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A scoring test on probabilistic seismic hazard estimates in Italy

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seismogenic structures or seismic waves propagation patterns) and statistical (e.g. average seismicity rates) elements. The last ones aim at managing the lack of information about important elements of seismic hazard (e.g., seismogenic activity of the faults) that results into an intrinsic aleatory character of seismic occurrences (the so called “aleatory uncertainty”). Actually, many PSHA procedures exist that mainly differentiate for the relative roles played by deterministic and statistical elements. Procedures span from purely deterministic approaches assuming a nearly complete knowledge of the seismic process (e.g., Peresan et al., 2011) to purely statistical analyses assuming a nearly complete ignorance of underlying physical processes (e.g., Kagan and Jackson, 1994; Frankel, 1995; Albarello and Mucciarelli, 2002), including balanced combinations of deterministic and statistical elements to manage aleatory uncertainty (e.g., Cornell, 1968; McGuire, 1978). Outcomes of these approaches may present strong differences and this makes mandatory any evaluation of the respective heuristic value and effectiveness. Arrogating ageless Shakespeare’s words “Shall I compare thee to a summer’s day”, comparison of subjects with different nature is always difficult. Actually, effectiveness of any considered procedure (which includes both computational aspects and data used to feed the model) is uncertain (an “epistemic uncertainty”) and this is managed by associating to each procedure a degree of “belief” (again in the form of a probability). Being hazard estimates ultimately the combination of relevant uncertainties (and complementarily of lack of uncertainty about deterministic elements), both aleatory and epistemic uncertainties have to be considered and contribute to the estimate of the hazard curve.

While each PSHA procedure is on purpose determined to manage the relevant aleatory uncertainty via probabilistic modelling, assessment and management of epistemic uncertainty are more controversial topics. Given any i th PSHA model H_i , epistemic uncertainty can be defined as the probability $P(H_i)$ expressing the degree of belief in the effectiveness of that model. This formalization allows the management of epistemic uncertainty within a coherent frame (Albarello and D’Amico, 2014). A key aspect is the way to assess $P(H_i)$, i.e., scoring H_i . Two general approaches

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model H_i provides a correct hazard estimate (Albarello and D'Amico, 2008). Given the model H_i and the set of sites $E_{\Delta t^*}$ where ground shaking has been monitored during the control interval Δt^* of duration equal to the hazard exposure time Δt , the model's likelihood L_i can be estimated from the control sample $E_{\Delta t^*}$. If the seismic occurrences e_s are mutually independent (in the PSHA computational model considered) and if, over the duration of the control interval, a total of N^* out of S sites have experienced ground shaking above any threshold g_0 , then we have

$$L_i = P(E|H_i, \Delta t) = \left\{ \prod_{s=1}^{N^*} P(e_s|H_i, \Delta t) \right\} \left\{ \prod_{s=N^*+1}^S [1 - P(e_s|H_i, \Delta t)] \right\}, \quad (1)$$

where each value $P(e_s|H_i)$ is the hazard estimated (i.e., the exceedance probability for g_0) by the i th model at the s th site for the exposure time $\Delta t = \Delta t^*$. In the case that time stationarity is assumed in the relevant PSHA model, the overall duration of the exposure time is of concern only; this is not true when time-dependent PSHA models are considered. Of course one should account that several possible combinations sites/events may exist that result in the same configuration of the available evidence: all sites characterized in H_i by the same exceedance probability are equivalent. It is worth to note, however, that likelihood value in Eq. (1) also depends on the number of sites considered and on the P values of concern: this implies that comparison among different models by using respective likelihoods should be performed by considering the same values for S and P . When this is not the case, any kind of “rescaling” is necessary. This rescaling could be performed by considering instead of Eq. (1) the “support” function l that is the log-likelihood ratio as defined by Edwards (1972) in the form

$$l_i = \left\{ \sum_{s=1}^{N^*} \ln [P(e_s|H_i, \Delta t)] + \sum_{s=N^*+1}^S \ln [1 - P(e_s|H_i, \Delta t)] \right\} - r [P(e_s|H_i, \Delta t), S], \quad (2)$$

where r is a reference log-likelihood value computed as in Appendix A as a function of $P(e_s|H_i)$ and S .

It can be seen (Kagan and Jackson, 1994) that probability distribution of the support I is nearly normal. This formulation allows using the reference value in the Appendix A and the relevant standard deviation to compute a studentized form of I as

$$Z_i = |I_i / \sigma_i(P, S)|, \quad (3)$$

where the denominator is provided in Eq. (A5). In general, values of Z_i near 0 indicate best performing models while $Z_i > 2$ indicate models providing outcomes significantly different from observations. In this case, the model should be considered as “unreliable”. In this frame, the value Z_i can be considered as the “score” of the i th model: smaller is Z better is the computational model.

