2012 EMILIA EARTHQUAKES

Seismic hazard in the Po Plain and the 2012 Emilia earthquakes

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1. Introduction

The Emilia earthquakes of May 20, 2012 (M_L 5.9, INGV; M_W 6.11, http://www.bo.ingv.it/RCMT/) and May 29, 2012 (M_L 5.8, INGV; M_W 5.96, http://www.bo.ingv.it/RCMT/) struck an area that in the national reference seismic hazard model [MPS04; http://zonesismiche.mi.ingv.it, and Stucchi et al. 2011] is characterized by expected horizontal peak ground acceleration (PGA) with a 10% probability of exceedance in 50 years that ranges between 0.10 g and 0.15 g (Figure 1), which is a medium level of seismic hazard in Italy. The strong impact of the earthquakes on a region that is not included among the most hazardous areas of Italy, and the ground motion data recorded by accelerometric networks, have given the impression to the population and the media that the current seismic hazard map is not correct, and thus needs to be updated.

Since the MPS04 seismic hazard model was adopted by the current Italian building code [*Norme Tecniche per le Costruzioni* 2008, hereafter termed NTC08; http://www.cslp.it/cslp/] as the basis to define seismic action (the design spectra), any modification to the seismic hazard model would also affect the building code.

The aim of this paper is to briefly present the data that support the seismic hazard model in the area, and to perform some comparisons between recorded ground motion with seismic hazard estimates and design spectra. All of the comparisons presented in this study are for the horizontal components only, as the Italian hazard model did not perform any estimates for the vertical component.

2. Reference seismic hazard map for the Emilia area

The reference Italian seismic hazard model (MPS04) was released in 2004, and it was adopted as an official document by Italian Law in 2006 (Prime Minister Ordinance 3519/2006). This model provides the basic data to be considered to update the seismic zoning of municipalities, and it was used in the determination of the design spectra in the Italian building code (NTC08). The MPS04 seismic hazard model was obtained using the standard Cornell probabilistic approach, by adopting a logic-tree strategy. This is conventionally used in probabilistic seismic hazard assessment (PSHA) as a tool to capture the epistemic uncertainty that is associated with the input elements of computational models.

The main input elements were: the CPTI04 earthquake catalog [CPTI Working Group 2004], the ZS9 seismic source zone model [Meletti et al. 2008], the 2.0 version of the Database of Individual Seismogenic Sources (DISS) [Valensise and Pantosti 2001], and a set of ground-motion predictive models based on Italian and European data [Ambraseys et al. 1996, Sabetta and Pugliese 1996, Malagnini et al. 2000, Malagnini et al. 2002, Morasca et al. 2002]. The estimates produced by each logic-tree branch were then combined with the relevant weights to obtain the median value (assumed as the reference hazard value) and the percentiles that express the relevant uncertainty.

The Emilia 2012 earthquake sequence occurred in northern Italy, inside the Po Plain, where thick sedimentary deposits cover the most external active fronts of the Apennine belt that overlie the Adria microplate. Figure 2 shows the seismogenic zones for the study region from the above-mentioned ZS9 model. Source zones 913, 914 and 918 correspond to the compressive structures (on the northeastern side of the Apenninic relief), source zones 915 and 916 include the extensional structures of the internal margin of the Apennines, and source zones 912 and 917 correspond to the blind thrusts that characterize the most external portion of the Apennines. These structural elements have been well known for many years, due to the huge subsurface exploration that was carried out by ENI for oil and gas reservoir identification. The epicenters of the earthquakes reported by CPTI04 catalog [CPTI Working Group 2004] are also shown in Figure 2. Even if the seismicity was mostly concentrated inside the seismic source zones 913 and 914, strong earthquakes have also occurred in the past within source zone 912, such as the 1346 (M_W 5.81), 1570 (M_W 5.48) and 1688 (M_W 5.88) earthquakes. For this seismogenic zone, the DISS database of potential seismogenic sources (in the 2.0 version available in 2004) reported information on faults that can

