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Exceedance of design seismic actions during the 2016-2017 central Italy seismic sequence: sensitivity to two seismic hazard models

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Abstract

In Italy, seismic ground motion intensity for structural design relies on probabilistic seismic hazard analysis (PSHA). Research has shown that, even in the case of a moderate magnitude earthquake, it is expected that ground motion intensities larger than the design counterparts are observed at some sites in the epicentral region. The area where such an exceedance has possibly occurred can be assessed via ShakeMap. In the case of seismic sequences, ShakeMap envelopes allow to identify the fraction of the region of interest subjected to at least one exceedance of design seismic actions. For the 2016-2017 central Italy sequence, ShakeMap envelopes reveal that exceedance of the design intensity enforced by the current building code occurred in an area covering thousands of square kilometers, depending on the spectral and exceedance return period of the design intensity. This study quantifies the exceedance area of ground motion intensity according to the PSHA results based on two alternative PSHA models for Italy. One is that at the basis of the official PSHA for Italy adopted by the current building code, known as MPS04; the other relies on a grid-seismicity source model deriving from a set of source models recently developed for a new PSHA study for the country (MPS19). Looking at ShakeMap envelopes, it is found that the estimated exceedance area is of the same order of magnitude for the two hazard models, at least for the spectral and exceedance return periods considered herein.

Keywords: *MPS04; MPS19; exceedance of PSHA seismic actions; ShakeMap envelope.*

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1. Introduction

On 24th August 2016, an earthquake with magnitude (M) equal to six struck central Italy. It occurred near Amatrice and heavily damaged the built environment in the surrounding areas, causing more than three-hundred fatalities overall (Luzi et al., 2017). This earthquake is considered to be the initiating event of a seismic sequence counting more than ten thousand M2+ earthquakes up to August 2019, nine of which with magnitude in the 5.0-6.5 range. Among these, five occurred within the end of 2016, including the M6.0 initiating event and the largest magnitude one (i.e., M6.5), denoted as the *mainshock* hereafter. The remaining M5+ earthquakes occurred in the vicinity of Amatrice, all on 18th January 2017.

Ground motion effects in the hit areas have been made available by *Istituto Nazionale di Geofisica e Vulcanologia* (INGV), which currently implements the ShakeMap (v4.0) tool (Wald et al., 1999). ShakeMap provides, specifically for one earthquake (if it has magnitude equal to or larger than 3.0), the map of the shaking for five ground motion intensity measures, that is, peak ground acceleration (*PGA*), spectral pseudo-acceleration, $Sa(T)$, at the vibration periods (T) equal to 0.3s, 1s and 3s, and macroseismic intensity in terms of *Mercalli-Cancani-Sieberg* scale (Michelini et al., 2020). ShakeMap includes the uncertainty in the ground motion, as described in Worden et al. (2018), and information about local soil condition based on the available large-scale geological maps.

ShakeMap data can be used to identify the area where structures could have been exposed to seismic actions larger than those enforced by the building code for design. Considering the central Italy 2016-2017 seismic sequence, Iervolino et al. (2021) elaborated ShakeMap *envelopes* to identify the area subjected to the most relevant shaking, in terms of different intensity measures, due to the nine M5+ earthquakes of the sequence. Ground motion intensities from the envelopes were compared to the design seismic actions mandated by the Italian building code, to delimit the area where they have been possibly exceeded during the sequence at least once. Such an area was quantified in even thousands of square kilometers, depending on the spectral and exceedance return period of the design intensity.

In Italy, ground motion intensity for seismic design of structures is the ordinate of a spectrum, with a pre-determined exceedance return period (T_r), obtained from the probabilistic seismic hazard analysis (PSHA; Cornell, 1968) for the construction site. The PSHA adopted by the current building code in Italy (CS.LL.PP., 2018) is described by Stucchi et al. (2011). Commonly named as MPS04 (Gruppo di Lavoro, 2004), it relies on the source model of Meletti et al. (2008) and a set of ground motion prediction equations (GMPEs) developed some decades ago.

Recently, Meletti et al. (2021) developed a new seismic hazard assessment study for Italy (MPS19). The PSHA is computed using different source models and a set of GMPEs appositely selected for Italy by Lanzano et al. (2020). As a by-product of this work, a grid-seismicity source model was also derived (Chioccarelli et al., 2021).