Other possibilities exist for testing any PSHA procedure against the evidence E (e.g., Schorlemmer and Gerstenberger, 2007; Schorlemmer et al., 2007). Counting is one of these procedures. In this case, a binary variable $e_s(g_0)$ is defined which assumes the value of 1 if during the control interval Δt^* (which has the same extension as the hazard exposure time Δt) at least one earthquake occurred producing a ground motion in excess of g_0 at the s th site; otherwise $e_s(g_0) = 0$. We define the “control sample” $E_{\Delta t^*}$ as the set of S realizations of the variable $e_s(g_0)$ at S sites. The i th considered PSHA computational model H_i provides a probability P_{si} for the event $e_s(g_0) = 1$ given by

$$P_{si} = P(e_s | H_i), \quad (4)$$

where the dependence on g_0 and Δt is omitted to simplify the notation. Expectation μ_{si} and standard deviation σ_{si} relative to the Bernoulli variable e_s result to be

$$\mu_{si} = \mu(e_s | H_i) = P_{si} \quad (5)$$

and

$$\sigma_{si} = \sqrt{P_{si}(1 - P_{si})} \quad (6)$$

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respectively. The number N^* of sites out of the S sites considered for testing that experienced at least one earthquake during Δt^* with ground shaking greater than g_0 is

$$N^* = \sum_{s=1}^S e_s. \quad (7)$$

In terms of probabilistic forecasts provided by the H_i PSHA computational model, N^* is a random variate with expectation

$$\mu_i(N^*) = \sum_{s=1}^S \mu_i(e_s) = \sum_{s=1}^S P(e_s|H_i). \quad (8)$$

In the hypothesis that e_s are independent realizations of the stochastic process modeled in the PSHA computations, one can assume that

$$P_i(e_s|e_z) = P_i(e_s), \quad (9)$$

where e_s and e_z are the realizations of the Bernoulli variable defined above at two generic s th and z th sites. In this case, the standard deviation of the random variable N^* is

$$\sigma_i(N^*) = \sqrt{\sum_{s=1}^S P_{si}(1 - P_{si})}. \quad (10)$$

When S is relatively large, the Lyapunov variant of the Central Limit Theorem (e.g., Gnedenko, 1976) implies that

$$\text{prob}[|N^* - \mu_i(N^*)| \geq 2\sigma_i(N^*)] \cong 0.05. \quad (11)$$

Equation (11) allows us to evaluate whether a potential disagreement between the experimental value N^* and the “forecast” $\mu_i(N^*)$ is statistically significant, thus making the H_i PSHA computational model “not confirmed” by the set of S observations.

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depending on the soil type and topographic class at the site, but also on the hazard estimated on the reference outcrop. The relevant correction coefficients computed at the 71 accelerometric stations considered for testing (Fig. 2) are reported in the Supplement File A; details are given in Sect. 3.2.3 of NTC08. These coefficients represent a first approximation to site-specific hazard, coherent with the common practice for buildings that do not require specific studies; they have been used to correct maximum PGA values observed on horizontal components in the time interval 1979–2004.

About available recordings, on 71 stations, 12 have no records at all, for this 25 year long period. In these cases, we assumed the sensitivity threshold of the early deployed accelerometers (0.01 g, i.e. 9.8 cm s^{-2}) as the maximum “observed” value. We checked possible problems with data completeness that nevertheless we acknowledge they cannot be properly fixed. For this purpose, PGA values expected at all the sites due to the occurrence of nearby earthquakes have been computed (synthetic “observations”), on the basis of epicentral information (CPTI11 earthquake catalogue, Rovida et al., 2011) and the Ground Motion Prediction Equation (GMPE) ITA10 by Bindi et al. (2011). In particular, synthetic PGA values have been considered potential observations at the relevant site if they exceed the sensitivity trigger threshold. Synthetic PGA values obtained at ALT (Auletta, Salerno) and PTL (Pietralunga, Perugia) stations are plotted in Fig. 3, and compared with effective recorded data: note that even if some data are possibly missing (blue circles in Fig. 1 correspond to values above the sensitivity threshold of the accelerometric network), on average, the maximum observed values in the time window considered for the analysis is coherent with the expectations. We estimated that missing maximum PGA should have occurred on less than 5% of stations, thus not affecting the results obtained. This analysis also suggested that completeness problems should be critical if testing were performed on the whole sequence of observations instead of only maximum observed PGA.

On the subset of selected stations, the observed maximum PGA values span from about 1 cm s^{-2} for $M < 4.5$ earthquakes at about 40–60 km distance (e.g. at ARI Ariano



Irpino, Avellino) to the 490 cm s^{-2} at NCR (Nocera Umbra, Perugia) for the main shock of the long lasting Colfiorito Umbria-Marche sequence (26 September 1997, $M_w = 6.0$ at 11 km distance). Station code, coordinates, site conditions and the maximum registered PGA values are given in the Supplement File A.

4 Models: PSHA in Italy

Italy has three maps, or groups of maps, of PSHA which have been turned into regulation acts, therefore having an impact on society: as shown in Fig. 4, these maps were released in 1979, 1996–1999 and 2004, and they were adopted by laws with some delays from their release, always after deadly earthquakes.

The 1979 map (Gruppo di Lavoro Scuotibilità, 1979) is expressed in terms of macroseismic intensity and belongs to the so-called generation of “historical probabilism”: essentially an earthquake catalogue, a given relationship for attenuating intensity (without uncertainties) and Gumbel type I statistics of shakings at the sites (Gumbel, 1958). The map was translated into seismic categories with given prescription rules after the 1980 Irpinia $M_w = 6.9$ earthquake (about 3000 casualties), and municipalities entered into regulation by a series of acts, from 1981 to 1984 (Petrini et al., 1980; Slejko, 1993).