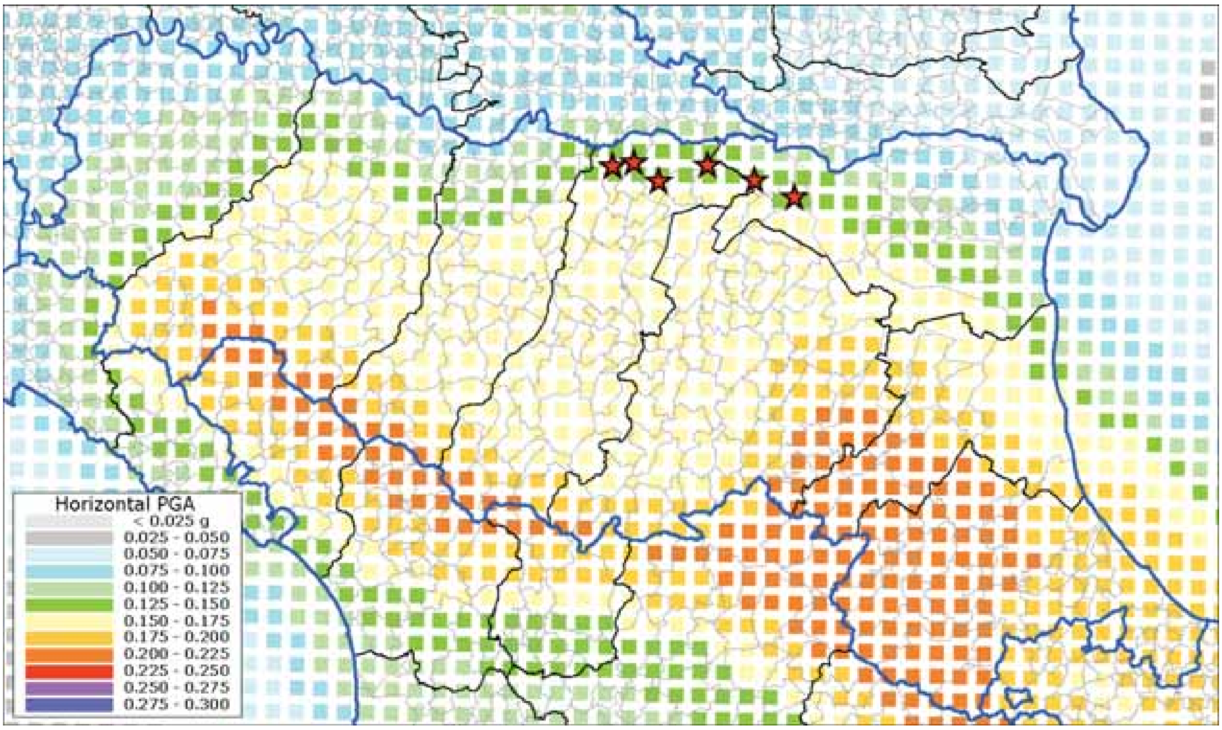

Figure 1. Seismic hazard map for the Emilia-Romagna region. The color at each grid point represents the expected horizontal PGA on rock with a10% probability of exceedance in 50 years (as indicated). Red stars, epicenters of the events of the 2012 Emilia sequence with magnitudes ≥5.