The objective of this simple study is to investigate how the area exposed to at least one exceedance of ground motion intensities according to PSHA, during the 2016-2017 central Italy seismic sequence, varies with the hazard model that the PSHA relies on. Two hazard models are taken into account. One considers the source model and one among the GMPEs used in MPS04. The other adopts the grid-seismicity source model derived from the source models of MPS19, coupled with a single GMPE among those suggested by Lanzano et al. (2020). The sensitivity of the exceedance area to the two PSHA models is analyzed by comparing the spectral accelerations from ShakeMap envelopes of M5+ earthquakes of the sequence, in terms of *PGA* and $Sa(T = 1\text{s})$, with those from the hazard maps with $T_r = 50yr$ and $T_r = 475yr$.

The paper is structured as follows. After presenting countrywide seismic hazard maps according to the PSHA results based on the two hazard models, ShakeMap envelopes of M5+ earthquakes of the central Italy sequence are briefly recalled. Subsequently, for each spectral and return period, the area including the sites exposed to at least one exceedance, during the sequence, of the spectral acceleration according to the two PSHA models is mapped and quantified. The study concludes with some final remarks.

2. Two seismic hazard models for Italy

This section briefly introduces the main features of the two hazard models for Italy, first; then, nationwide PSHA results, obtained using (separately) the both of them, are presented via seismic hazard maps, in terms of *PGA* and $Sa(T=1\text{s})$ with $T_r = 50yr$ and $T_r = 475yr$.

The PSHA results used in this study are linked to two different seismic hazard models, that is, MPS04 and MPS19. MPS04, which is currently the reference PSHA in Italy for seismic structural design, relies on thirty-six seismic source zones without background seismicity. It features a logic tree with several branches. The first PSHA model considered herein adopts the models of the branch named 921 of MPS04 (see Stucchi et al., 2011). According to this branch, for each source zone, seismicity is defined in terms of the so-called *activity rates*, that is, annual rates of earthquakes associated to (surface) magnitude bins that are 0.3 magnitude units wide. The lowest magnitude bin is centered at M4.3 for all zones (with the exception of the Etna's volcanic area, being M3.7), whereas the central value of the largest magnitude bin can be as high as 7.3, depending on the zone (e.g., Cito and Iervolino, 2020). The GMPE is that of Ambraseys et al. (1996). The predominant style-of-faulting of the sources (see Meletti et al., 2008) is also accounted for in the PSHA via the correction factors proposed by Bommer et al. (2003). In the following, the PSHA results based on the models of branch 921 of MPS04 are denoted as $PSHA_{04}$ and are assumed as a benchmark.

MPS19, the recent hazard model for Italy, is based on ninety-four source models (Visini et al., 2021), which are combined via logic tree. The whole logic tree, including the GMPEs, counts about six-hundred branches, and therefore its implementation in PSHA can be challenging. However, a relatively easy-to-implement weighted average grid-seismicity source model was also developed. It covers the whole national territory via point-like seismic sources, about eleven thousand in number. Forty-six activity rates, with width equal to 0.1 magnitude units, are given for each point source. The minimum (moment) magnitude bin is centered at M4.5 across all the country. The largest magnitude is M9.0 in about 85% of the country and M8.3 in the remaining areas. For each seismic source, the probabilistic distribution of the style-of-faulting is also defined. This grid-seismicity source model, coupled with the GMPE of Bindi et al. (2011), form the second hazard model used in this study, and the PSHA results based on it are referred to as $PSHA_{19}$.

The $PSHA_{04}$ and the $PSHA_{19}$ hazard maps were computed via the REASSESS software (Chioccarelli et al., 2019), in which the above introduced models are embedded. The maps were compiled using a grid of about ten thousand sites covering the whole Italy (Sardinia Island is not taken into account, as MPS04 does not provide hazard results for the region). Because the Ambraseys et al. (1996) GMPEs considers the largest ground motion intensity between the two horizontal component of shaking, whereas the one by Bindi et al. (2011) uses the geometric mean, the $PSHA_{19}$ results were adjusted to be comparable with $PSHA_{04}$. The adjustment was carried out according to Beyer and Bommer (2006), which resulted into amplifying the accelerations from $PSHA_{19}$ hazard map by 10% for *PGA* and 20% for $Sa(T=1\text{s})$, for all return periods considered.

