Seismic hazard in Central Italy and the 2016 Amatrice earthquake

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Abstract

The Amatrice earthquake of 24 August 2016 (Mw 6.0) struck an area that in the national reference seismic hazard model (MPS04) is characterized by expected horizontal peak ground acceleration (PGA) with 10% probability of exceedance in 50 years higher than 0.25 g. After the occurrence of moderate-to-large magnitude earthquakes with a strong impact on the population, such as the L'Aquila 2009 and Emilia 2012 ones (Mw 6.1 and 5.9, respectively), possible underestimations of the seismic hazard by MPS04 were investigated, in order to analyze and evaluate the possible need for its update. One of the most common misunderstanding is to compare recorded PGA with the PGA value with 10% probability of exceedance in 50 years only. Moreover, by definition, probabilistic models cannot be validated (or rejected) on the basis of a single event. However, comparisons of forecasted shakings with observed data are useful for understating the consistency of the model. It is then worth highlighting the importance of these comparisons. In fact, MPS04 is the basis for the current Italian building code to provide the effective design procedures and, thus, any modification to the seismic hazard values would also affect the building code.

In this paper, comparisons between recorded ground motion during the Amatrice earthquake and seismic hazard estimates are performed, in order to evaluate the consistency between predicted and observed accelerations.

I. INTRODUCTION

Since 2006 Italy has a reference seismic hazard model in accordance with the Prime Minister Ordinance 3519/2006, which ratified the MPS04 (Mappa di Pericolosità Sismica 2004) seismic hazard model [MPS Working Group, 2004; Stucchi et al., 2011; http://zonesismiche.mi.ingv.it/] as the basic elaboration to be considered to update the seismic classification of municipalities. Later in 2009, MPS04 has been used also for the determination of the design spectra in the Italian building code [Norme Tecniche per le Costruzioni, 2008 (NTC08)].

The MPS04 model was produced in the aftermath of the Mw 5.7 San Giuliano (Southern Italy) 2002 earthquake that struck an area not considered as seismic before. The main requirements of MPS04 were the adoption of up-to-date and worldwide accepted methodological approaches, updated input data, and transparent and reproducible procedures with clear description of the operating choices and related uncertainties.

Several input elements were specifically updated, such as the CPTI04 earthquake catalog [CPTI Working Group, 2004; http://emidius.mi.ingv.it/CPTI04/], the ZS9 seismic source zone model [Meletti et al., 2008], and the DISS database of potential seismogenic sources, originally defined in [Valensise and Pantosti, 2001]. Two ground-motion predictive models, two available models based on Italian and European data were selected [Sabetta and Pugliese, 1996; Ambraseys et al. 1996], together with two newly-developed ones [Malagnini et al., 2000 and 2002; Morasca et al., 2002]. A logic-tree approach was then adopted in order to manage the epistemic uncertainty associated with the input elements, and the median hazard value (assumed as reference estimate) was computed together with the percentiles to show model uncertainties.

The resulting MPS04 model provides, on a 5-km-spaced grid, PGA and spectral accelerations computed for 10 periods (from 0.1 to 2 seconds), for 9 probabilities of exceedance in 50 years (from 2% to 81%, corresponding to return periods from 2475 to 30 years), for rocky soil conditions and flat topography. All the data of MPS04 are accessible through a webGis application [http://esse1-gis.mi.ingv.it/; Martinelli and Meletti, 2008].

The 24 August 2016 Amatrice (Central Italy) Mw 6.0 earthquake occurred in an area with the highest seismic hazard in Italy, where the PGA values expected with a probability of exceedance of 10% in 50 years are higher than 0.25 g (Fig. 1).