The other maps belong conceptually to the generation of the “seismotectonic probabilism” (Muir Wood, 1993). The second group of maps was released in 1996 (Slejko et al., 1998), and refined in 1998–1999 (Albarelo et al., 2000): they are maps in terms of macroseismic intensity and PGA (for additional details refer to Table 1, Project frame GNDT). The refinements, mostly due to changes in seismicity rates interpolation and GMPEs, came after the long and highly damaging Umbria-Marche sequence (known as Colfiorito sequence, 11 casualties) in 1997–1998. These maps were the basis of the revision of seismic code approved in 2003, after the collapse of a school in San Giuliano of Puglia (2002 Molise earthquake) that killed 27 pupils

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one or a limited number of return periods (i.e. thresholds of exceedance probability in given exposure time). Figure 5 shows the comparison of expected PGA values for the models having approximately the same return period (i.e., 475 years, or 10% probability of exceedance in 50 years) at two localities, in Northern (Modena) and Southern Italy (Potenza); remarkably, the Po Plain and Southern Apennines have been set as priority regions by the first year of DPC-INGV research agreement. As time-dependent models (blue labels in Fig. 5) refer to origin time set up in 2010, they cannot be used in our retrospective testing. In Tables 1 and 2 the list of selected models and their references are given; a synoptic graphical representation of results referred to the whole Italy is given in Fig. 6. Individual pictures are given in the Supplement File B.

The SHARE model (Giardini et al., 2013, represented in Fig. 6 by ID 9 frame) has not been stored in the repository of S2-2012 project. SHARE results have been progressively released since 2013, and are available at the SHARE Portal <http://www.efehr.org:8080/jetspeed/portal/hazard.psml>.

All the PGA values used for the scoring test are given in an excel file (Supplement File A). The values refer to the computation node nearest to the selected accelerometric sites previously described. These data are provided for stimulating additional testing by the scientific community.

5 Results

In order to compare observations and predictions provided by each PSHA model, the time span covered by both should be the same. In general, PSHA outcomes have the form of a PGA value g_0 characterized by a fixed exceedance probability in a time span of duration Δt (the exposure time) at the s th site (see above). Actually, being all the considered PSHA models based on the assumption that the seismogenic process is Poissonian, the following relation holds

$$P_{si} = P(e_s | H_i, \Delta t) = 1 - e^{-\lambda_{si}(g_0)\Delta t}, \quad (12)$$

where $\lambda_{si}(g_0)$ is the annual rate of exceedance for the threshold g_0 and P is the exceedance probability at the s th site, for the relevant exposure time Δt and acceleration threshold g_0 if the i th model is considered.

In the case we are considering, Δt lasts 25 years (i.e., the time span contemporary covered by 71 accelerometric observations, see above). However, most of the PSHA models provide hazard values for a different exposure time $\Delta t'$ (in general 30 or 50 years), i.e. $P(e_s|H_i, \Delta t')$. Thus, in order to apply Eqs. (1)–(11), some conversion tool is necessary to compare hazard estimates and observations. This conversion takes advantage of the stationary Poissonian character of seismic occurrences assumed by considered PSHA models. In this case, in fact, one has that

$$P'_{si} = P(e_s|H_i, \Delta t') = 1 - e^{-\frac{\ln[1-P(e_s|H_i, \Delta t)]}{\Delta t} \Delta t'} \quad (13)$$

The above formula can be used to compute the exceedance probability relative to the acceleration threshold g_0 for a given exposure time ($\Delta t'$) when the exceedance probability is supplied for another exposure time (Δt). The value P'_{si} is then considered for testing.

Since some models also provide g_0 values corresponding to different exceedance probabilities, they were scored by considering each realization as an independent “forecast”. In general, since in the same model lower exceedance probabilities correspond to longer return times and to higher g_0 values, different scoring can be attributed to different parts of the hazard curve.

Thus, for each PSHA model, a set of P'_{si} values is computed for the sites considered for testing, for $\Delta t = 25$ years. Consequently, the binary variable $e_s(g_0)$ is computed: equal to 1 when at the s th site the value g_0 was exceeded in the time interval 1979–2004, and to 0 otherwise.

On this basis, the score Z (Eq. 3) was computed for each PSHA model. This value is considered as the empirical score of the model: as lower is Z as most effective results the relevant model. The overall number of exceedances (Eq. 6) was also compared with the values expected in the relevant PSHA model (Eq. 8): if this difference exceeds

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two times the relevant standard deviation (Eq. 10), the PSHA model is considered to be not compatible with observations (Eq. 11).

5.1 Scoring models at the national scale

Except ID 7 and 8, all models have nation-wide coverage, thus allowing the scoring on the full set of 71 selected accelerometric stations. Some models have been given for different return periods; they give a final set of 12 realizations from 7 models. Comparison of expected vs. observed occurrences, are shown in Fig. 7; models are sorted accordingly to the relevant return period.