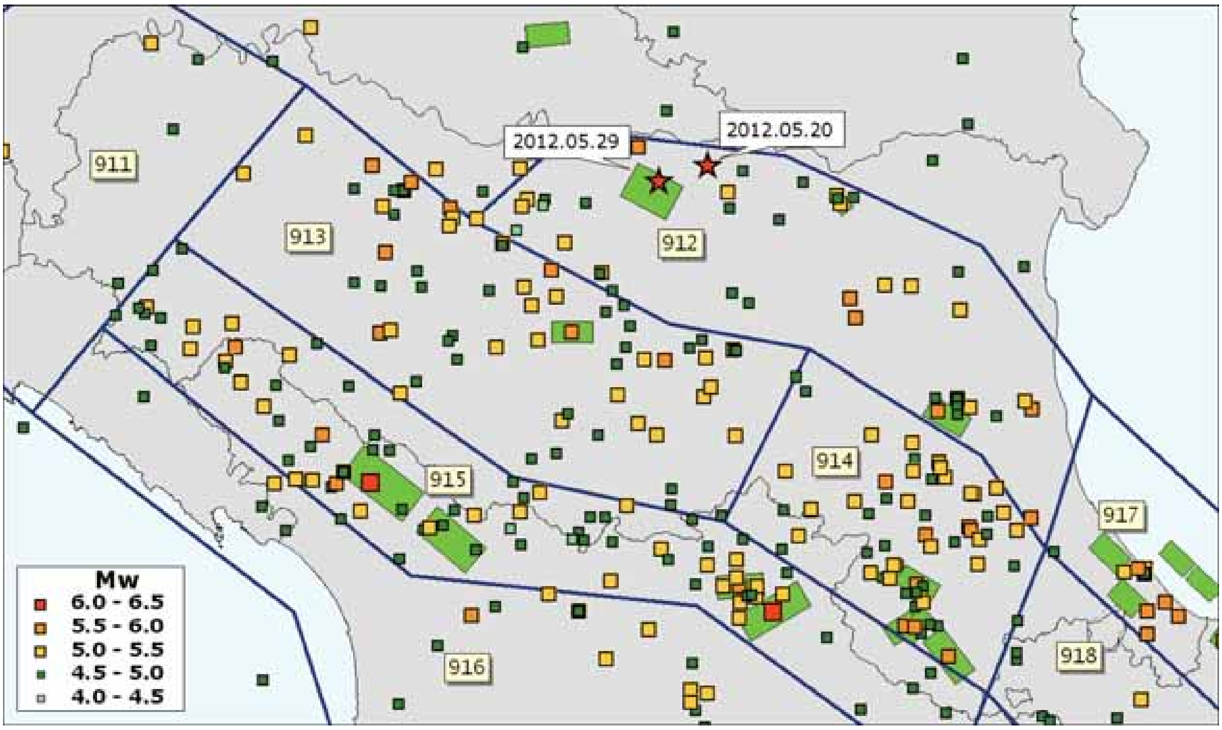

Figure 2. Seismic source zones from the ZS9 model (blue lines), potential seismogenic structures from the DISS database (green boxes), and earthquakes from the CPTI04 catalog (magnitudes mainly derived from historical data) in the northern Apennines. Red stars, epicenters of the two main events of the Emilia earthquake sequence.

generate earthquakes up to magnitude 6.2.

All of this information was considered to derive the seismicity rates and define the maximum magnitude (M_{max}) to be adopted in the assessment of seismic hazard.

The seismicity rates adopted in MPS04 for source zone 912 are shown in Figure 3. Two methods were followed for their computation: in the AR branch, the rates were estimated independently for each magnitude bin, while in the GR branch, the rates were fitted assuming the Gutenberg-Richter frequency–magnitude distribution. For both of these branches, the rates for the M_{max} (magnitude bin = M_W 6.14 ±0.115) were derived from geological considerations only. Figure 3 also shows the cumulated number of earthquakes in 1000 years (without any consideration about catalog completeness) reported by the CPTI04 [CPTI Working Group 2004] and CPTI11 [Rovida et al. 2011] catalogs, together with the seismicity rates assessed for the same source zone in the framework of the ongoing Seismic Hazard Harmonization in Europe (SHARE) project (http://www.share-eu.org). The small differences between the CPTI04 and CPTI11 catalogs are mainly due to the updated procedures used in the CPTI11 catalog for magnitude determination from macroseismic data points. Anyhow, the seismic rates adopted in MPS04 appear to be conservative with respect to the observations and to an independent estimate, such as that of the SHARE project.

The output of the reference MPS04 seismic hazard model is given in terms of horizontal ground accelerations on rock for several return periods and several spectral periods, computed on a regular grid (5-km spacing) that covers the whole Italian territory. For each grid point, the PGA and uniform hazard spectra (UHS) are available for nine probabilities of exceedance in 50 years, ranging from 2% to 81%, and corresponding to return periods from 2475 years to 30 years. The data are accessible through a webGis application (http://esse1-gis.mi.ingv.it) [Martinelli and Meletti 2008]. Figure 4 shows the UHS for the grid point ID15173 (longitude, 11.0935°; latitude, 44.8608°), which is the closest node to the only permanent station of the national accelerometric network (Rete Accelerometrica Nazionale, RAN) located in the epicentral area of the first event (i.e., MRN, Mirandola). The UHS computed for the nine return periods are plotted to represent the whole range of expected values. The 16th percentile curve for the return period of 30 years, and the 84th percentile curve for the return period of 2475 years, are also shown, to illustrate the wide uncertainty of the PSHAs.

