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Improving Earthquake Loss Estimates by Interferometric Synthetic Aperture Radar

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The usefulness for rescue teams of near-real-time loss estimates after major earthquakes is advancing rapidly. The difference in the quality of data available in highly developed compared to developing countries dictates that different approaches be used to maximize mitigation efforts. In developed countries, extensive information from tax and insurance records, together with accurate census figures, furnish detailed data on the fragility of buildings and on the number of people at risk. For example, these data are exploited by the method to estimate losses used in the Hazards U.S. Multi-Hazard (HAZUS-MH) software program (http://www.fema.gov/plan/prevent/hazus/). However, in developing countries, the population at risk is estimated from inferior data sources and the fragility of the building stock is often derived empirically, using past disastrous earthquakes for calibration [*Wyss,* 2004].

Real-time estimates of damage to buildings are based on calculating the acceleration of ground motion in settlements near a reported earthquake and depend critically on accurate knowledge of hypocenter and magnitude. The uncertainties of hypocenters are near one kilometer in California and Japan (where dense networks of seismometers are in place) but 15 kilometers for earthquakes in most parts of the world. This uncertainty leads to the problem of unstable loss estimates in real time for earthquakes in developing countries.

This article shows that hypocenter locations based on modeling surface deformations derived by interferometric synthetic aperture radar (InSAR) are in excess of an order of magnitude more accurate than those based on records of the loose network of worldwide seismographs, the teleseismic hypocenter, and therefore lead to more than an order of magnitude more precise loss estimates. This is demonstrated here by a case study of the M 6.6 earthquake of 26 December 2003 beneath Bam, Iran. After this earthquake, real-time estimates of losses were unstable, ranging from 20 to 17,000 fatalities, because they were based on the teleseismic hypocenter . However, with InSAR, the origin of the radiated energy can be pinpointed to within a few hundred meters. In favorable cases, when a radar satellite happens to pass over the epicentral area shortly after the earthquake, it may be possible to shorten to a few hours the process of taking a radar image, constructing an interferogram, designing a source model, and estimating the losses accurately.

Data and Methods

The most precise locations for earthquakes in developing countries are issued by the U.S. Geological Survey (USGS). Their manually reviewed solutions for magnitude and location become available within about 20 minutes, and the solution for focal mechanism usually is distributed within about two hours after the event. The database on population and building stock, used by us in our computer tool (QUAKELOSS) to estimate losses, has been compiled and calibrated over the years [*Shakhramanjyan et al.*, 2001], and the reliability of the newest version of our loss estimating method has been independently verified [*Wyss,* 2004].

The steps in calculating losses are the following. (1) Calculate the shaking intensities resulting from an earthquake. (2) Estimate the probable degree of damage to the local building stock. (3) Estimate the effect of damaged and collapsing buildings on the occupants. In developing countries, real-time loss estimates focus on the number of casualties, because emphasis is on rescuing the injured, which are proportional in number to the fatalities.

To derive the surface deformations that result from an earthquake, three InSAR images of the area are necessary. The first pair is used to calculate the exact topography for the area in question. As soon as a significant earthquake happens, one can derive the detailed topography of the stricken area from images existing in the database of satellite images. Then, one needs to wait until a post-earthquake InSAR image becomes available, in order to construct an interferogram from which the surface deformation can be deduced. In the case of Bam, images from ascending (to the north) as well as descending (to the south) satellite paths were available. From these images, the topography of the surface deformation can be mapped in units of the radar wavelength. Finally, a rupture model can be constructed, which matches the observed surface deformation.

Coseismic surface deformations provide strong constraints on parameters of the earthquake source. After initial research indicated that coseismic surface deformation can be mapped in detail by SAR interferometry [e.g., *Massonnet et al.*, 1993], the method has been refined to yield the precise positioning of the ruptured area, as well as the slip distribution on it [e.g., *Pedersen et al.*, 2003; *Wang et al.*, 2004; *Wright et al.*, 1999]. The modeling procedure includes three steps. (1) On the basis of the principle that the horizontal gradient of the deformation should take its maximum near and along the ruptured segment, a high-pass filter is applied to the deformation data, in order to identify the position and orientation of the fault. (2) The dip angle of the rupture plane can be estimated by a number of forward modeling runs, using a simplified homogeneous slip model. (3) The inhomogeneous slip distribution on the rupture plane is then inverted by least squares fitting to the InSAR data.