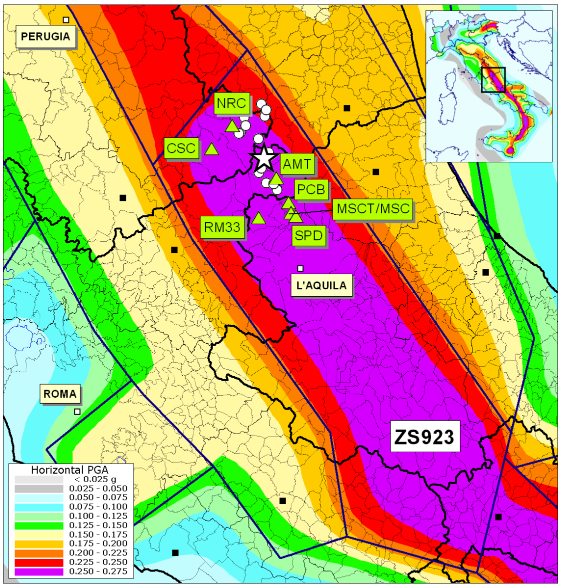

Figure 1. Seismic hazard map (MPS04) for Central Italy (top inset: map for whole Italy) in terms of horizontal PGA on rock with 10% probability of exceedance in 50 years. Epicenters of the 24 August 2016 main shock (white star) and events with Mw ≥4 (white dots) of the sequence in the first 40 days are also shown. Green triangles show the accelerometric stations considered in this study. Seismic source zones of the ZS9 model are indicated with blue lines.

The area is a portion of the Apenninic belt, a young chain formed in the Tortonian, when the Tyrrhenian Sea started its opening and the compressional thrust fronts migrated towards the East and the North East. At present, the extensional tectonic features reach the axial belt, whereas the compressional front is located along the Adriatic coastline.

The Amatrice event struck a region that, in the ZS9 seismic source model, belongs to a large area source [ZS923], characterized by prevalent normal faulting focal mechanisms and a maximum magnitude of 7.2, and where a number of strong earthquakes occurred in the past (Fig. 2), including the 2009 Mw 6.1 L'Aquila event.

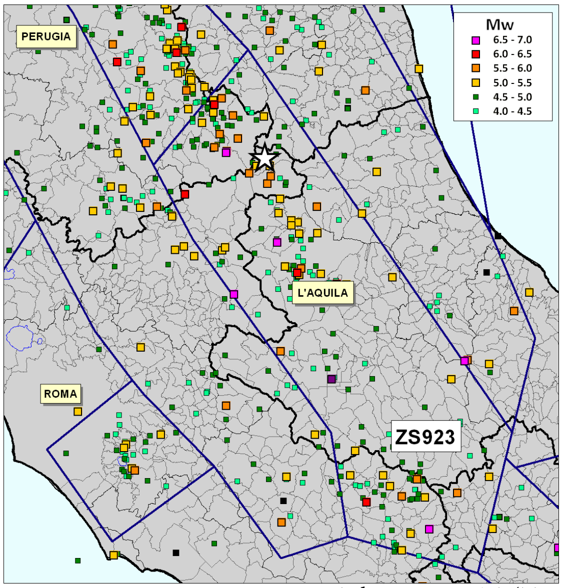

Figure 2. Seismic source zones of the ZS9 model (blue lines) and earthquakes from the CPTI04 catalogue (moment magnitudes mainly derived from historical data). White star is the epicenter of the 24 August 2016 Mw 6.0 event.

The seismic histories of villages located in the area confirm the occurrence of frequent and strong earthquakes in the last 400 years [Castelli et al., 2016]. The seismogenic potential of ZS923, in terms of activity rates and range of magnitude (mainly derived from historical seismicity), shows that a Mw 6.0 or larger has a rate of occurrence of about one event every 50 years (Fig. 3). Figure 3 also shows that using the last release of the Italian parametric catalogue CPTI15 [Rovida et al., 2016] does not substantially modify the magnitude-frequency distribution of ZS923, especially for rates of occurrence of Mw≥6.0 events.

