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Post-seismic assessment of existing constructions: evaluation of the shakemaps for identifying exclusion zones in Emilia

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Abstract. The Emilia, May-July 2012, earthquake has dramatically highlighted the only the hazards facing the people in insufficiently secured workplaces, but also the socio-economic consequences of interruption of production activities. After the event, in order to guarantee suitable safety levels, the Italian government asked for a generalized seismic retrofit of buildingsaffected by the earthquake under consideration. Considering that Emilia is one of the most industrialized Italian region, the number of the industrial buildings to be verified could however lead to not acceptable resumption of production time. So, with the aim to speed up the recovery, were leaved out from this request the buildings which had undergone a strong enoughshaking without any damage. In practice, the earthquakes were being used as a "test" to evaluate the seismic structural strength. Besides, the Italian government provision specifies also the zones, within which buildings that escaped evident damage are exempt from obligatory checks, and termed "exclusion zones", shall be individuated using the data provided by the Italian National Institute of Geophysics and Volcanology in the form of so-called "shakemaps". Obviously, the precision of such data greatly influences the determination of the exclusions zones and so all the economic issues related to them. Starting from these considerations, the present paper describes an evaluation of the reliability of the procedure of shakemap generation with specific regard to the seismic events that struck the Emilia region on May 20 and 29, 2012.

Keywords: emilia earthquake; shakemap; exclusion zone; post-seismic assessment; regression law

1. Introduction

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The recent seismic events of May 20 and 29, 2012, which involved a large part of the Emilia Region of Italy, have dramatically highlighted not only the hazards facing the people in insufficiently secured workplaces, but also the socio-economic consequences of interruption of production activities. The Emilia-Romagna region, with an area of about 22’000 km^2 (7.4% of the national area), is in fact home to nearly 80,000 industrial facilities (12% of all those in Italy), one third of them being warehouses. The most frequent typology isreinforced concrete (85% of the total), more than two thirds of the pre-cast type.34% of the workers in Emilia-Romagna regionare employed in heavy and medium industry, which accounts for 25% of its gross regional product (ISTAT 2012).

Thus, the considerable economic losses incurred following the earthquakes were due not only to direct damage (in terms of construction and repair costs), but also to the losses associated with the interruption of production activities caused by both the obvious immediate inaccessibility of some buildings (due to the risk of collapse), as well as their being deemed unusable through safety inspections according to governing antiseismic regulations.

Precisely in order to enable resumption of production activities in the Emilian municipalities affected by the earthquakes as quickly possible, while at the same time guaranteeing suitable safety levels, on June 6, 2012 the Italian government issued decree n. 74, subsequently converted, with modifications, into law by the Italian Parliament (no. 122 of August 1, 2012), whose provisions pursue two main objectives. The first, short-term, goal was to ensure rapid issue of temporary usability permits based on evaluations applying simplified criteria in order to enable prompt resumption of production activities. The second, aimed at themid-to-long term, called for conducting complete seismic vulnerability checks and any necessary structural strengthening operations to guarantee a safety level sufficient to withstand a spectralaction equal to 60% of the actions prescribed by governing regulations for new constructions.

As already thoroughly described in Braga *et al.* (2014), the provisions of the above-cited law for the middle-to-long term are profoundly different from those which are usually applied to existing constructions throughout the rest of Italy, for which, in fact, barring particular operations or circumstances, the safety levels required for restoration and reinforcement do not reach levels comparable to those prescribed for new constructions. Although such stringent requirements are surely aimed at drastically reducing the seismic vulnerability of existing constructions, they involve obvious inconsistencies. In order to mitigate such inconsistencies, and their consequences, without however reducing the safety level of production facilities, empirical building safety verification procedures have been introduced into post-seismic safety checks. These procedures exempted from the newly prescribed seismic vulnerability checks any building involved in the various Emilia events that performed well under a seismic actions characterized by spectral accelerations of over 70% of the spectral acceleration prescribed by the normative design spectrum for the same zone. Good performance was conservatively defined by the above-cited law as a stress and deformation state within the linearelastic field, both for the structural, non structural and installations building components.In practice, the earthquakes were being used as a "test" to evaluate the seismic structural strength. Although certainly reasonable, such a procedure however calls for determining, based on data recorded during the seismic events, the zones where the spectral acceleration exceeded 70% of the design value prescribed by the Technical Regulations for Constructions (Ministry of Infrastructures 2008). These zones, within which buildings that escaped evident damage are exempt from obligatory checks, have been termed “exclusion zones”.