Hazard maps are shown in Fig. 1 and Fig.2, referring to $T_r = 50yr$ and $T_r = 475yr$, respectively. Each figure is structured such that panels from (a) to (c) refer to *PGA*, while those from (d) to (f) pertain to $Sa(T=1\text{s})$. From left to right, panels show the hazard maps on rock site conditions according to $PSHA_{04}$, those for $PSHA_{19}$ (adjusted for the largest horizontal component), and their relative differences measured as $\Delta = Sa_{PSHA19} - Sa_{PSHA04} / Sa_{PSHA04}$. The leftmost and rightmost maps also show the MPS04 source zones, whereas the grid-seismicity source model is not represented because, as discussed, it covers the whole Italy. It appears that $PSHA_{04}$ and $PSHA_{19}$ maps generally show a similar pattern. For instance, in each hazard map, the largest accelerations are found in the central and southern Italy, along the Apennines mountain chain and Calabrian Arc, and in north-eastern area. However, some differences can be found in both the cases of *PGA* and $Sa(T=1\text{s})$ for both return periods, as the maps in the rightmost panels of Fig. 1 and Fig.2 show. Looking at $T_r = 50yr$, it can be observed that $PSHA_{19}$ results are lower than those of $PSHA_{04}$ across almost all the country, for both the spectral ordinates, especially in the areas within some MPS04 source zones (Fig. 1c and Fig. 1f). The fact that MPS04 zones do not cover the whole country, as the grid-seismicity source model does instead, is one possible reason, among others, for the geographical distribution of the differences between the hazard maps. In the case of $T_r = 475yr$, that is, considering larger seismic hazard, the effect of MPS04 zones on these differences is even more evident.

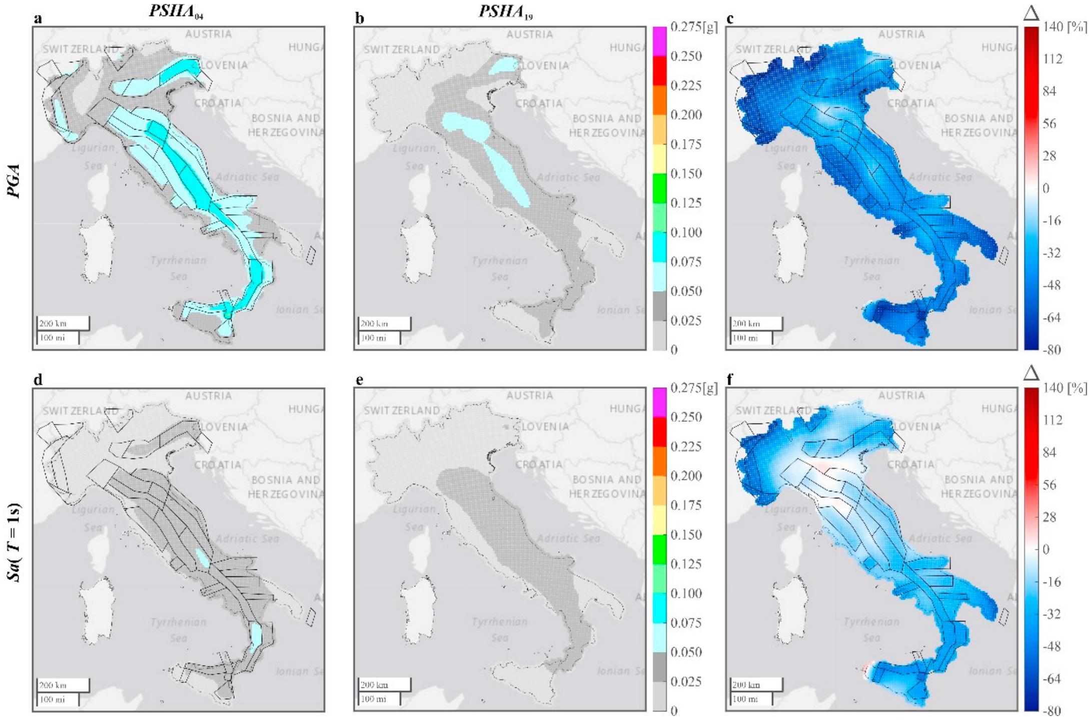

Fig. 1 – Seismic hazard maps with $T_r = 50\,yr$ in terms of PGA (panels from a to c) and $Sa(T = 1\text{s})$ (panels from d to f) on rock site conditions according to $PSHA_{04}$ (left) and $PSHA_{19}$ (middle), and their relative differences (right).