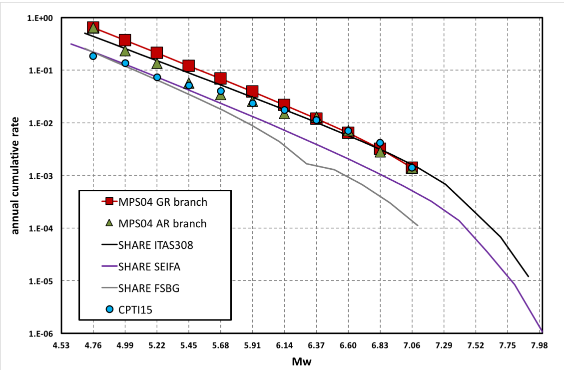

Figure 3. Annual seismicity rates for the two approaches adopted in MPS04 (i.e., GR=Gutenberg-Richter rates; AR=activity rates) for source zone ZS923 and for the three SHARE seismicity models: ITAS308 are the rates associated with the area source, SEIFA are the Kernel-smoothed stochastic rates, FSBG are the rates obtained combining fault sources (for Mw≥6.4) and background seismicity (Mw<6.4). CPTI15 are the rates obtained for source zone ZS923 using the most recent release of the catalogue CPTI15 [Rovida et al., 2016].

In addition, Figure 3 displays the seismicity rates for the sources that include the Amatrice area according to the three alternative earthquake source models considered in the SHARE European seismic hazard map [Woessner et al., 2015]. They consist of: i) an area source model, ii) a combination of faults and background seismicity (FSBG), and iii) a kernel-smoothed, zonation-free stochastic earthquake rate model that considers seismicity and cumulated fault moment (SEIFA). In the first model, the area source ITAS308 corresponds to ZS923 and is characterized by seismicity rates close to those of MPS04, except for the different evaluation of the maximum magnitude. On the contrary, rates for the FSBG and SEIFA models are lower than those of MPS04.

This paper is focused on the 24 August Mw 6.0 earthquake and does not take into account the following large events of 26 and 30 October 2016 (Mw 5.9 and 6.5, respectively).

II. Seismic hazard and ground-motion recordings of the Amatrice earthquake

Recorded accelerations of the 24 August 2016 Mw 6.0 mainshock (data are available at http://esm.mi.ingv.it) were compared with the hazard values provided by the MPS04 model. As known, the comparison of the observed ground motion from a single event with the shaking values expected with a certain probability of exceedance in a given time period is not a correct validation of a probabilistic seismic hazard (PSH) model. However, a comparison of recorded response spectra and peak ground-motion parameters with PSH estimates allows evaluating the relative "position" of a given earthquake with respect to the range of PSH values in order to understand their consistency, as shown by studies on other recent earthquakes [e.g. Meletti et al., 2012].
As shown in Figure 4, the maximum horizontal PGA recorded by the Amatrice accelerometric station (AMT), the nearest to the epicenter (about 9 km; Fig. 1 and Table 1), was 0.87 g. Such value is compared with the hazard curve, which represents the annual frequency of exceedance (AFOE) of different levels of PGA (AFOE is expressed in Figure 4 also as its inverse, that is the return period). The hazard curve in Figure 4 is referred to the node of the MPS04 computational grid closest to the AMT station. To make the comparison meaningful, we corrected the MPS04 hazard curve computed for soil class A (i.e. rock or very stiff soil with Vs30 > 800m/s) by applying the coefficient for soil class B (the class of the AMT station, [ITACA Working Group, 2016]) prescribed by the Italian building code (NTC08). The resulting hazard curve returns expected PGA values ranging from 0.09 g to 0.54 g. Fig-

ure 4 also shows the hazard curve evaluated by SHARE for the same site, modified for soil class B as for the MPS04 curve. PGAs expected by the SHARE curve are lower than MPS04 ones for AFOE ≥0.02 yr-1 (i.e. return periods ≤50 years), and higher than MPS04 ones for lower AFOE (i.e. longer return periods). At the longest return period considered by the MPS04 model (2475 years, AFOE = 0.0004 yr-1), the SHARE curve gives a PGA of ~0.7 g. To investigate the impact of the ground-motion predictive equations (GMPE) on seismic hazard estimates, we re-evaluated the MPS04 curve retaining the same earthquake rate model but using the ITA10 equation [Bindi et al., 2011] instead of the originally adopted GMPEs. The resulting hazard curve returns the highest estimates of PGA, that is ~0.9 g at return period of 2475 years.