Despite of the fact that some models tend to slightly underestimate the observed number of exceedances, in all the cases these discrepancies are not significant by following Eq. (11). This, however, does not mean that all the models equally fit observations. In fact, when the score factor Z is considered (Fig. 7b), one can see that significant differences exist in the performances of the considered models at the different return times.

The best performing model is the 1996 GNDT model at intermediate return time (ID 1, RT = 284 years) followed by the MPS04-like area-based source model using Cauzzi and Faccioli (2008) GMPE (ID 5) for 984 year return period; notably, models obtained under different theoretical assumptions or computational choices behave nearly the same: as an example one can see the results provided by the ID6 model (smoothed seismicity approach by Akinci et al., 2010), the ID5 one (the one provided by Meletti et al., 2009 with the standard Cornell-McGuire approach, by considering the same single Ground Motion Prediction Equation used in ID5), and ID9 (produced in the frame of the SHARE project). On the other hand, same model performs in different ways at different return times of 94 years: e.g. see the ID 1 best performing at a return time of 284 years and providing a worse performance at a shorter return time (Fig. 7b). As models that explore different parts of the hazard curve have controversial scoring (i.e., different scores for different return times), it is not easy to identify a single “best” performing model.

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3. None of the considered models can be considered as the best performing at all the considered return times;
4. Testing done on sub-regions reveals different features with respect to the national scale, but the reasons should be investigated with other cases;
5. GMPEs could hamper the differences of alternative source modeling, but this is not a general rule.

This study focuses some open questions to be addressed in the future, like:

1. Site-specific PSHA or calibrated amplification functions at the accelerometric stations are necessary to avoid the over-simplification here adopted; they may play a key role in scoring results: specific activities have been planned on these subject in the prosecution of S2 Project started in 2014 (see Tasks 2 and 4, at <https://sites.google.com/site/ingvdpc2014progettos2/>);
2. Completeness of accelerometric records relative to accelerometric sites is a critical aspect for validation; we overcome the problems by considering the maximum PGA in a quite long time period, but further analyses are needed to fully exploit the observations provided by the actual Italian databases.

This study shows that the likelihood estimates accompanied by other testing procedures are able to provide useful indications about performances of competing models and could represent a basic tool for driving new researches devoted to a best practice for hazard assessment.

Appendix

Being r the reference log-likelihood computed by considering a set of S observations relative to sites characterized by an exceedance probability P , one has

$$r = N^* \ln(P) + (S - N^*) \ln(1 - P), \tag{A1}$$



where N^* is the number of sites where the ground-motion threshold characterized by the exceedance probability P has been exceeded during the control interval considered. One has

$$r = N^* (\ln(P) - \ln(1 - P)) + S \ln(1 - P). \quad (\text{A2})$$

- 5 Sampling properties of r only depend on the random variate N^* (being all the other parameters fixed). This variable N^* is the sum of S realization of a binomial variable characterized by a probability P of occurrence. The expected value of N^* is then SP , while its variance is $P(1 - P)$.

Thus, the expected value $\mu(r)$ of r is

$$10 \mu(r) = SP \ln(P) + S(1 - P) \ln(1 - P) = S[P \ln(P) + (1 - P) \ln(1 - P)]. \quad (\text{A3})$$

One can see that $\mu(r)$ monotonically increases with S , is a symmetric function of P with a minimum for $P = 0.5$ and values 0 for $P = 1$ and $P = 0$, respectively. The relevant sampling variance is

$$\sigma^2(r) = SP(1 - P) [\ln(P) - \ln(1 - P)]^2 \quad (\text{A4})$$

- 15 with a standard deviation equal to

$$\sigma(r) = [\ln(P) - \ln(1 - P)] \sqrt{SP(1 - P)}. \quad (\text{A5})$$

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Table 1. List of selected PSHA models.

Project frame	Model ID	Filename of PSHA results	Description*
GNDT	1	PS4_1996_PGA_10–30-50y	First PSH map for Italy using seismotectonic probabilism. Catalogue of declustered events till 1980 (NT4.1), area sources (ZS4), GMPE on undifferentiated soil condition (Amb95). PGA values computed on a 0.1° grid. Exceedance prob. of 10 % in 10, 30 and 50 years
	2	SSN-GNDT99_PGA	Consensus map refining the previous model; logic tree for GMPE (Amb96, SP96). PGA given on irregular grid (communes), exceedance probability of 10 % in 50 years, 50 percentile
MPS04 – S1 2004–2006	3	Appennino_Meridionale_MPS04_ag_002 Pianura_Padana_MPS04_ag_002	Italian PSH map developed on rules stated by law (Ord. 3274/03). PGA values computed on a 0.02° step grid. Catalogue of declustered events till 2002 (CPT104), area sources (ZS9), logic tree including alternative GMPEs (Amb96, SP96, REG.A, REG.B). Exceedance prob. of 10 % in 50 years, percentile 16, 50 and 84. Data points collected by S2-2012 Project refer only to the priority areas of Po Plain and Southern Apennines: the data sampled on a 0.05° grid on the whole country here used are available at http://zonesismiche.mi.ingv.it/
	4	S1_2004-2006_SA_0.0s_D2_39-2	Same approach and input data of previous model 3, MPS04, additional probabilities of exceedance in 50 years have been computed during the project S1 (2004–2006): 2 and 39 % are selected in this analysis. PGA values on a 0.05° step grid for all Italy. 16, 50 and 84 percentile

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Table 1. Continued.