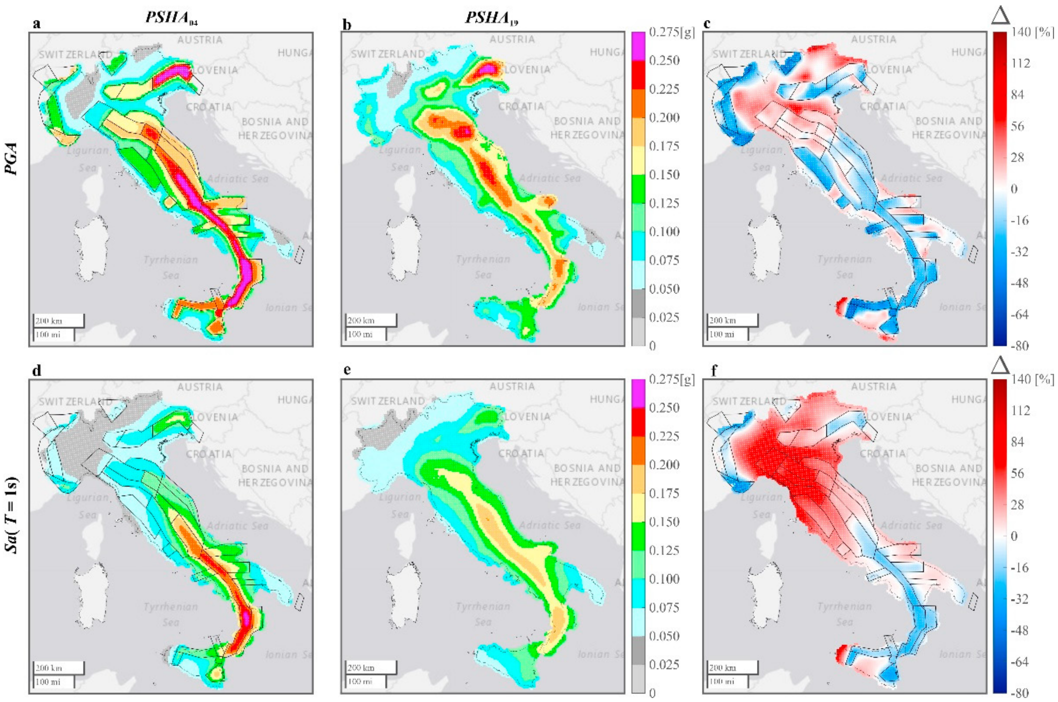

Fig.2 - Seismic hazard maps with $T_r = 475\,yr$ in terms of PGA (panels from a to c) and $Sa(T = 1\text{s})$ (panels from d to f) on rock site conditions according to $PSHA_{04}$ (left) and $PSHA_{19}$ (middle), and their relative differences (right).

Fig.2c shows that $PSHA_{19}$ results, in terms of PGA, are lower than $PSHA_{04}$ ones in the moderate-to-high hazardous areas of the country found within the MPS04 zones in Sicily, along the Apennines, in southern and central Italy, north-east and north-west regions (bluish areas). The opposite is found at the sites found outside the MSP04 zones (reddish areas), and in the areas within some MPS04 zones in the Emilia region (northern Italy). Fig.2d reveals that, for $Sa(T=1\text{s})$, the areas where $PSHA_{19}$ hazard is larger than $PSHA_{04}$ are more widespread and include several MPS04 zones in northern and central Italy.

