalities in the cases of the 2003 *M* 6.7 Bam and the 2008 *M* 6.9 Iwate–Miyagi earthquakes. By considering additional information on epicenter and magnitude from GeoForschungsZentrum (GFZ) and EMSC, and using expert judgment on depth and likely location of the epicenter, we have been able to keep the error in fatality estimates to a factor of 2 in many of the difficult cases. In 74 out of 77 potentially critical earthquakes that occurred over the years of our service, we have been able to classify the event correctly as a disastrous (more than 400 fatalities) or inconsequential event, as required by our sponsors. If we could receive direct source parameters in real time from countries with high quality seismograph networks, the error in fatality estimates could be reduced by one to two orders of magnitude.

Data and Resources

The epicenter determinations from local networks were obtained from the Italian earthquake catalog at http://emidius.mi.ingv.it/CPTI/home.html (last accessed December 2009); the Japanese earthquake catalog, JMA epicenters, at http://www.jma.go.jp/en/quake/ (last accessed December 2009); and the Taiwanese earthquake catalog at http://tecdc.earth.sinica.edu.tw/index3.html (last accessed December 2009). The epicenter estimates revised by the USGS were obtained from http://earthquake.usgs.gov/earthquakes/eqarchives/epic/ (last accessed December 2009). Distribution times of epicenter estimates can be found at http://www.seismo2009.ethz.ch/redpuma/redpuma_ami_list.html (last accessed December 2009). Estimated losses over the last seven years after strong earthquakes worldwide in real time were provided by the World Agency for Planetary Monitoring and Earthquake Risk Reduction (http://www.wapmerr.org/, last accessed November 2009). Collapse rates for Bam were provided by the World Housing Encyclopedia (www.world-housing.net, last accessed November 2009). Real-time epicenter estimates were obtained from the e-mail messages distributed by the agencies that generate the information.

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