Project frame	Model ID	Filename of PSHA results	Description*
S2 2008–2010	5	S2_2008-2010_SA_0.0s_MPS04_D2.1	MPS04-like model using different software (CRISIS vs. SEISRISKIII used by mod.1–4) and GMPE (CF08, no logic tree). Gridded seismicity based on ZS9. PGA (SA at $T = 0$ s) values on a 0.1° step grid for the whole of Italy, for 3 and 6% exceedance probability in 30 years.
	6	S2_2008–2010_SA_0.0s_HAZGRID_D2.2	Zone free smoothed seismicity, based on CPTI04 and instrumental datasets: same GMPE, sampling and return period of the previous model 5.
S2 2012	7	S2_2012-2013_SA_0-1_TimeIndep_AppMerid_D5.2	PSH estimates developed by the S2-2012 project, for priority area Southern Italy. Combination of smoothed seismicity approach (CPTI11, instrumental datasets) and characteristic model on faults (DISS3.1.1), under Poissonian assumption, GMPE logic tree (AB10, BA08, ITA10, CF08). Spectral acceleration at 0 (PGA) and 1 s. Probability of exceedance of 2, 5, 10 and 81 % in 50 years.
	8	S2_2012-2013_SA_0-2_PianuraPadana_D4.1	PSH estimates developed by the S2-2012 project, for priority area Po Plain. It derives from model 5 for several spectral accelerations (0–2 s). Rock and site specific conditions, implemented by regulation amplification factors on 1:100 000 scale soil map.
SHARE	9	Latest PSHA for Europe, first regional project in GEM initiative (http://www.globalquakemodel.org/). New European historical and instrumental catalogues, full logic-tree of GMPE set on tectonic regionalization, combination of area sources, distributed seismicity and larger events concentrated on faults, with new maximum magnitude scheme for the whole region. Results progressively released via the SHARE portal.	

* For the explanation of acronyms refer to the references listed in Table 2.



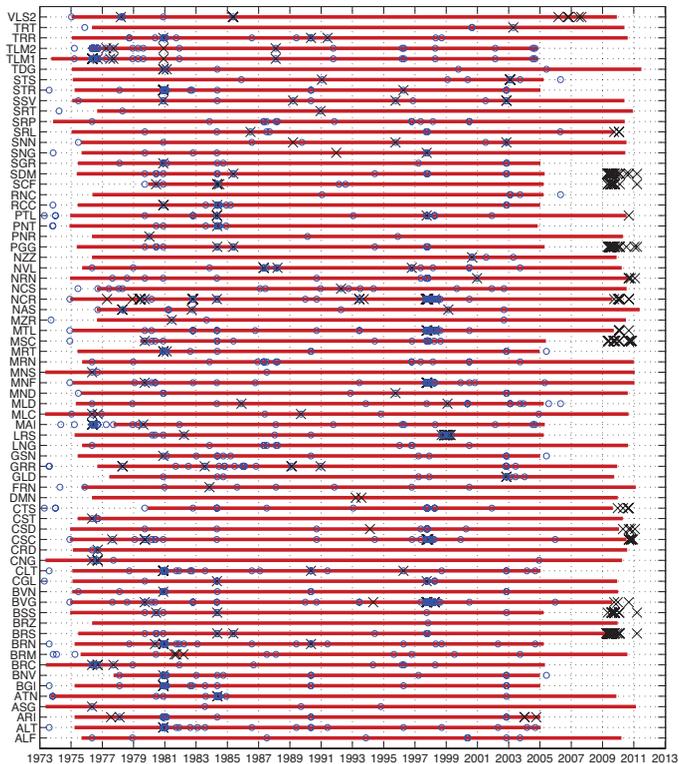


Figure 1. ON-OFF status for accelerometric stations declared to be continuously operating for at least 30 years, as reported on ITACA V1.1 database (Pacor et al., 2011, 2013). Blue circles show potential triggering conditions, computed as $(\text{mean PGA} + 1 \text{ SD}) > 0.01 \text{ g}$, using CPT11 earthquake catalogue (Rovida et al., 2011) and ITA10 GMPE (Bindi et al., 2011); black plusses are the effective recordings available. Data acquired on continuous-mode recording in 2009–2011 have not been considered for the existing time gap between the analogical and new digital equipments.

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Figure 2. Location of the accelerometric stations considered for empirical testing. Dotted pins refer to stations on A or A* (* for hypothesized conditions) type soil in Eurocode classification, pins colour represents a simplified amplification factor for PGA (NTC, 2008) used to accomplish stratigraphic and topographic site response: green = 1, yellow = 1.2–1.35, violet = 1.5. See Appendix A and Supplement for details. The stations in small turquoise pins, in the list of stations in Fig. 1, have been discarded in this analysis as they do not satisfy the ON status in the 1979–2004 time window.