3. ShakeMap envelopes

ShakeMap envelope, in terms of a chosen ground motion intensity measure, provides (an estimate of) the largest shaking that has been possibly observed in the area struck by a seismic sequence. In order to build the envelope, one needs the ground motion intensities given by ShakeMap for the earthquakes belonging to the considered sequence. Taking, for each point of a grid discretizing the area of interest, the largest shaking value among those provided by ShakeMap for the considered events, gives the sought envelope. The envelopes presented in this section account for the nine M5+ earthquakes of the 2016-2017 central Italy sequence. They are shown in Fig. 3, in terms of PGA (a) and $Sa(T=1\text{s})$ (b).

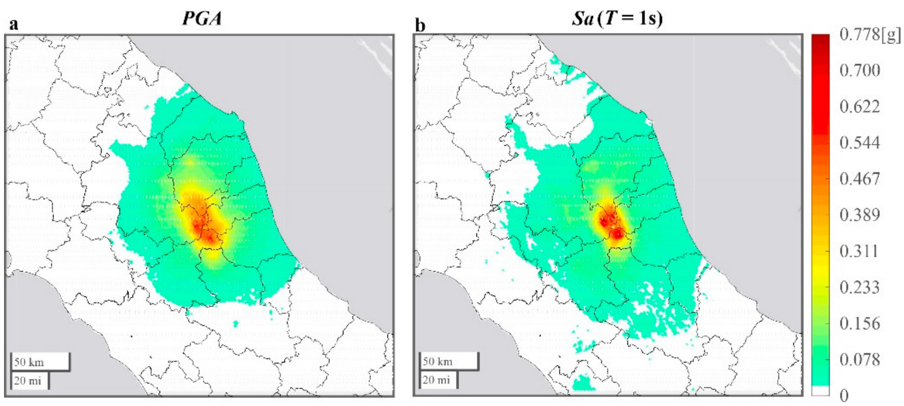

Fig. 3 – ShakeMap Envelope for the nine M5+ earthquakes of the sequence in terms of PGA (a) and $Sa(T=1\text{s})$ (b).

The grid used for the envelopes features about 99000 points covering an inland area about 62000 km^2 wide (envelope data are from Iervolino et al., 2021). The envelopes show that the largest estimated intensities are distributed along the Apennine, that is, the northwest-southeast direction (see Luzi et al., 2017 for insights). According to ShakeMap, the largest ground motion intensity of the sequence is equal to 0.65 g and 0.77 g in the case of PGA and $Sa(T=1\text{s})$, respectively.

4. Exceedance area

Fig. 1 and Fig.2 show that some differences between the $PSHA_{04}$ and $PSHA_{19}$ results can be found in the area of the ShakeMap envelopes. In fact, both PGA and $Sa(T=1\text{s})$ with $T_r=50yr$ from $PSHA_{19}$ hazard map are lower than $PSHA_{04}$ in almost the whole central Italy. The same is also found for the PGA with $T_r=475yr$, whereas, in the case of $Sa(T=1\text{s})$, there are some areas where $PSHA_{19}$ results are larger than $PSHA_{04}$. As a consequence, herein it is assessed how much these differences affect the estimation of the area subjected to at least one exceedance due to the nine M5+ earthquakes of the 2016-2017 seismic sequence. The area where at least one exceedance has possibly occurred during the sequence is quantified by comparing the ground motion intensities from the previously discussed ShakeMap envelopes to the $PSHA_{04}$ and $PSHA_{19}$ hazard maps. In doing so, the spectral accelerations from hazard maps are interpolated on the ShakeMap grid used for the envelope and are adjusted for the site conditions as accounted for by ShakeMap via soil-specific amplification coefficients, provided by the GMPEs, as discussed in Iervolino (2016). The comparison of ShakeMap envelopes with the $PSHA_{04}$ and $PSHA_{19}$ hazard maps, adjusted for site conditions, is given in the left and right columns of Fig. 4, respectively, in terms of *PGA* (panels a and b) and $Sa\left(T=1\text{s}\right)$ (panels c and d).