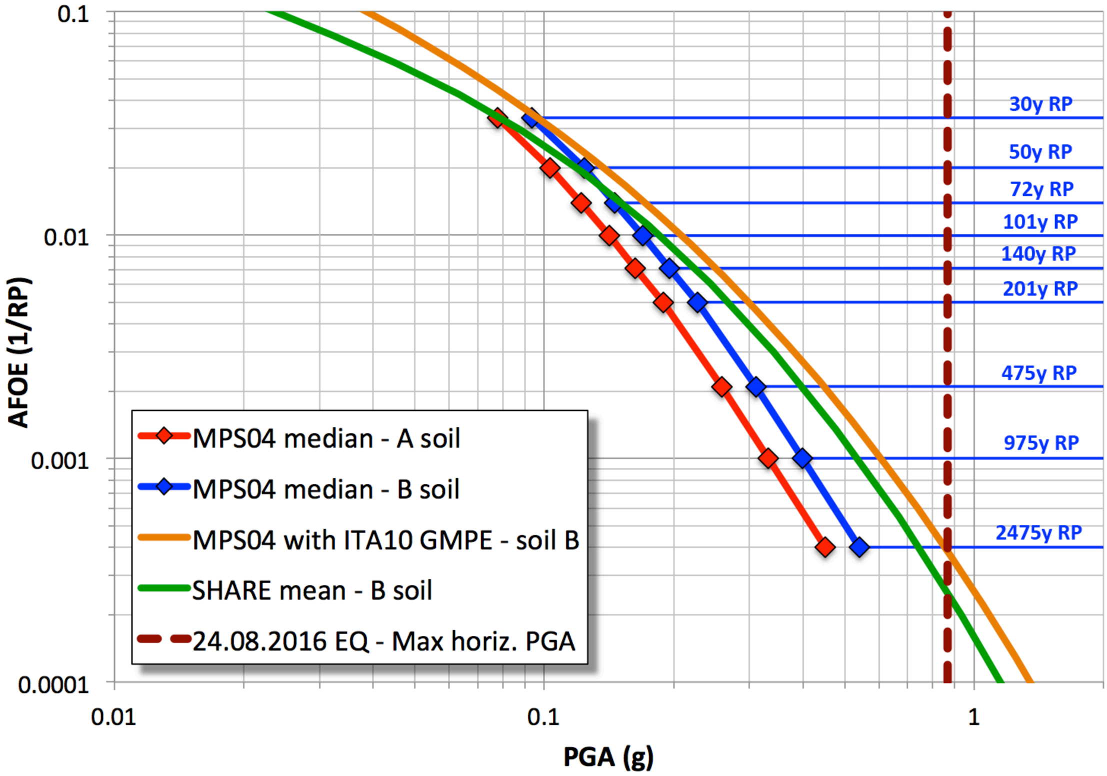

Figure 4. Comparison of the maximum horizontal PGA of the Amatrice Mw 6.0 mainshock recorded at the AMT station with the hazard curves of MPS04 (for soil class A and B), SHARE (for soil class B) and MPS04 modified by using ITA10 GMPE (for soil class B) [Bindi et al., 2011] at the node of the computational grids closest to AMT site. Because we have no data about the return period of the PGA recorded at AMT, it is shown as a vertical line. Potentially, the intersection between this vertical line and the hazard curve returns the approximated return period of that horizontal ground shaking for that site.

It is clear from Figure 4 that the MPS04 curve, even modified for soil class B, does not reach the PGA recorded at AMT. However, adopting a more recent GMPE shifts the hazard curves towards higher values, making the ground shaking recorded at AMT consistent with expected PGA for return period of 2475 years.