Given that the spectral accelerations design value depends mainly on the geographical coordinates, as specified in (Ministry of Infrastructures 2008), on the soil category and on the building dynamic behavior, the major problem in defining the exclusion zones is to relate those information with the data registered in occasion of the seismic events. A possible procedure for defining such exclusion zones has been described in Braga *et al*. (2014). It is based, as expressly required by Parliamentary Law no. 122 of August 1, 2012, on using the data provided by the Italian National Institute of Geophysics and Volcanology (INGV) in the form of so-called "shakemaps" (INGV 2012).

Generating the shakemaps associated to a specific seismic event is performed by applying the model proposed by Wald *et al*. (1999), in this case adapted by the INGV for the Italian territory (Michelini *et al*. 2008). It is based on processing the data recorded by the accelerometer stations present in the territories subjected to earthquakes. By interpolating these data, suitably modified to take account of the varying soil characteristics, it is possible to evaluate the values of the ground shaking parameter of interest as a function of the sites' geographical coordinates. In the event that not enough data have been recorded in a specific area, the calculation is supplemented by an estimate of the shaking parameter calculated through suitably formulated attenuation laws.

Clearly, in order for the procedure for shakemap generation to be considered reliable, the final result must be consistent with the actual values recorded during the seismic event. Unfortunately, the results of such procedure are often influenced by the hypotheses assumed in formulating the attenuation law utilized, especially in areas where accelerometer recordings are scarce.

With the aim of highlighting the critical nature of this aspect, the present paper describes an evaluation of the reliability of the procedure of shakemap generation with specific regard to the seismic events that struck the Emilia region on May 20 and 29, 2012. To this end, the data recorded during these events have been analyzed, together with the procedures used by the INGV for creating the associated shakemaps. The analysis involved repeating the procedure for shakemap generation, and thereby obtain terms for comparison with results available in the literature, with the ultimate aim of evaluating the sensitivity of the results to the hypotheses underlying the calculation procedures.

2. Procedure for shakemap generation

Following every seismic event within the Italian territory, the INGV gathers all the data recorded by the accelerometer stations in the area affected by the earthquake (up to a maximum distance of about 300 km from the epicenter). Within minutes of cessation of the seismic event, such information is published by the INGV (http://shakemap.rm.ingv.it/shake/archive/). Specifically, apart from the magnitude of the surface waves and the epicenter coordinates, the INGV also provides the coordinates of all the accelerometer stations and the peak values of ground acceleration (PGA), ground velocity (PGV) and spectral accelerations (PSA), the latter two of which are calculated for a period equal to 0.3, 1.0 and 3.0 s) for every channel available at the station in question. The peak values of the aforesaid shaking parameters are thus generally provided, according to the available channels, for the three directions: north-south, east-west and vertical. In addition to such data, the INGV also publishes on the site information regarding the velocity, V_{S30}, of shear waves evaluated on a square grid, with points spacing of approximately 0.0083 decimal degrees and total dimensions 180×200 km. All these data are used as input for the ShakeMap® software developed by the Geological Survey's Earthquake Hazards Program (Wald *et al*. 2006), for calculating the corresponding peak value of the shaking parameters for each point on the aforesaid grid.

As described in detail by Michelini*et al*. (2008), the procedure for generating shakemaps can be summarized in the followings steps:

- reprocessing and organizing the data recorded by the accelerometer stations;
- data correction to refer them to a rigid soil equivalent;
- creation of a grid of so-called "phantom" points to make up for the lack of recorded data from some points;
- calculating the law of regression for estimating the shaking parameters of the phantom points;
- correcting the data to account for the actual conditions at the sites;
- interpolation of the recorded data and the numerically evaluated values in order to construct a continuous surface representing the relevant shaking parameter;
- generation of the shakemaps.