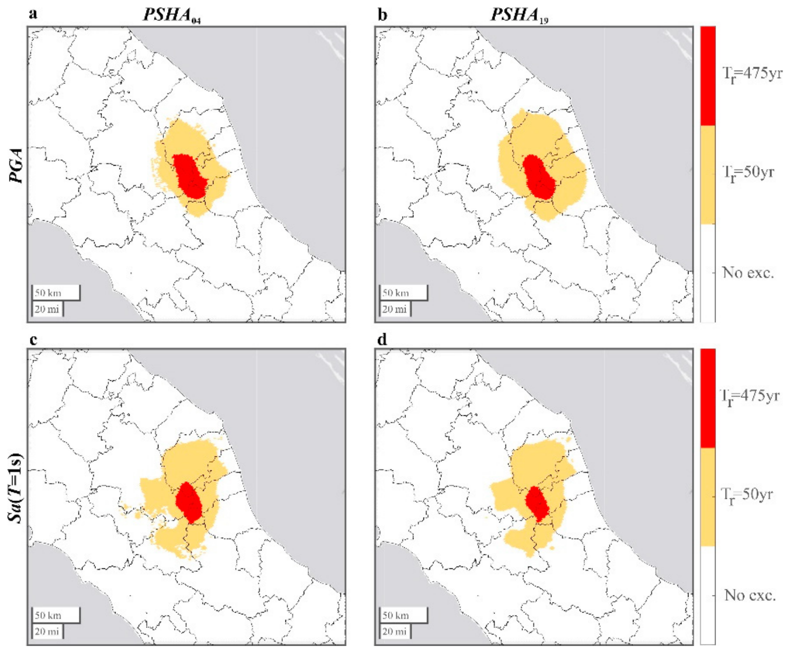

Fig. 4 – Exceedance area of the *PGA* (panels a and b) and $Sa\left(T=1\text{s}\right)$ (panels c and d) with $T_r=50yr$ and $T_r=475yr$ from the seismic hazard map based on $PSHA_{04}$ (left) and $PSHA_{19}$ (right) considering ShakeMap envelopes.

In each map, the white area denotes the non-exceedance; i.e., it identifies the grid points where none of the M5+ earthquakes of the sequence caused exceedance of the ground motion intensity from PSHA. The area colored in orange includes those sites that, according to ShakeMap estimates, possibly experienced at least one exceedance (i.e., due to one among the nine M5+ events) of the spectral acceleration with $T_r=50yr$ between August 2016 and January 2017. For some of these sites, the acceleration from ShakeMap envelope is even larger than the PSHA counterpart with $T_r=475yr$; i.e., the reddish areas. This happens especially in the areas around the epicenter of the M6.5 earthquake, the effects of which are in fact the most relevant of the sequence (see Iervolino et al., 2021).

The comparison between the maps for $PSHA_{04}$ and $PSHA_{19}$ seems to suggest that the area exposed to at least one exceedance of ground motion intensities according to PSHA, during the central Italy sequence, is of the same order of magnitude for the two hazard models used in the analyses. In quantitative terms, the exceedance of the *PGA* with $T_r=50yr$ as per $PSHA_{04}$ is estimated in an area covering about 5000 km^2, and it is about 7000 km^2 in the case of $PSHA_{19}$. This is the case, among the considered spectral and exceedance return periods, in which the (absolute) difference between the exceedance areas is the largest, and it is somehow expected. In fact, in central Italy, the most relevant differences between $PSHA_{04}$ and $PSHA_{19}$ hazard results are found for the *PGA* with $T_r=50yr$ (see Fig. 1 and Fig.2). The exceedance of the *PGA* with $T_r=475yr$ has possibly occurred at least once during the sequence in an area covering about 1000 km^2 in both the cases of $PSHA_{04}$ and $PSHA_{19}$, with a difference less than 50 km^2. In fact, moving to $Sa\left(T=1\text{s}\right)$, the difference between results found for the two hazard models is about 500 km^2 in the case of $T_r=50yr$, being the exceedance area about 7000 km^2 and 6500 km^2 for $PSHA_{04}$ and $PSHA_{19}$, respectively. Such a difference reduces to about 200 km^2 in the case of $Sa\left(T=1\text{s}\right)$ with $T_r=475yr$, as the estimated exceedance area is about 800 km^2 for $PSHA_{04}$ and 600 km^2 for $PSHA_{19}$.