Moreover, we are considering the PGA observed at a site very close to the epicenter. As shown in Table 1, a strong decrease of the recorded PGA is observed at the other accelerometric stations located at epicentral distances lower than 25 km. Since the level of seismic hazard is almost the same at AMT and at the other considered stations, one can see that the minimum and maximum observed PGA (~0.1 and ~0.4 g) intersect the hazard curve of MPS04 at return periods between ~30 and 975 years, respectively.

In Figure 5, the horizontal acceleration response spectra (5% damping) recorded at the AMT station for the 24 August mainshock are compared with the Uniform Hazard Spectra (UHS) computed by the MPS04 model, corrected for soil class B, for probabilities of exceedance of 10% and 2% in 50 years, corresponding to return periods of 475 and 2475 years, respectively. As above, we then computed the UHS by replacing the GMPEs adopted in MPS04 with ITA10 equation [Bindi et al., 2011]. It is worth noting that the MPS04 model returns estimates of the maximum component of the horizontal ground shaking, as defined in the adopted GMPEs, whereas the [Bindi et al., 2011] model estimates the geometrical mean of the horizontal components of ground shaking. Figure 5 shows that, for the 475 years return period, the MPS04 UHS is generally lower than the maximum of the E-W and N-S components of the recorded spectrum. For the 2475 years return period, the MPS04 UHS is always higher than the N-S recorded spectrum, while it is higher than the E-W spectrum at periods longer than ~0.5 s and lower at shorter periods.