Such procedure therefore enables creating a surface that represents the peak values of the considered shaking parameter as a function of the geographical coordinates, and consequently drawing the contour lines delimiting the areas characterized by lower (or higher) shaking parameter values, as schematically illustrated in Fig. 1.

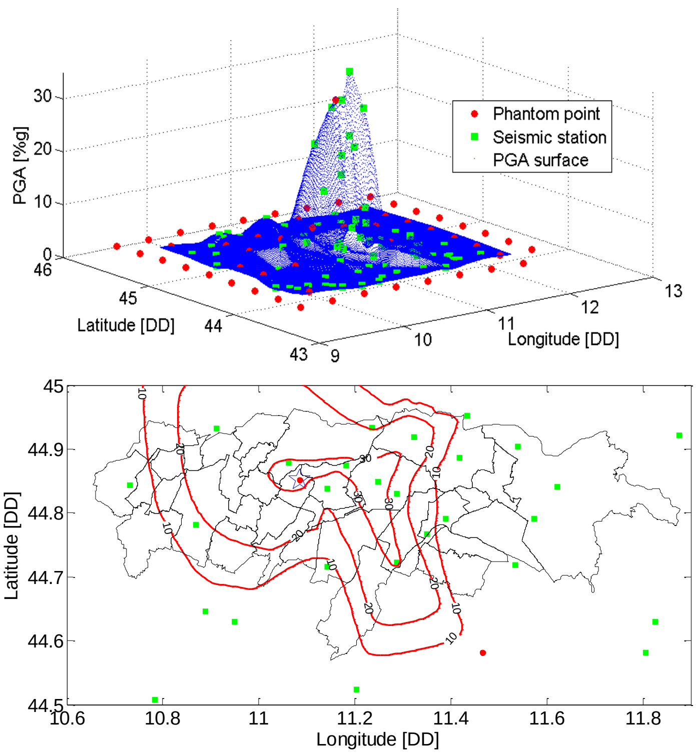


Fig. 1 Surface representing the PGA pattern as a function of the geographical coordinates (up) and associated contour lines (down), with indications of town borders for the May 29, 2012 Emilia earthquake of magnitude 5.8.

Table 1 Data recorded by the accelerometer stations on the May 29, 2012 earthquake in Emilia

Station Code	Lat [DD]	Lon [DD]	regression distance [km]	intensity	Channel 1 Code	PGV [cm/s]	PGA (% g)	PSA 0.3 (% g)	PSA 1.0 (% g)	PSA3.0 (% g)	Channel 2 Code	…
MRN	44.878	11.062	8.1	8.2	HGN	47.00	26.50	74.41	56.07	7.75	HGZ	…
MODE	44.630	10.949	31.8	4.6	HNZ	2.49	3.30	7.49	2.93	0.46	HNE	…
MDN	44.646	10.889	33.2	4.4	HGN	3.80	3.36	7.34	5.50	0.97	HGZ	…
NVL	44.843	10.732	34.2	4.8	HGN	2.40	5.20	13.25	2.96	0.74	HGE	…
ZPP	44.524	11.204	38.3	4.0	HGN	4.30	2.34	5.20	6.12	1.83	HGZ	…
…	…	…	…	…	…	…	…	…	…	…	…	…

Such procedure is obviously influenced by various choices and hypotheses that can significantly affect the resulting shakemaps, and consequently, with regard to the issues at hand, the extent of the area exempted by reason of the aforementioned law from the safety verification process normally prescribed by government enforcedregulations. Thus, with the aim of fully understanding the reliability of the results provided, the procedures described in the technical documentation accompanying the ShakeMap software (Wald *et al*. 2006) and the indications provided by the INGV (Michelini *et al*. 2008) have been followed as carefully and faithfully as possible in the checks described in the following.

2.1 Reprocessing and organizing the data recorded by the accelerometer stations

The data recorded by the accelerometer stations in earthquake areas are provided in the form illustrated in Table 1, which shows, by way of example, some data for the earthquake that occurred in Emilia on May 29, 2012 (event ID 7223045800).

Each station provides, apart from the site's geographical coordinates and distance from the earthquake epicenter, the associated values of PGA, PGV and PSA for every channel available at the station. In the following, the shakemaps have been generated considering, for each shaking parameter, the maximum value of the components in the north-south and east-west directions, thus neglecting the vertical component.