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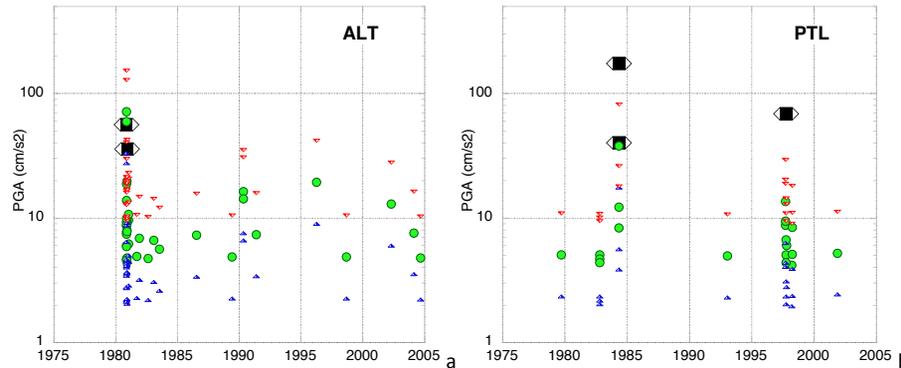


Figure 3. Observed and synthetic PGA values at two stations in the time span 1975–2005. **(a)** observed (b/w symbols, values as reported in ITACA 1.1. database and Pacor et al., 2013) and computed PGA values at ALT (Auletta, Salerno) station, in Southern Apennines; **(b)** PTL (Pietralunga, Perugia) station in Central Italy. Mean ± 1 standard deviation computed values, represented respectively by green circle, red and blue triangles, have been obtained by ITA10 GMPE applied to CPTI11 earthquake catalogue; synthetic PGA are plotted if MeanPGA+1sd is greater than 0.01 g, as in Fig. 1.

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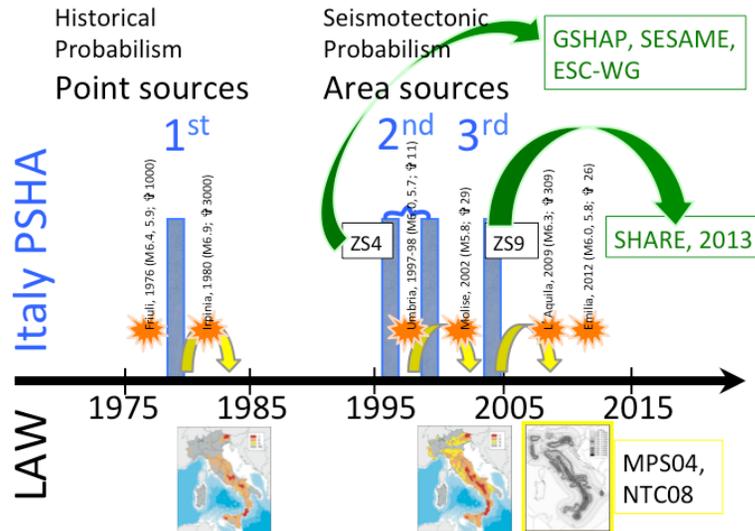


Figure 4. Timeline of PSHA maps in Italy relevant for regulation; orange symbols represent deadly earthquakes occurred in the last 40 years.

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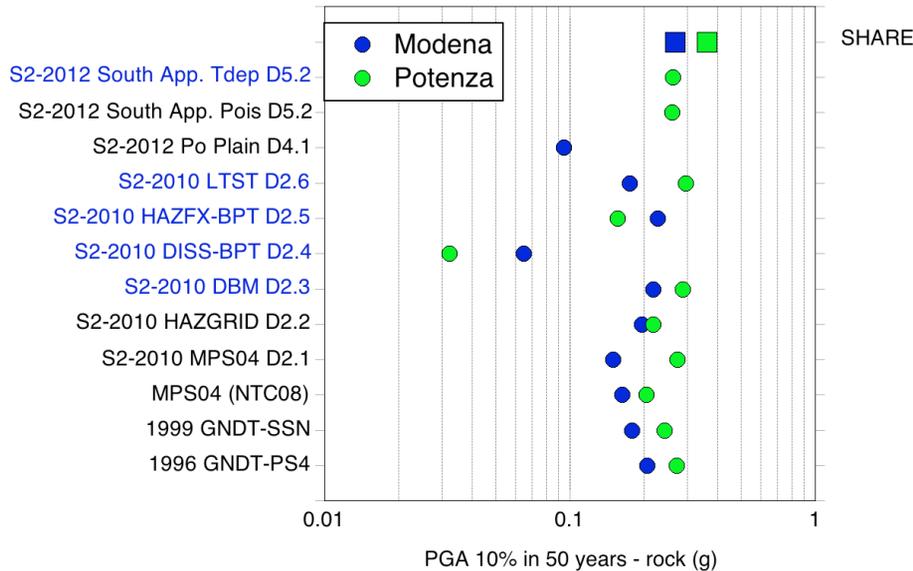


Figure 5. Comparison at two sites of expected PGA values (with 10% probability of exceedance in 50 years) from collected PSHA models (redrawn from Faccioli and Vanini, 2013). Modena is located in the Po Plain, at about 20–30 km distance from the main earthquakes of the 2012 Emilia sequence; Potenza is at about 90 km distance from the recursive sequences that affected the border of Calabria and Basilicata Regions, in Southern Apennines, since 2011. Time-dependent models listed in this graph (labels in blue) have not been used in this analysis.