5. Conclusions

In this study, the ground motion intensity, from ShakeMap envelopes for the M5+ earthquakes of the 2016-2017 central Italy seismic sequence, were compared to the PSHA results for the hit area, in terms of PGA and $Sa(T=1\text{s})$ with 50 and 475 years exceedance return period. For each spectral and return period, the ground motion intensity in the area struck by the sequence was derived from two countrywide seismic hazard maps, which were computed via PSHA using (separately) two different hazard models. One is related to that adopted by the PSHA lying at the basis of the building code in Italy, known as MPS04. The other is based on an average grid-seismicity source model, derived from a set of source models used for a recent PSHA study for Italy, named MPS19. After a brief analysis of the differences between the hazard maps based on these two models, the study investigated how the area subjected to at least one exceedance of the ground motion intensities according to PSHA, estimated using ShakeMap envelopes, varies with the hazard model. The following was found.

- The differences between the two hazard models is such that $PSHA_{19}$ results, in terms of PGA and $Sa(T=1\text{s})$ with $T_r = 50yr$, are lower than $PSHA_{04}$ across almost the whole country, especially in the areas within the MPS04 source zones. For $T_r = 475yr$, $PSHA_{19}$ tends to be lower than $PSHA_{04}$ in the moderate-to-high hazardous areas of the country, including the area struck by the 2016-2017 central Italy seismic sequence; in the areas outside MPS04 zones, $PSHA_{19}$ results tend to be larger than $PSHA_{04}$.
- For the considered vibration and return periods, the estimated area exposed to at least one exceedance is of the same order of magnitude for the considered PSHA models. Such an area is in the 5000-7000 km^2 range for $T_r = 50yr$ and 600-1000 km^2 for $T_r = 475yr$, depending on the spectral ordinate and the PSHA model. For $T_r = 50yr$, the absolute difference between the exceedance areas is about 2000 km^2 and 500 km^2 for PGA and $Sa(T=1\text{s})$, respectively; in the case of $T_r = 475yr$, it reduces to 50 km^2 for PGA and 200 km^2 for $Sa(T=1\text{s})$.

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References

Ambraseys, N.N., Simpson, K.A., Bommer, J.J., 1996. Prediction of horizontal response spectra in Europe. Earthquake Engineering and Structural Dynamics, 25(4), 371–400. https://doi.org/doi:10.1002/[SICI]1096-9845[199604]25:4<371::AID-EQE550>3.0.CO;2-A.

Beyer, K., Bommer, J.J., 2006. Relationships between Median Values and between Aleatory Variabilities for Different Definitions of the Horizontal Component of Motion. Bulletin of the Seismological Society of America, 96, 1512–1522. https://doi.org/10.1785/0120050210

Bindi, D., Pacor, F., Luzi, L., Puglia, R., Massa, M., Ameri, G., Paolucci, R., 2011. Ground motion prediction equations derived from the Italian strong motion database. Bulletin of Earthquake Engineering, 9(6), 1899–1920. https://doi.org/10.1007/s10518-011-9313-z

Bommer, J., Douglas, J., Strasser, F., 2003. Style-of-Faulting in Ground-Motion Prediction Equations. Bulletin of Earthquake Engineering, 1, 171–203. https://doi.org/10.1023/A:1026323123154

Chioccarelli, E., Cito, P., Iervolino, I., Giorgio, M., 2019. REASSESS V2.0: software for single- and multi-site probabilistic seismic hazard analysis. Bulletin of Earthquake Engineering, 17, 1769–1793. https://doi.org/10.1007/s10518-018-00531-x

Chioccarelli, E., Cito, P., Visini, F., Iervolino, I., 2021. Sequence-based hazard analysis for Italy considering a grid seismic source model. Annals of Geophysics, 64(2). https://doi.org/10.4401/ag-8586

Cito, P., Iervolino, I., 2020. Rarity, proximity, and design actions: mapping strong earthquakes in Italy. Annals of Geophysics, 63(6). https://doi.org/10.4401/ag-8516

Cornell C. Allin., 1968. Engineering Seismic Risk Analysis. Bulletin of the Seismological Society of America, 58, 1583–1606.

CS.LL.PP., 2018. Decreto Ministeriale: Norme tecniche per le costruzioni. Gazzetta Ufficiale della Repubblica Italiana, n.42, 20 febbraio, Suppl. Ordinario n.8 Ist. Polig. e Zecca dello Stato S.p.a., Rome (in Italian).