However, the least squares fitting method may generate unrealistic oscillations. *Wang et al.* [2004] proposed an efficient algorithm, which avoids these artificial effects. The new algorithm is faster and always provides a stable inversion result for the slip distribution, so that there can be a reduction in the time delay to distribute a reliable loss estimate.

Results for the 2003 Bam Earthquake

The differential InSAR interferograms for the Bam area were obtained by images of descending passes on 11 June 2003, 3 December 2003, and 7 January 2004, and by images of ascending passes on 16 November 2003, 25 January 2004, and 29 February 2004. The interferogram obtained from the descending passes shows excellent quality and covers the complete epicentral area (Figure 1). The maximum slip was calculated for a depth of four kilometers at the location marked by the star in Figure 1 [*Wang et al.*, 2004]. The seismic moment of the model source equaled a moment magnitude of M_w 6.5. The estimated losses, based on these parameters, are compared in Table 1 (case 5) with estimates calculated in real time and with estimates derived from assumed errors in source parameters.

Several estimates of the number of fatalities, which were based on the QUAKELOSS system, were distributed by e-mail in near-real-time to the community of users (Table 1). The first estimate (Table 1, case 1) was based on the automatic location derived by the USGS, which contained a body wave magnitude, m_b. In this estimate, the depth published by the USGS was replaced by an expert depth estimate of 20 kilometers. This resulted in a maximum number of fatalities, F_{max}, of 85. About 10 minutes later, a second estimate of F_{max} = 1000 was distributed, using a refined value for the epicenter and the surface wave magnitude, M_s, contained in the USGS reviewed location, which followed the automatic one (Table 1, case 2).

The instability of the loss estimate for Bam at first was not recognized in real time. A third alert distributed 9.6 hours after the earthquake, which considered error limits of the USGS hypocenter, yielded a result of a maximum of 3000 fatalities (Table 1, case 3). After that message had been distributed, a revised USGS location became available, which yielded approximately the same result (Table 1, case 4).

Still, on 26 December 2003, additional loss estimates were calculated to explore the possible range of uncertainties (Table 1, cases 6 and 7). The depth used in these calculations varied from 20 to 5 kilometers, the largest and smallest depths believed to be possible in the Bam region. The magnitudes varied from the smallest USGS estimate minus 0.2 units, to the largest USGS estimate plus 0.2 units. In this exercise, the maximum estimate reached 16,720 fatalities. The resulting minimum and maximum values are given as cases 6 and 7 in Table 1. Using the InSAR location and depth, and M_s 6.7, the maximum number of fatalities is estimated at 12,700 (Table 1, case 5).

Advantages of InSAR Input for Loss Estimates

Although the real-time loss estimate after the Bam earthquake was not satisfactory from a scientific point of view, it was satisfactory from a practical point of view. On the basis of the estimate of 1000 fatalities 1.5 hours after the event, the Swiss Humanitarian Aid rescue team decided to mobilize.

InSAR, with its highly accurate models of the rupture plane, offers a solution to the problem of unstable loss estimate, if images become available rapidly. This substantial improvement over the best teleseismic solutions is especially important for the depth estimates because an energy release at 20 to 40 kilometer depth is much less harmful than an energy release at four kilometers. However, the delay of weeks with which the earthquake model based on InSAR becomes available is too long for it to be useful in the decision-making process of rescuers and disaster managers. They need quantitative information on losses during the first day or days when no information flows from the epicentral area.

Photographs of the damage taken from satellites (Figure 2) also may be used to assess the losses, if the images become available rapidly. The advantage of photographs is that the damage to buildings is directly visible by inspection; it does not have to be calculated. Advantages of InSAR images are that they can be obtained at night and in spite of cloud cover. However, obstacles for successful radar interferometry are heavy vegetation and rugged topography, which are elements that prevent coherence. Thus, InSAR modeling does not solve the problem of unstable loss estimate in all cases.