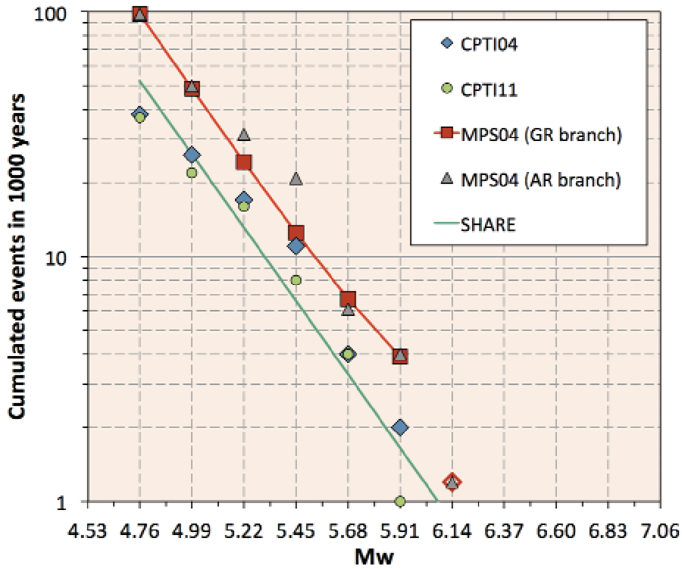

Figure 3. Comparison between the cumulative number of earthquakes in the CPTI04 and CPTI11 catalogs and the seismicity rates for the GR and AR branches of MPS04 and for the SHARE project (as available on July 2012) for seismic source zone 912. All rates are normalized to 1000 years.

3. Comparison of probabilistic seismic hazard assessments and ground-motion recordings of the Emilia earthquakes

The two main shocks of the Emilia seismic sequence of May 20 and 29, 2012, together with the April 6, 2009, L'Aquila event (M_W 6.3), are the strongest earthquakes to have occurred in Italy since the release of the reference MPS04 seismic hazard model and of the current Italian building code (NTC08), which has been in force since July 1, 2009. Of course, the seismological community and the media looked at the seismic hazard model in the area to test the model performance against the new observations, in the same way as happened after the L'Aquila 2009 earthquake [see e.g., Crowley et al. 2010, Stucchi et al. 2010, Masi et al. 2011]. In that case, the assumptions and modeling choices made in the MPS04 hazard study were in line with the observations [see Crowley et al. 2010, for a more detailed analysis].

As is well known from a statistical point of view, it is not possible to validate a probabilistic hazard estimate with data observed for a single earthquake: indeed, on one side, there is a ground-motion value expected with a certain probability of occurrence, while, on the other, there is just one observed value and we cannot know if it represents the maximum expected value, the most probable value, or something else. On the contrary, a meaningful way to assess the reliability of a PSHA map, e.g., for a 475-year return period, should be to observe whether, over a period of 50 years, more than 10% of the computational sites have experienced ground motions higher than those predicted [see e.g., Albarello and D'Amico 2008]; indeed, even several consecutive 50-year periods of observations would be required to make this test robust.

What it is possible to do is to compare the recorded accelerations with the probabilistic hazard model (the range of expected values and their uncertainties) to understand if they are consistent with each other. Furthermore, any comparisons must be performed by considering the same conditions. This means that the values for the same shaking parameter (in our case, the maximum horizontal acceleration) and for the same soil class should be compared.

Figure 5 shows the maximum horizontal PGAs produced by the two Emilia earthquakes up to an epicentral distance of 200 km. While the main shock was only recorded by RAN permanent stations, for the second shock, data obtained by 16 temporary stations that were installed in the epicentral area in the aftermath of the first shock are also available [Dolce et al. 2012]. The strong-motion data were manually post-processed, adopting the procedure used for the Italian Accelerometric Archive (ITACA) database and described by Paolucci et al. [2011] and Pacor et al. [2011].