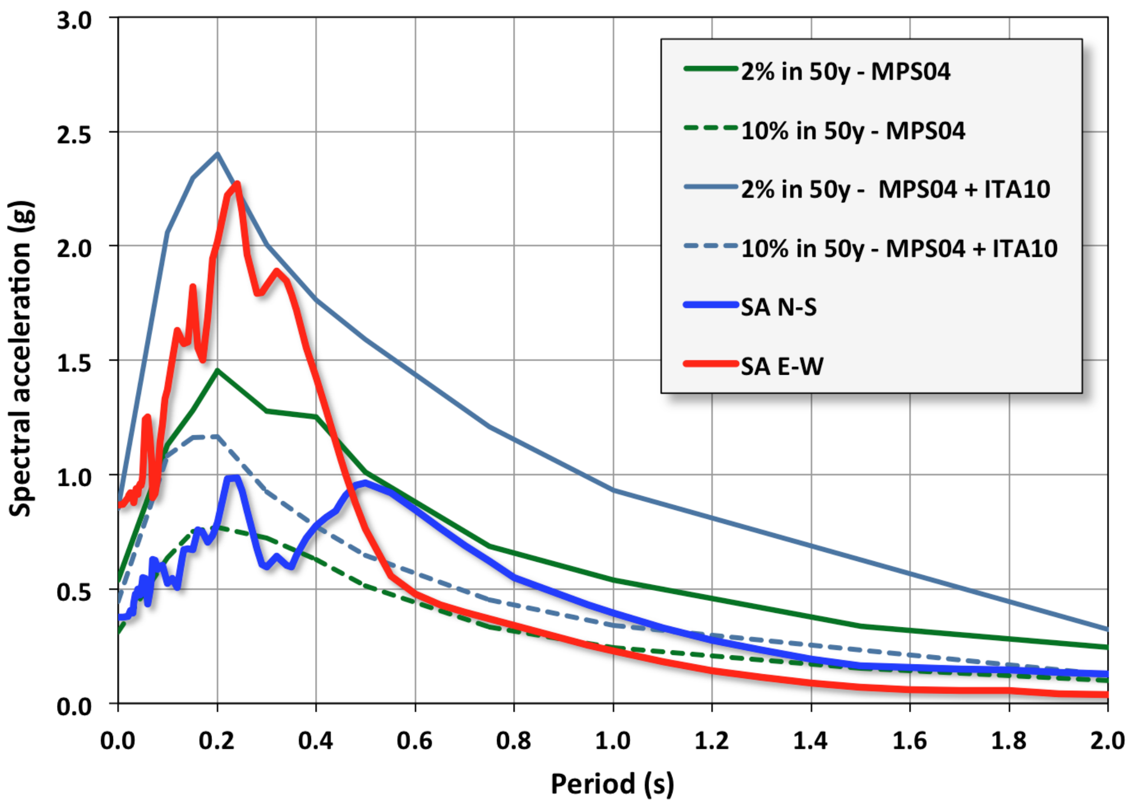

Figure 5. Comparison between the horizontal acceleration response spectra (5% damping, N-S and E-W components) of the 24 August Mw 6.0 mainshock recorded at AMT station and the UHS of MPS04 for soil class B and of MPS04 modified using the ITA10 GMPE [Bindi et al., 2011] (for soil class B), at the node of the computational grid closest to AMT, for 2% and 10% probability of exceedance in 50 years.

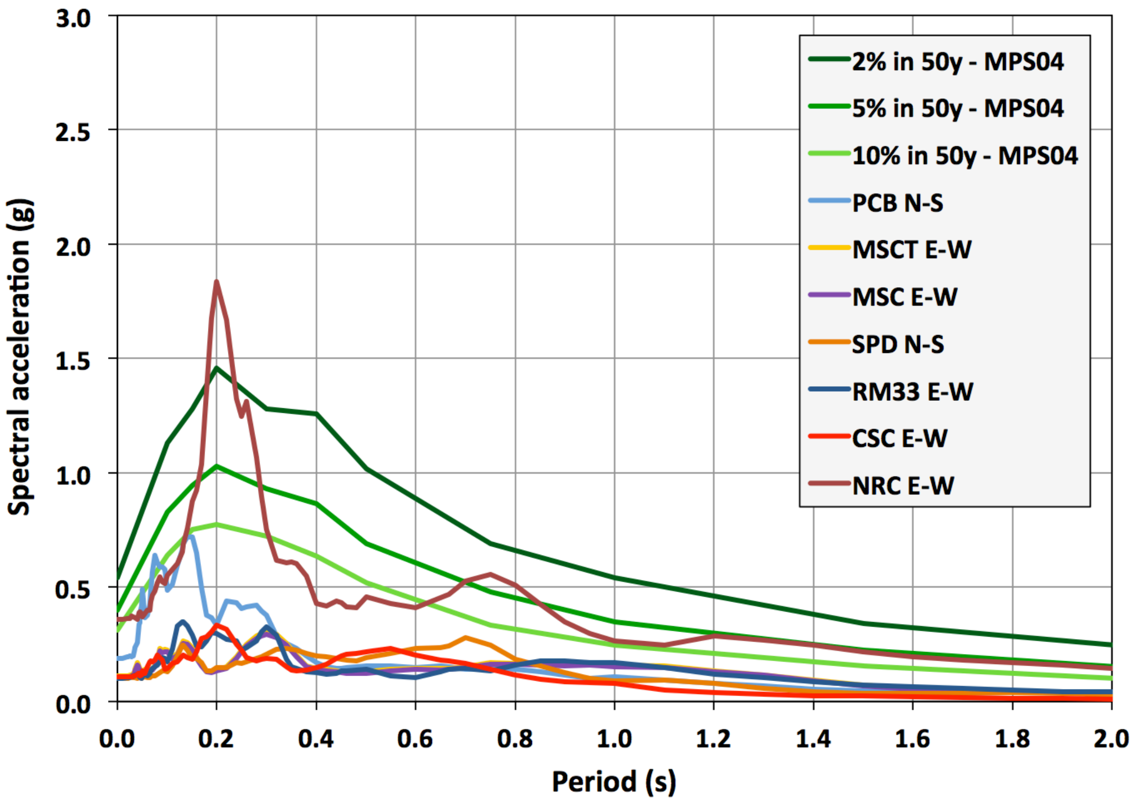

Figure 6. Comparison between the maximum horizontal acceleration response spectra (5% damping) of the Amatrice Mw 6.0 mainshock recorded at the stations located between 16 and 25 km from the epicenter and the UHS of MPS04 for soil class B, at a node located at about 20 km to the southeast of AMT, for 2%, 5% and 10% probability of exceedance in 50 years. The station codes refer to Figure 1 and Table 1.