However, the authors of this article propose the following.

1. Under the most favorable conditions (when a satellite pass, yielding a coherent interferogram, occurs within a few hours) it is possible to contribute to a highly accurate loss estimate by InSAR in near-real-time. The M_w 8.0 earthquake near Antofagasta, Chile, on 30 July 1995 was such a case. A radar image of the epicentral area became available from the radar satellite EOS 2 within one hour of the earthquake's occurrence [*Reigber et al.*, 1997].

2. The recently introduced method [*Wang et al.*, 2004] to rapidly find an adequate source model that fits the observed surface deformation usefully contributes to keeping the delay to a minimum.

3. It is important to establish routines that allow for a rapid distribution of radar images after a critical pass, and that allow for similar rapid distribution from the archives. Satellite operators should be alerted to point satellites that may be in the vicinity of disasters to the area affected. Such a procedure is in place for satellite photographs by UNOSAT (http://unosat.web.cern.ch/unosat/).

4. Given the fact that more satellites will be in orbit in the future, it is realistic to work toward the goal of reducing the delay of InSAR-based earthquake models to the point where they can be made in near-real-time.

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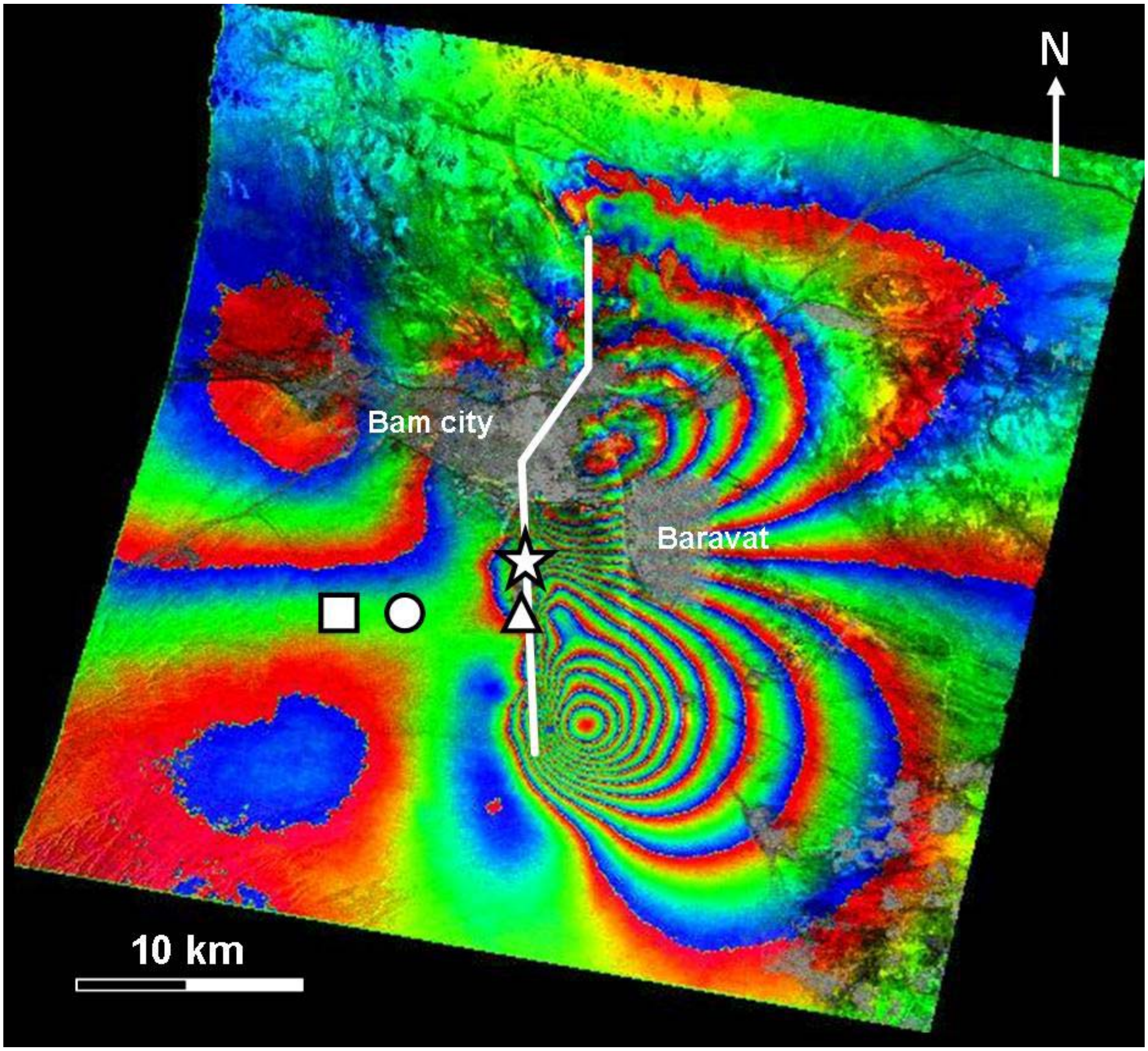