The highest values were registered for the May 29, 2012,

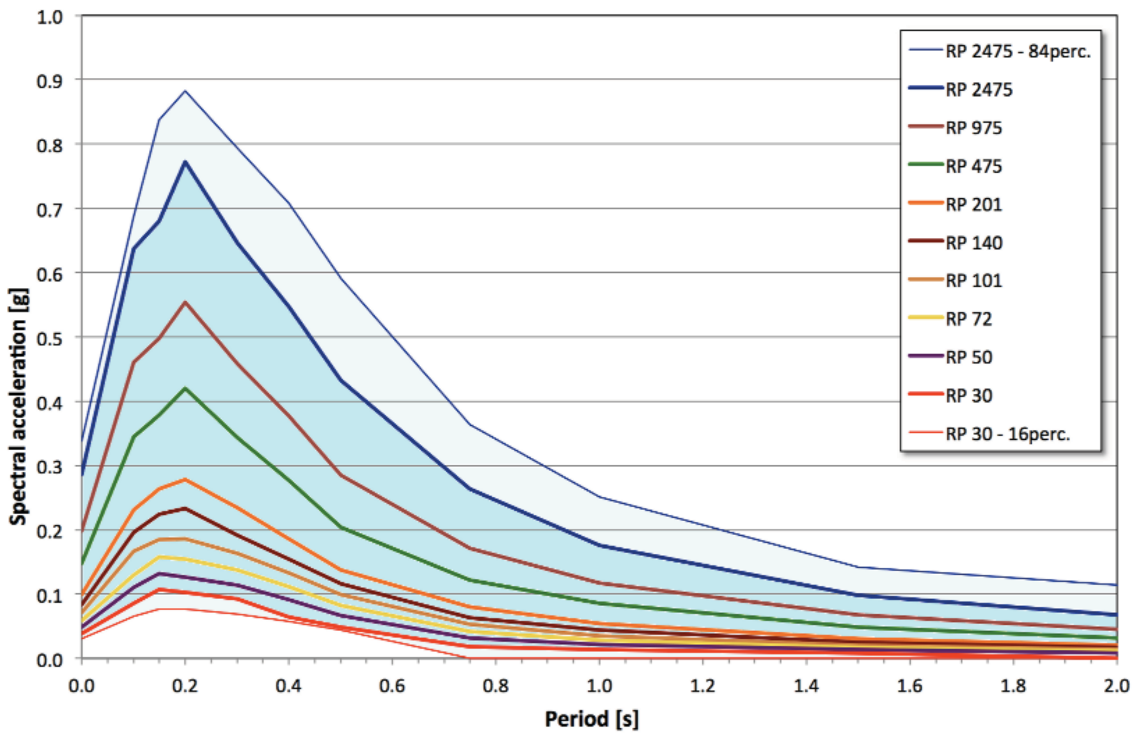

Figure 4. Acceleration uniform hazard spectra for several return periods (as indicated) considered in MPS04 at the grid point closest to the Mirandola (MRN) station.

