Reality Check: Seismic Hazard Models You Can Trust

One is well advised, when traveling to a new territory, to take a good map and then to check the map with the actual territory during the journey.
Wasserburg *[2010]*

City planning boards, real estate investors, and average citizens naturally desire information that can help them decide where to live, build, and spend their money. Scientists are skilled in building models that use data from past events to predict the likelihood of similar events in the future. Thus, earthquake hazard maps based on models and observations are an appealing tool for risk evaluation, investment decisions, and emergency response preparation.

However, before earthquake hazard maps can be used for practical risk estimation, they must be based on sound Earth sciences. This includes rigorous testing against the available real seismic data to avoid the geophysical equivalent of medical malpractice. Overreliance on untested seismic hazard maps can cause a failure to predict risk levels accurately. Underpredicting earthquake risks can lead to fatalities and significant economic losses [*Wyss et al.*, 2012]. Overpredicting risks can drive investment in expensive and excessive safety measures.

We assert that current probabilistic methods to quantify earthquake hazards have serious problems. These methods rely on uncertain probabilistic assessments; overreliance on these methods can lead to significant confusion about what earthquake hazards actually may be. Instead, a deterministic approach may help us to achieve reliable hazard assessments by realistic and physically sound modeling of specific scenarios.

The Problem with Probabilistic Methods

Probabilistic methods of estimating earthquake hazard (the one by *Cornell* [1968] and its reappraisals) are not based on physically sound models and have some fundamental flaws [*Castaños and Lomnitz*, 2002; *Cyranoski*, 2011]. In particular, the dimensionless probability of exceedance (the probability that a given level of ground shaking will be exceeded in a given period of time) is erroneously equated to the dimensional rate of occurrence (the number of events per given period of time [*Wang*, 2011]), making problematic even the math of probabilistic seismic hazard analysis (PSHA).

Disastrous earthquakes are low-probability events locally; however, in any of the earthquake-prone areas worldwide they reoccur with 100% probability sooner or later. Very uncertain and long times between events and/or low probabilities—which provide the basis to downgrade the expected ground shaking—can and do lead to community officials systematically neglecting the most dangerous hazard. With this approach, disastrous earthquakes will keep occurring as catastrophic "surprises."

Seismic Hazard Map Reality Check

We used PSHA, namely, the Global Seismic Hazard Assessment Program (GSHAP) [*Giardini et al.*, 1999], as our guide on a journey to the actual territory of earthquake hazards [*Kossobokov and Nekrasova*, 2012]. Our study disclosed a gross inadequacy: the GSHAP estimates were exceeded in each of the 88 earthquakes with a magnitude (*M*) greater than or equal to 7.5 that struck around the world from 1990 to 2009. These estimates were also exceeded in the 12 deadliest earthquakes that shook between 2000 and 2011 (more than 700,000 total fatalities). Such a poor performance could have been foreseen with a simple check against earthquakes in the past before the GSHAP results were disseminated.

A check of the new map issued by the Seismic Hazard Harmonization in Europe (SHARE) project [*Giardini et al.*, 2014] discloses a further step away from seismic reality. A quick glance at the map "displaying the 10% exceedance probability in 50 years for peak ground acceleration" [*Giardini et al.*, 2014, p. 261] (Figure 1) captures the problem of seismic hazard assessment in Romania—an underestimation of the area where potential intensity is IX or higher ("violent" on the modified Mercali scale of earthquake effects, classified as an acceleration more than 40% that of gravity).

The well-established complex geometry of ground shaking from intermediate-depth earthquakes in the Vrancea zone of Romania suggests a donut-like pattern of seismic intensity on a large scale [*Radulian et al.*, 2000]. This is evident in the neodeterministic seismic hazard assessment (NDSHA) map (Figure 1a; see torus) but does not exist on the SHARE map (Figure 1b).

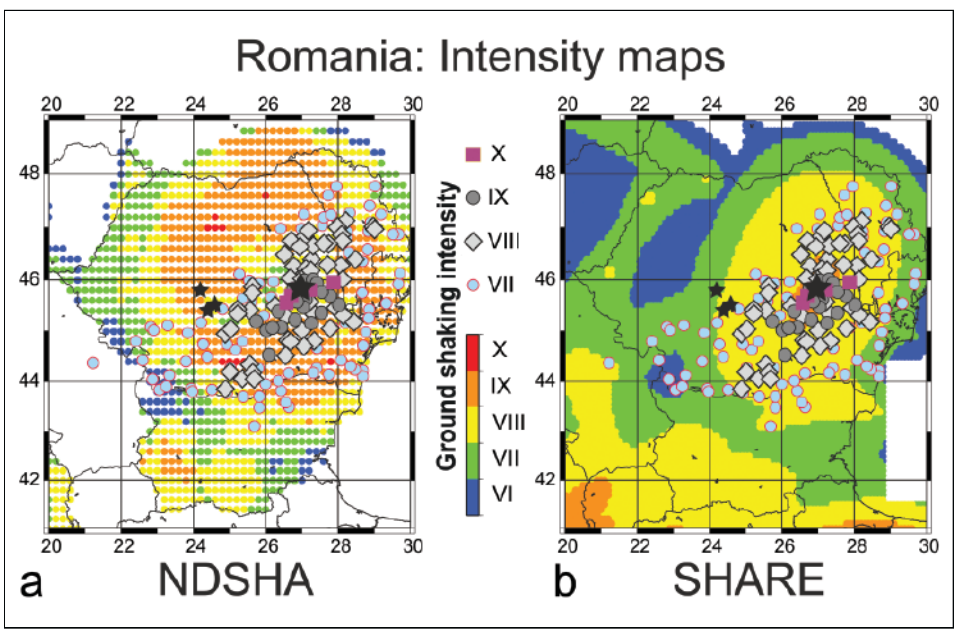

Fig. 1. Seismic hazard assessment for Romania. (a) Neodeterministic seismic hazard assessment (NDSHA) method [Radulian et al., *2000]; (b) Seismic Hazard Harmonization in Europe (SHARE) project* [Giardini et al., *2014]. Colored regions represent shaking intensities calculated using each method. Color-coded symbols indicate observed shaking intensities. The large star marks the shock epicenter of the 1940* M*7.7 earthquake in Vrancea, and smaller stars are epicenters of violent shocks in the Fagaras zone in 1550, 1571, and 1590.*