Fig. 1. Map of the fault model (solid white line) based on InSAR interferometry for the Bam, Iran, earthquake of 26 December 2003. The colored fringes map the deformation of the surface of the Earth in the direction of the view from the satellite in units of the radar wavelength (2.8 centimeters) from red to red. The star denotes the center of maximum slip derived by InSAR, and the circle, square, and triangle mark USGS epicenters 1, 2, and 4, respectively (Table 1).

Fig. 2. Quickbird image of a section of Bam, (right) before and (left) after the 26 December 2003 earthquake. Now discernible damage is seen at the power relay station (lower left) and to some houses at the center, but the collapse of most buildings is evident. These images were not available for loss estimates and rescue planning during the days after the earthquake.

Table 1. Range of Fatalities Estimated for Bam, Iran (observed 23,000), and Delay Times

Case	Source	Latitude (deg)	Longitude (deg)	Depth (km)	Magnitude (M_s)	Fatalities		Delay (hours)
						Min	Max	
1	USGS A	29.1	58.3	20 (33)^a	6.2^b	26	85	1.33
2	USGS M	29.10	58.27	20 (33)^a	6.7	410	1,000	1.5
3	Error limit	29.10	58.35	10	6.7	1,500	3,000	9.6
4	USGS M	29.10	58.35	(10)^a	6.7	1,500	3,590	11
5	InSAR	29.10	58.35	4	6.7	6,570	12,700	this paper
6	Minimum	29.26	58.25	20	6.0	2	11	26 Dec P.M.
7	Maximum	29.10	58.35	5	6.9	8,910	16,720	26 Dec P.M.

[a] Depths in parentheses are USGS values, and depths used are bold.

[b] m_b; A = automatic location, M = manual; F final hypocenter listed in significant earthquakes.

References

Massonnet, D., et al. (1993), The displacement field of the Landers earthquake mapped by radar interferometry, *Nature*, *364*, 138–142.

Pedersen, R., et al. (2003), Fault slip distribution of two June 2000 M_w 6.5 earthquakes in South Iceland estimated from joint inversion of InSAR and GPS measurements, *Earth Planet. Sci. Lett.*, *213*, 487–502.

Reigber, C., et al. (1997), The Antofagasta 1995 earthquake: Crustal deformation pattern as observed by GPS and D-INSAR, paper presented at the Third ERS Symposium on Space at the Service of our Environment, Eur. Space Agency, Florence, Italy, 17–21 March.

Shakhramanjyan, M. A., et al. (2001), Advanced procedures for risk assessment and management in Russia, *Int. J. Risk Assess. Manage., 2,* 303–318.

Wang, R., et al. (2004), The 2003 Bam (SE Iran) earthquake: Precise source parameters from satellite radar interferometry, *Geophys. J. Int., 159,* 917–922.

Wright, T. J., et al. (1999), Source parameters of the 1 October 1995 Dinar (Turkey) earthquake from SAR interferometry and seismic bodywave modelling, *Eath Planet. Sci. Lett., 172,* 23–37.

Wyss, M. (2004), Real-time prediction of earthquake casualties, in *Disasters and Society—From Hazard Assessment to Risk Reduction,* edited by D. Malzahn and T. Plapp, pp. 165–173, Logos, Berlin.