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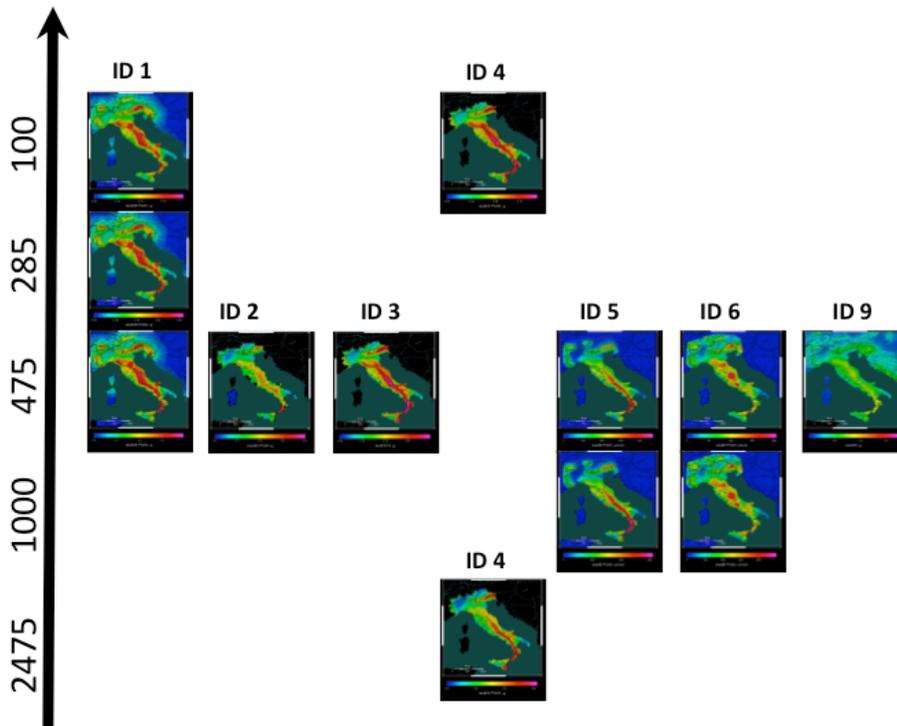


Figure 6. Synoptic view of PSHA maps collected by S2-2012 Project at the national scale. Model ID refers to Table 1, the vertical axis shows approximately the return period the elaborations refer to; on *x* axis, a rough timeline of results release (from 1996 till 2013). The colour scale is automatically adjusted on values (in particular the SHARE model have extremely high values out of the represented are); all the maps and graphic details are given in Supplement File B.

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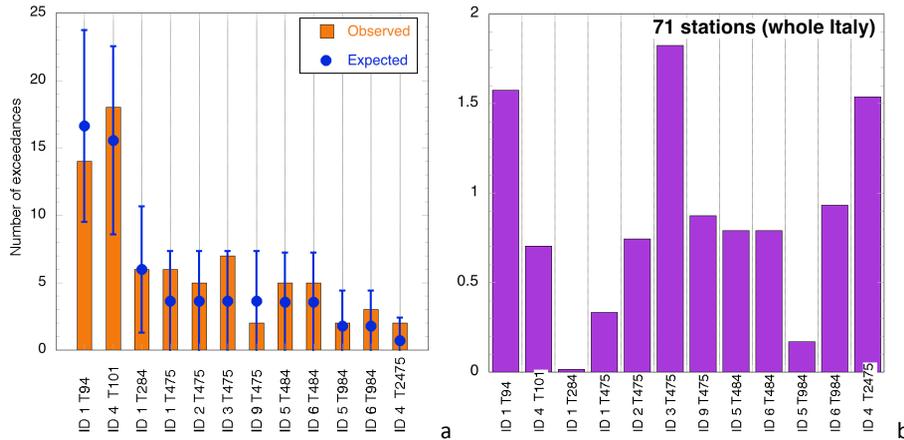


Figure 7. Results of scoring for national based PSHA models. **(a)** Observed vs. computed number of stations exceeding the predicted PGA values g_0 . Results are sorted according to the return period and subordinately on model IDs. **(b)** Final scores, the y axis represents the absolute value of Z score as given in Eq. (3); the lower the best. Model IDs are given in Table 1; Tyear indicates the mean return time the elaboration refers to.

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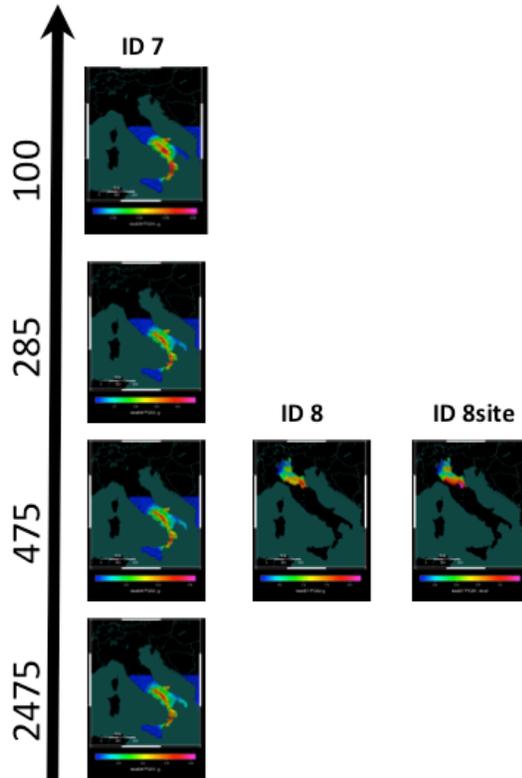


Figure 8. Synoptic view of regional PSHA maps collected by S2-2012 project. Model IDs refer to Table 1; the vertical axis shows approximately the return period the elaborations refer to. The colour scale is automatically adjusted on values; all the maps and graphic details are given in Supplement File B.