2.2 Data correction to an equivalent rigid soil

The recorded values of the shaking parameters are obviously influenced by the type of soil where the accelerometer station is located. In order to be able to calibrate an attenuation law as a function of the distance from the epicenter, the data to be processed must however be "homogeneous", that is, free of local site effects. The recorded data have thus been referred to a "equivalent" rigid soil through the procedure proposed by Borcherdt (1994), which corrects the recorded values for site effects by dividing them by a coefficient, Fa, which is a function of PGA (or PGV) and V_{S30}(shown in Table 2), according to the Eq. (1).

For calculating coefficients Fa in the present context, the V_{S30}values provided by the INGV in

Table 2 Site effects amplification factors (Fa). For low periods (from 0.1 to 0.5 s) the factors are calculated via equation 7A (Borcherdt 1994), while for medium period values (from 0.4 to 2.0 s) equation 7B is instead used

V_{S30} [m/s]	Short Period (PGA) [m/s^2]				Mid - Period (PGV) [m/s]			
	0	1.50	2.50	3.50	0	1.50	2.50	3.50
686	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
724	0.98	0.99	0.99	1.00	0.97	0.97	0.97	0.98
464	1.15	1.10	1.04	0.98	1.29	1.26	1.23	1.19
372	1.24	1.17	1.06	0.97	1.49	1.44	1.38	1.32
301	1.33	1.23	1.09	0.96	1.71	1.64	1.55	1.45
298	1.34	1.23	1.09	0.96	1.72	1.65	1.56	1.46
163	1.65	1.43	1.15	0.93	2.55	2.37	2.14	1.91