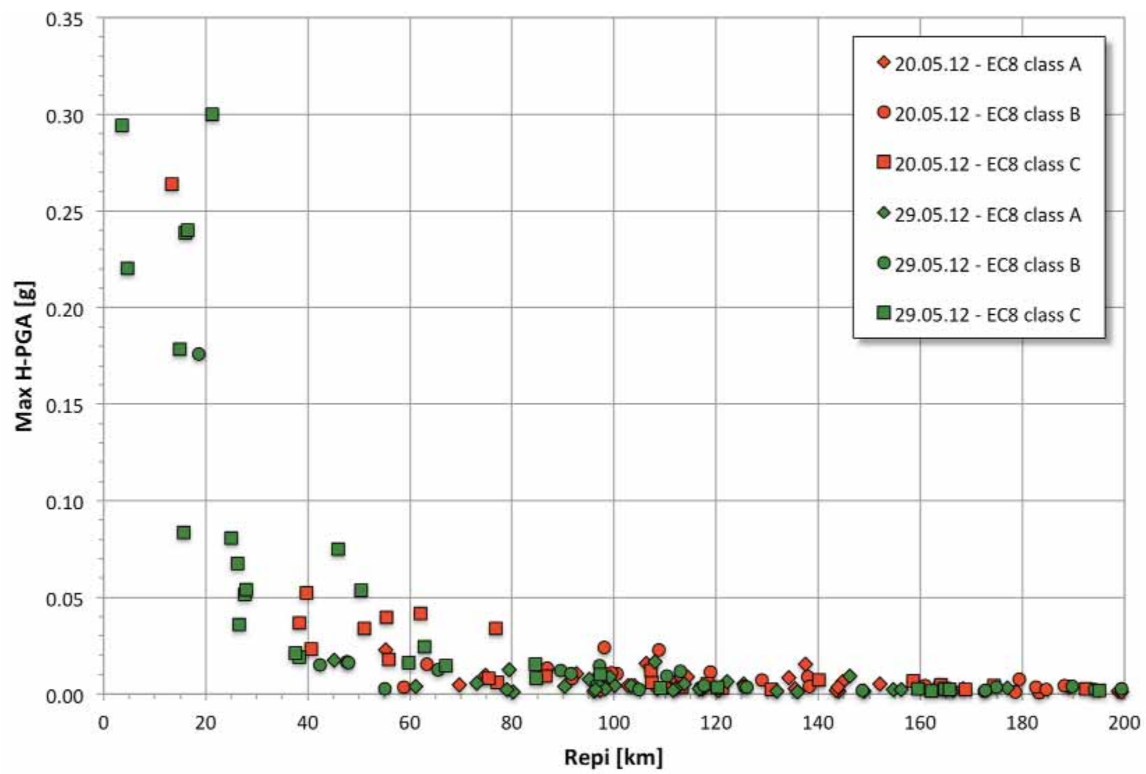

Figure 5. Larger horizontal PGAs (in g) *versus* the epicentral distance recorded for the May 20 and 29, 2012, earthquakes. The EC8 [CEN 2004] soil class of each station (as assigned based on the geological map) is also indicated.

event at the RAN stations of Cento (CNT, a newly installed permanent station) and of Mirandola (MRN) (0.30 g and 0.29 g, respectively), and for the May 20, 2012, earthquake at the MRN station (0.26 g). As shown in Figure 5, for the first event, only one record (i.e., at MRN) is available within 35 km of the epicenter, while for the second earthquake, 13 recordings were acquired, thus allowing the PGA decay with distance to be better depicted. Values larger than 0.15 g were