Instead, the UHS obtained by MPS04 using the [Bindi et al., 2011] GMPE for 2475 years return period is always higher than the maximum recorded response spectrum. Figure 6 compares the UHS evaluated by MPS04, corrected for soil class B, with the maximum component of the recorded horizontal ground shaking for stations located at epicentral distances less than 25 km (Fig. 1 and table 1). UHS in Figure 6 are computed for a site located at about 20 km to the southeast of AMT. The response spectrum at NRC (Norcia) station, the second nearest station to the epicenter of the 24 August earthquake, shows a sharp peak at 0.2 s that is higher than the UHS for 2475 years and a second peak at ~0.7-0.8 s which exceeds the UHS for 975 years. At the other stations, instead, the maximum horizontal components are always lower than the MPS04 UHS for 475 years return period.

Table 1: *Data of the accelerometric stations considered in this study (http://esm.mi.ingv.it).*

Station code	*EC8 Soil class*	*Epic. distance (km)*	*PGA (g)*
AMT	B*	8.5	0.8673
NRC	B	16.0	0.3733
PCB	B*	17.7	0.3077
CSC	B	19.6	0.1068
MSC	B*	21.3	0.1055
MSCT	B*	21.3	0.1101
RM33	B*	21.9	0.1023
SPD	B*	23.2	0.1018

III. CONCLUSIONS

A comparison between available recordings for the 24 August 2016 Amatrice earthquake and expected accelerations provided by the reference seismic hazard model (MPS04) for Italy was performed. As shown in Figures 4 and 5, at the accelerometric station closest to the epicenter (AMT), the observed accelerations exceed the expected values given by MPS04. Recorded spectra for the other stations located at epicentral distances lower than 25 km are instead consistent with expected accelerations (Figure 6).

In order to understand possible reasons for the "failure" of the MPS04 model at AMT station, we investigated the impact of the adoption of different GMPEs on PSH assessment.

To this purpose, we computed the hazard using the same earthquake rate model of MPS04 but a more recent GMPE (i.e. ITA10 [Bindi et al., 2011]) than those originally adopted. Results show a strong increase of expected values for both PGA (Fig. 4) and UHS (Fig. 5), thus making the PSH estimates consistent with the observations.

As known, recent GMPEs produce higher hazard estimates, due to the larger values of uncertainty (standard deviation) with respect to older GMPEs (e.g. [Bommer and Abrahamson, 2006]).

Moreover, it is worth noting that the ITA10 equation was derived from an Italian strong-motion dataset that includes also recordings in the near field, that were lacking in previous GMPEs used for the MPS04 model (e.g. [Sabetta and Pugliese, 1996]).

Anyway, the very high accelerations recorded at AMT (the largest PGA ever recorded in Italy) could be due to pulse-like motions in the near field as discussed in [ReLUIS-INGV Workgroup, 2016]; a similar effect was also observed for the L'Aquila 2009 Mw 6.1 earthquake [Chioccarelli and Iervolino, 2010].

As mentioned above, the aim of this study was not to validate the MPS04 model, but rather to evaluate the "relative position" of the 24 August 2016 earthquake with respect to the range of PSH values proposed in that model.

Any PSH model, however, has to be considered with respect to the available data and knowledge at the time of its release. MPS04 adopted the best input data available in 2004, and the same applies to the SHARE project ten years later. As an example we showed how the use of a recent GMPE changes the hazard.

For this reason, the Italian reference seismic hazard model is currently under re-evaluation (https://ingvcps.wordpress.com/), taking into account state-of-the-art methodological approaches, input data, and computational codes.

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