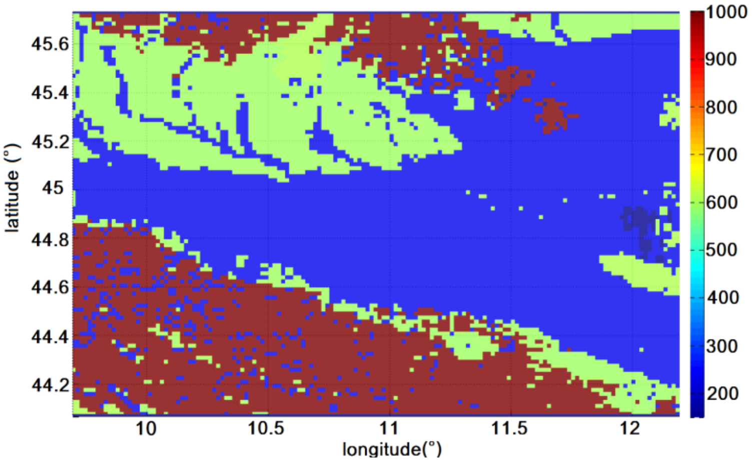


Fig. 2 V_{S30}(m/s) as a function of geographical coordinates

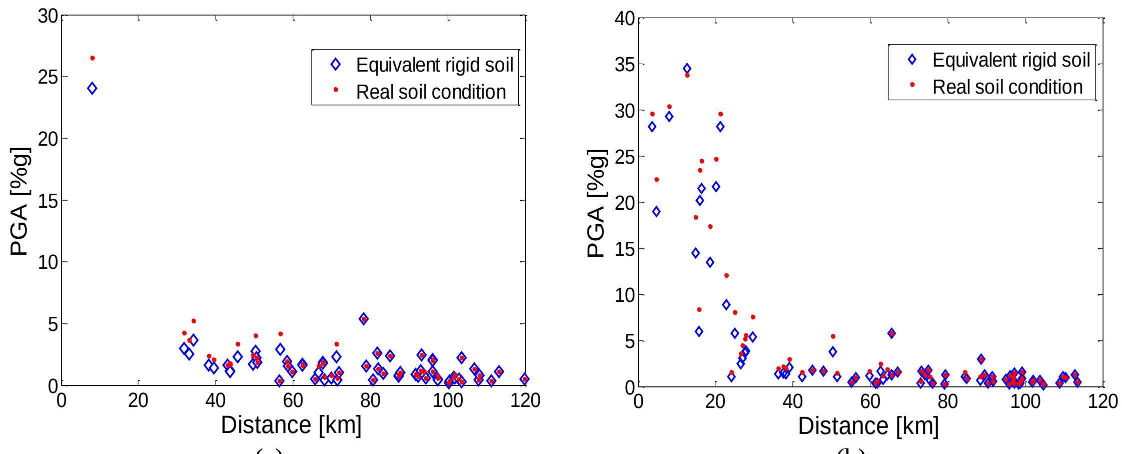


Fig. 3 Recorded PGAs and values adjusted to equivalent rigid soil for the May 20, M=5.9, (a) and 29, M=5.8, (b), 2012 earthquakes in the Po plains of Emilia.

the download section of its Website were used within this work. As described by Michelini *et al.* (2008), such values have been evaluated based on the geological map of Italy (in scale 1:100,000) drawn and published by the National Geologic Service. Fig. 2 shows the V_{S30}values of the Emilia Region as a function of longitude and latitude. The map clearly highlights that, based on these data, the great majority of the terrain of the Emilia Po plains is classifiable as belonging to category C (following the classification proposed by the Technical Regulations for Constructions (Ministry of Infrastructures, 2008)), in that the mean value of $V_{S30}$is generally equal to 230 m/s.

As an example, Figs. 3(a)-(b) shows the recorded PGA values, together with those referred to an equivalent rigid soil, for the earthquakes that occurred in the Po plains of Emilia on May 20 and 29, 2012, respectively of magnitude 5.9 and 5.8, as a function of the distance from the epicenter of the relative seismic event. It can be noted that, after the first significant event of May 20, several further seismic stations were activated. So, for the seismic event of May 29, the number of available data is greater.

2.3 Calculating the regression law

Based on the rigid-soil adjusted data it is possible to calibrate a law that enables estimating the shaking parameter value as a function of the epicentral distance. Such estimate has been made utilizing the same regression law proposed by Ambraseys *et al.* (1996) and Bommer *et al.* (1999) and adopted by the INGV for earthquakes of magnitude M_S greater than 5.5. Its general formulation is specified in Eq. (2).

$$\log_{10}(y) = C_1 + C_2 \cdot M_S + C_3 \cdot r + C_4 \cdot \log_{10}(r) + \sigma P \tag{2}$$

where

- y is the relevant shaking parameter;
- M_S is the magnitude of the surface waves;
- r is a function of the epicentral distance in km, d, and is defined as

  $$r = \sqrt{d^2 + h_o^{\,2}}$$

  where h_o is a parameter to be determined together with C_1, C_2, C_3 and C_4;
- σ is the standard deviation of $\log_{10}(y)$;
- P is a constant that takes a value of 0 if the aim is to evaluate the mean value of $\log_{10}(y)$, while it is equal to 1 if the aim is to evaluate the 85th percentile.

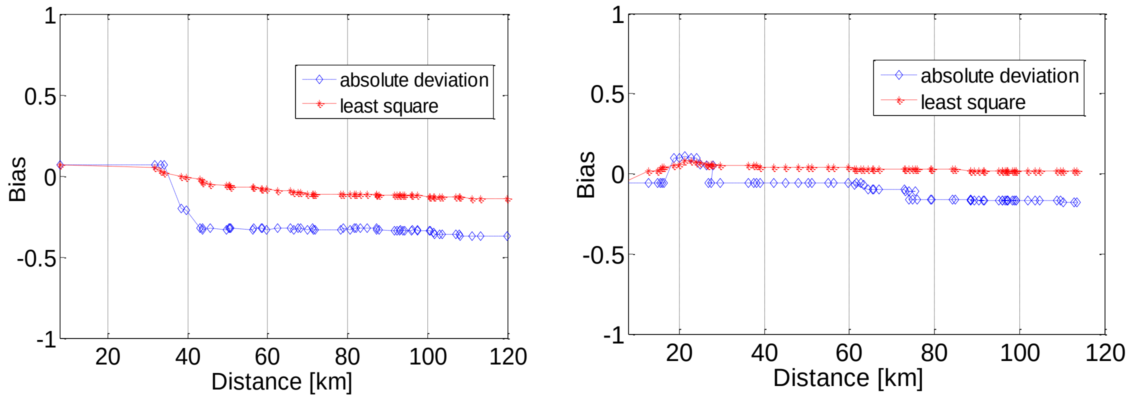
The values of constants h_o, C_1, C_2, C_3 and C_4 that best describe the attenuation laws of the shaking parameters typical of European earthquakes have been evaluated by Ambraseys based on numerous data recorded in Europe and adjacent areas (Ambraseys *et al.* 1996). Based on these results, the regression law for calculating the mean value of the shaking parameter, y, takes the expression of Eq. (3).