National Geographic Romania

Rescue operations after the M7.7 *Vrancea earthquake in Romania, which shook on 10 November 1940*

The neodeterministic approach uses scenario-based assessments based on physical modeling of seismic wave propagation at various scales and, unlike PSHA, does not make mathematically questionable assumptions about local site responses. In the Romanian example, NDSHA recognizes the area of high seismic hazard in the Fagaras zone, to the west of Vrancea, which experienced a series of violent shaking events in the second half of the 16th century. These events were missed by the PSHA SHARE map.

For the largest instrumental event in the Vrancea zone of intermediate-depth earthquakes, the *M*7.7 earthquake of 10 November 1940 (large star in Figures 1a and 1b), the SHARE map inadequately describes the areal extent of the observed intensity VII–VIII ("very strong" to "severe") on the southwesternmost part of the violent ground shaking area at about 44°N, 23°E [*Kronrod et al.*, 2013]. (To facilitate checking, we converted the peak ground acceleration (PGA) values from both NDSHA for Romania [*Radulian et al.*, 2000] and the SHARE data source to the same macroseismic intensity scale.) Evidently, the simplistic geometries associated with the SHARE map are unable to capture the complex pattern of intensity distribution displayed by real observations [e.g., *Kronrod et al.*, 2013, and references therein], where maximum intensities are shifted with respect to the epicenter of an earthquake.

A Closer Look

A deeper analysis of SHARE maps [*Nekrasova et al.*, 2014] performed for Italy reveals that even relative to GSHAP, the new regional assessment shifts the distribution functions of ground shaking intensity away from reality, toward exceedingly high values (Figure 2). This discrepancy is seen by running models at 10% and 2% probability of exceedance over a period of 50 years.

Specifically, the empirical probability function based on the SHARE10% map deviates from distributions of the observed ground shaking by 80%, and the SHARE2% graph is an outlier in Figure 2 shifted by four units of intensity from the two distributions based on

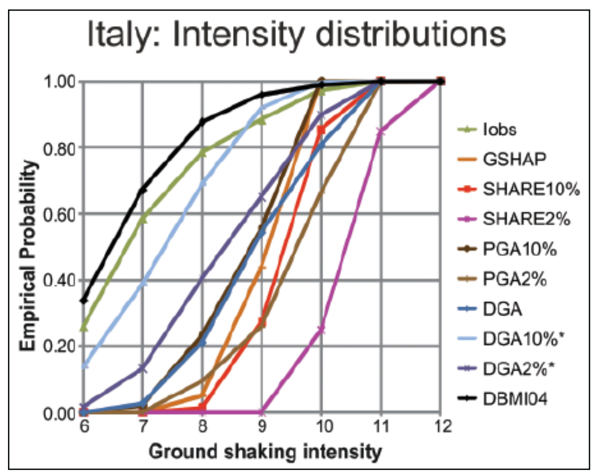

*Fig. 2. Empirical probability functions of the macroseismic intensity in Italy, comparing the probabilistic peak ground acceleration (PGA) and the neodeterministic design ground acceleration (DGA) methods with the observed ground shaking. The green line (Iobs) represents observed data taken from the SHARE European Earthquake Catalogue, and the black line (DBM104) represents direct seismic observations [*Stucchi et al., *2007]. Other lines represent probabilistic seismic hazard analysis (i.e., the Global Seismic Hazard Assessment Program (GSHAP) [*Giardini et al., *1999], SHARE10% and SHARE2 (models run at a 10% and 2% probability of exceedance over a period of 50 years) [*Giardini et al., *2014], and PGA10% and PGA2%) and NDSHA (i.e., DGA, DGA10%*, and DGA2%* [*Nekrasova et al., *2014]). Note that PGA10% and PGA2% are used to form the official seismic hazard map of Italy.*

observations. Available alternative maps, such as the neodeterministic DGA10%* [*Nekrasova et al.,* 2014], provide a better fit to the observed ground shaking in Italy than the PSHA products.

A Stable Foundation for Decision Making

Giardini et al. [2014, p. 261] wrote, "Thus, future safety assessments of and improvements to the built environment will be able to rely on these [SHARE] calculations." However, we show that such safety assessments and improvements can hardly rely on the SHARE calculations, at least in Romania and Italy. Given the above analysis, other state-of-the-art methods of modeling realistic earthquake scenarios allow for more realistic seismic hazard assessment [e.g., *Panza et al.,* 2012].

Therefore, we urge the necessary revision of widespread PSHA maps. Physically sound deterministic methods [*Italian Chamber of Deputies,* 2011] would enable the maximal magnitude of an expected earthquake for seismically hazardous areas to be estimated with a statistically justifiable reliability [*Kijko,* 2012]. Deterministic scenarios of catastrophic earthquakes may provide a comprehensive basis for decision making for land use planning, adjusting building codes, regulations, and operational emergency management.

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For more on efforts to resolve seismic hazard assessment debates, see p. 12.