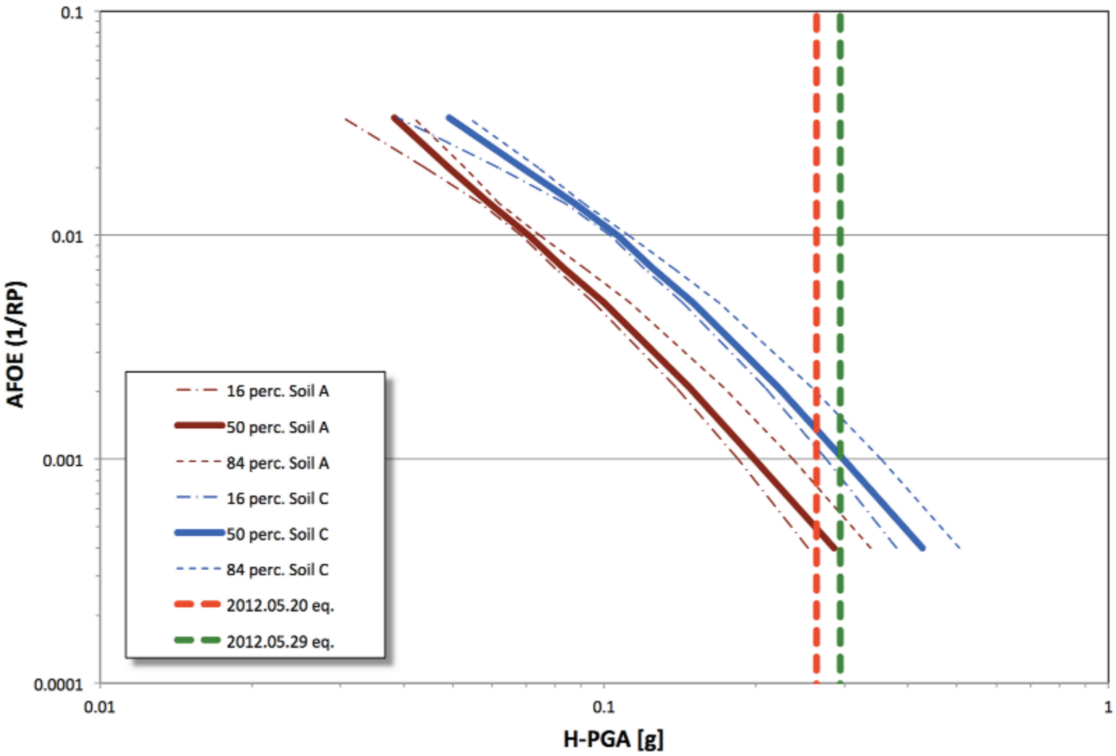

Figure 6. Comparison between the hazard curves for soil types A and C, computed at the node of the computational grid closest to Mirandola and the maximum horizontal PGAs recorded at the MRN station for the May 20 and 29, 2012, earthquakes. The 16th and 84th percentile curves represent the epistemic uncertainty of the probabilistic seismic hazard estimate.

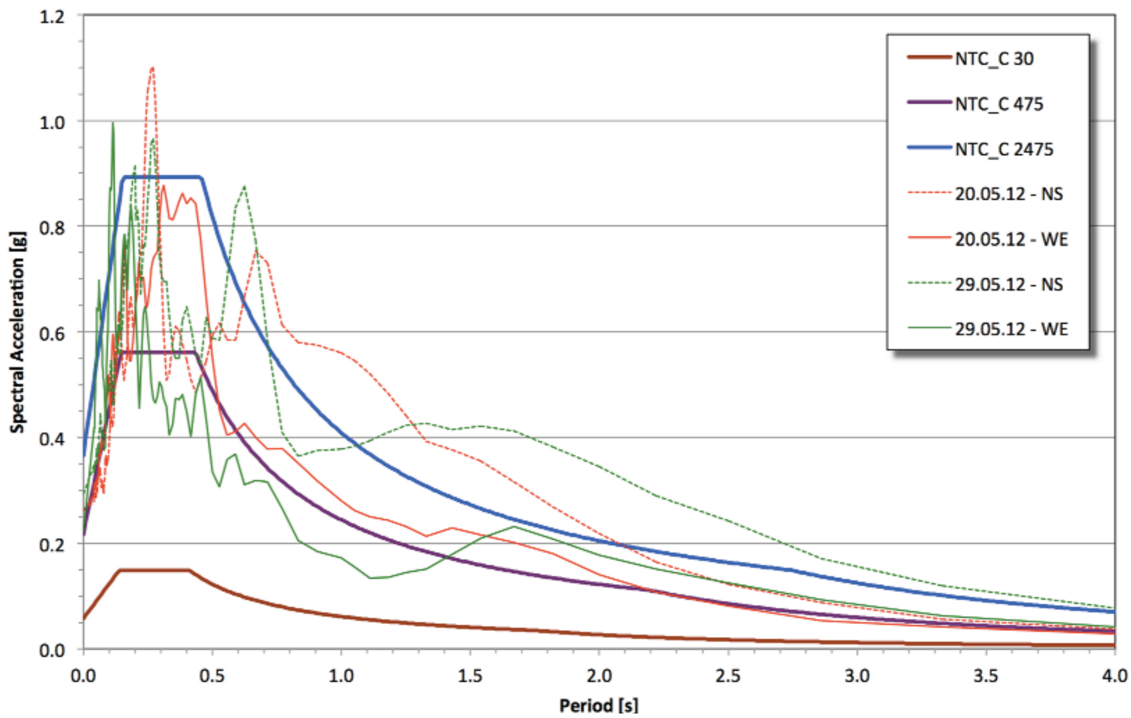

Figure 7. Comparison between the horizontal acceleration response spectra recorded at the MRN station for the two main events of the Emilia sequence, and the design code spectra prescribed by NTC08, for soil type C, for 30, 475 and 2475-year return periods (as indicated).

only observed in the first 20 km, and the PGA quickly decreased beyond this distance.