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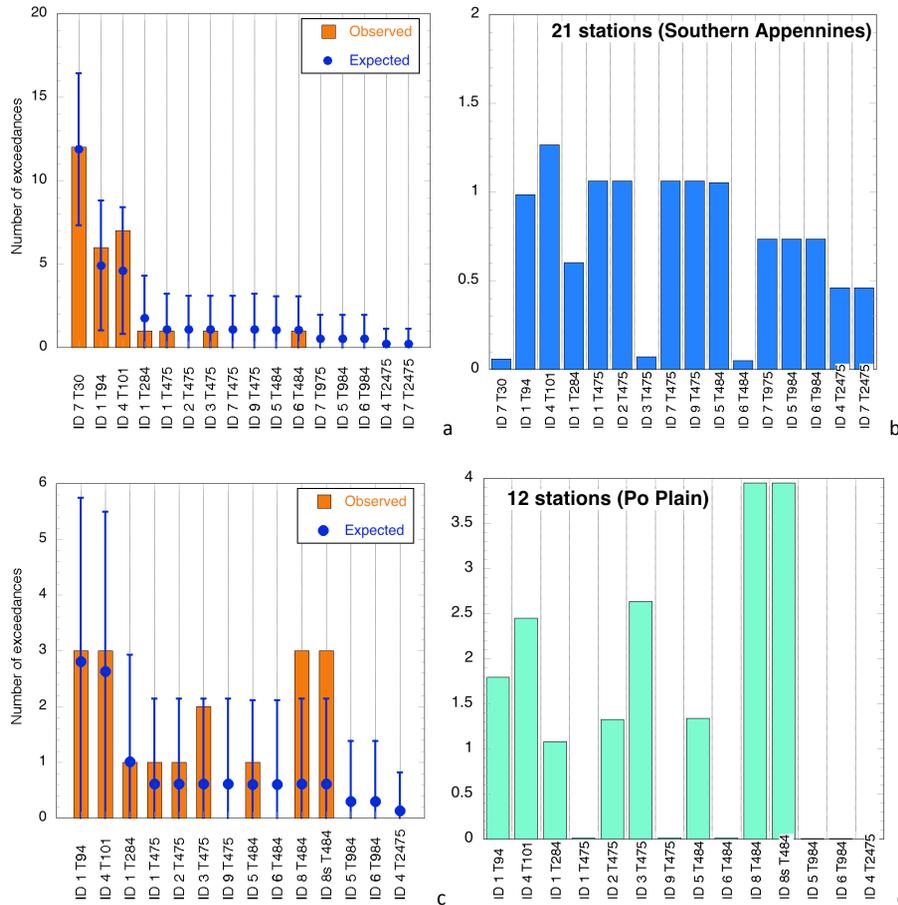


Figure 9. Results of scoring for sub-regions in Italy, as in Fig. 7: **(a)** and **(b)** Southern Appennines; **(c)** and **(d)** Po Plain.

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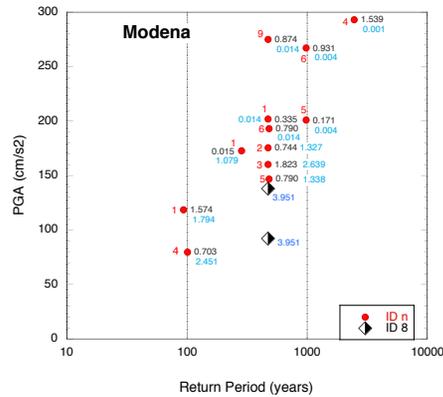
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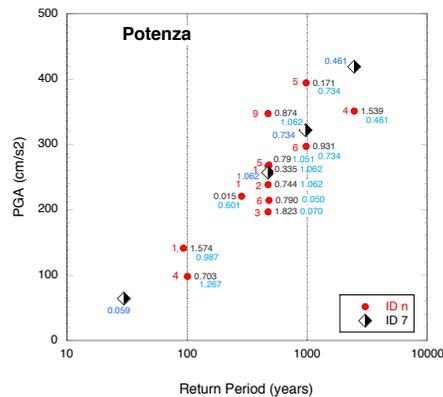


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a



b

Figure 10. PSHA and scores at two selected sites. **(a)** Modena, in the Po Plain; **(b)** Potenza in the Southern Apennines. Red dots and b/w diamonds represent the national and regional models, black and blue labels respectively the absolute Z values (Eq. 3) on the whole set and regional subsets of stations.

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