Gruppo di Lavoro., 2004. Catalogo Parametrico dei Terremoti Italiani, versione 2004 (CPTI04), INGV. http://emidius.mi.ingv.it/CPTI/.

Iervolino, I., 2016. Soil-invariant seismic hazard and disaggregation. Bulletin of the Seismological Society of America, 106(4), 1900–1907. https://doi.org/10.1785/0120160072

Iervolino, I., Cito, P., Felicetta, C., Lanzano, G., Vitale, A., 2021. Exceedance of design actions in epicentral areas: insights from the ShakeMap envelopes for the 2016–2017 central Italy sequence. Bulletin of Earthquake Engineering, 19(13), 5391–5414. https://doi.org/10.1007/s10518-021-01192-z

Lanzano, G., Luzi, L., D'Amico, V., Pacor, F., Meletti, C., Marzocchi, W., Rotondi, R., Varini, E., 2020. Ground motion models for the new seismic hazard model of Italy (MPS19): selection for active shallow crustal regions and subduction zones. Bulletin of Earthquake Engineering, 18(8), 3487–3516. https://doi.org/10.1007/s10518-020-00850-y

Luzi, L., Pacor, F., Puglia, R., Lanzano, G., Felicetta, C., D'Amico, M., Michelini, A., Faenza, L., Lauciani, V., Iervolino, I., Baltzopoulos, G., Chioccarelli, E., 2017. The Central Italy Seismic Sequence between August and December 2016: Analysis of Strong-Motion Observations. Seismological Research Letters, 88(5), 1219–1231. https://doi.org/10.1785/0220170037

Meletti, C., Galadini, F., Valensise, G., Stucchi, M., Basili, R., Barba, S., Vannucci, G., Boschi, E., 2008. A seismic source model for the seimic hazard assessment of the Italian territory. Tectonophysics, 450(1), 85–108. https://doi.org/10.1016/j.tecto.2008.01.003

Meletti, C., Marzocchi, W., D'Amico, V., Lanzano, G., Luzi, L., Martinelli, F., Pace, B., Rovida, R., Taroni, M., Visini, F., group, M.P.S., 2021. The new Italian seismic hazard model (MPS19). Annals of Geophysics, 64. https://doi.org/10.4401/ag-8579

Michelini, A., Faenza, L., Lanzano, G., Lauciani, V., Jozinović, D., Puglia, R., Luzi, L., 2020. The New ShakeMap in Italy: Progress and Advances in the Last 10 Yr. Seismological Research Letters, 91(1), 317–333. https://doi.org/10.1785/0220190130

Stucchi, M., Meletti, C., Montaldo, V., Crowley, H., Calvi, G.M., Boschi, E., 2011. Seismic Hazard Assessment (2003-2009) for the Italian Building Code. Bulletin of the Seismological Society of America, 101(4), 1885–1911. https://doi.org/10.1785/0120100130

Visini, F., Pace, B., Meletti, C., Marzocchi, W., Akinci, A., Azzaro, R., Barani, S., Graziella, B., Barreca, G., Basili, R., Bird, P., Bonini, M., Burrato, P., Busetti, M., Carafa, M., Cocina, O., Rodolfo, C., Corti, G., D'Agostino, N., Zuccolo, E., 2021. Earthquake Rupture Forecasts for the MPS19 Seismic Hazard Model of Italy. Annals of Geophysics, 64. https://doi.org/10.4401/ag-8608

Wald, D.J., Quitoriano, V., Heaton, T.H., Kanamori, H., Scrivner, C.W., Worden, C.B., 1999. TriNet "ShakeMaps": Rapid Generation of Peak Ground Motion and Intensity Maps for Earthquakes in Southern California. Earthquake Spectra, 15(3), 537–555. https://doi.org/10.1193/1.1586057

Worden, C.B., Thompson, E.M., Baker, J.W., Bradley, B.A., Luco, N., Wald, D.J., 2018. Spatial and Spectral Interpolation of Ground-Motion Intensity Measure Observations. Bulletin of the Seismological Society of America, 108(2), 866–875. https://doi.org/10.1785/0120170201