The larger horizontal PGAs recorded at MRN, which was the RAN station nearest to both of the epicenters, are compared with the seismic hazard estimates computed at the node of the computational grid closest to the MRN station (Figure 6). For this, we consider the hazard curve; i.e., the expected PGA for different return periods (or the inverse; i.e., the annual frequency of exceedance, AFOE, of different PGAs). To make this comparison meaningful, we applied the NTC08 coefficient for soil-type C sites (like the one of MRN station, see Figure 5), to the original hazard curve of the MPS04 model computed for soil class A (i.e., rock or very stiff soil, with $V_{s30} \geq 800$ m/s). As shown in Figure 6, the expected PGA ranges from 0.05 g to 0.43 g (from the shortest to the longest return period), and the highest recorded PGA (for the May 29, 2012, event) was 0.29 g, which was thus consistent with seismic hazard estimates.

In Figure 7, the horizontal acceleration response spectra (5% damping) recorded at the MRN station for the two main events of the Emilia sequence are compared with the design code spectra corrected for soil type C, as prescribed by NTC08, for the shortest, the longest, and the most 'standard' return period considered (i.e., 30, 2475 and 475 years, respectively).

Both recorded spectra largely exceed the code spectrum for 475 years, as they look much closer to that expected for 2475 years, especially in the case of the WE components, which always lie below this latter, except for the sharp peak at 0.1 s observed for the May 29, 2012, event. Major differences emerge instead for the NS components, which go over the 2475-year design spectrum for several period ranges; i.e., at 0.27 s, around 0.6 s to 0.7 s, and at longer periods. In particular, the bulge observed at the intermediate-to-long periods (between 0.7 s to 2 s for the main shock, and beyond 1 s for the second shock) appears to be widely unpredicted by the code spectrum. However, preliminary site response analyses based on horizontal-to-vertical spectral ratios of noise measurements suggest remarkable site amplification for periods longer than about 1 s at MRN and other stations inside the Po Plain [Bordoni et al. 2012, this volume; Dolce et al. 2012]. Such amplifications are also, in many cases, coupled with the generation of large-amplitude surface waves that affects the spectral amplitudes at long periods. Moreover, the spectral accelerations at periods greater than about 2 s recorded at most of the stations inside the Po Plain are underestimated by the recent ground-motion predictive model developed for Italy [Bindi et al. 2011], whereas the opposite holds for stations outside the Po Plain [Luzi et al. 2012]. Finally, it is worth mentioning that the MRN station is located just few kilometers from the earthquakes epicenters, and the large amplitude difference between the NS and WE components might be due to near-source directivity effects that typically increase the ground-motion amplitude in the strike-normal direction (i.e., NS for both earthquakes, given the fault-plane solutions by http://www.bo.ingv.it/RCMT/) [e.g., Somerville et al. 1997].

Except MRN and CNT (which only had a large peak at 0.3 s), all of the other stations that recorded the events of the Emilia sequence showed response spectra below code spectra.

However, if response spectra from single earthquakes are compared with seismic design code spectra, the conceptual difference between the two objects should be kept in mind. Indeed, code spectra are based on uniform hazard spectra computed by PSHA (in particular, spectral shapes in NTC08 are those that more closely fit the UHS provided by the reference seismic hazard model) [see Montaldo et al. 2007], where each spectral ordinate has the same return period (or probability of exceedance in a fixed time span). Thus, for a given return period, different spectral ordinates of the UHS can be caused by different earthquakes taken into account by the PSHA; i.e., all possible events that can occur within a given area [see also Crowley et al. 2010]. Furthermore, in the case of NTC08, code spectra only consider the median computed UHS, thus neglecting information on the relevant large uncertainty. As shown in Figure 4, for the 84th percentile curve for 2475-year return period, the expected acceleration on rock nearly reaches 0.9 g at 0.2 s, even without any soil correction (from class A to C), which would certainly raise the curve up to the peak values observed for the two Emilia main events.

In conclusion, even considering all of the mentioned issues concerning the comparison of a record from a single event with a probabilistic estimate, the analysis performed in our study shows that the accelerometric evidence from the 2012 Emilia earthquakes are consistent with the reference seismic hazard model of Italy that was adopted for the NTC08 building code.

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