$$\log_{10}(y) = -1.39 + 0.266 \cdot M_S - 0.922 \cdot \log_{10}(r) \tag{3}$$

with h_o equal to 3.5 and d expressed in km.

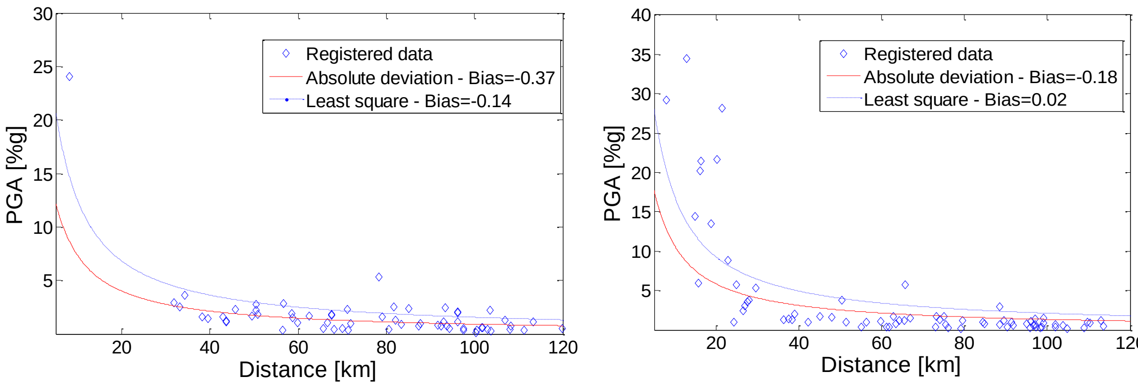
Eq. (3) is a general formulation and obviously cannot be used directly to predict the shaking parameter attenuation of a specific seismic event, in that it does not take into account the peculiar characteristics of the event itself or the area in which it occurs, which may also vary widely across the European continent.

Thus, Eq. (3) must be suitably adjusted by means of a calibration parameter α (i.e. "bias"), so



(a) (b)

Fig. 4 Bias as a function of the distance from the epicenter of the most distant accelerometer station considered a) May 20, 2012 earthquake; M=5.9b) May 29, 2012 earthquake; M=5.8.



(a) (b)

Fig. 5 Regression law calculated considering the data from all accelerometer stations within a 120 km radius of the epicenter of the earthquake on: a) May 20, 2012; M=5.9 and b) May 29, 2012 M=5.8

that the results of the attenuation law are as close as possible to the data actually recorded during the seismic event in question.

Calibration parameter α can be calculated using various methods and assuming different hypotheses that can have a considerable influence on the shaking parameters estimated via the attenuation law. Herein, Authors have assumed a bias correction law corresponding to a vertical translation of the attenuation curve in the bi-logarithmic plane $\log_{10}(y)$-$\log_{10}(r)$,as expressed by Eq. (4).

$$\log_{10}(y) = -1.39 + \alpha + 0.266 \cdot M_S - 0.922 \cdot \log_{10}(r) \qquad (4)$$

In conformity with the specifications set forth in the technical documentation to the ShakeMap® software (Wald *et al*. 2006), the bias has therefore been calculated both via the least squares method (i.e., minimizing the sum of the squares of the distances between the recorded data and the regression law), as well as by minimizing the sum of the absolute values of the differences between the recorded data and those calculated by means of the attenuation law (i.e. the method of Least Absolute Deviations, LAD) for each accelerometer station. It is worth stressing that, according to Wald *et al*. (2006), because of the natural dispersion of the recorded data, the method of least absolute deviations provides results that are less subject to error than the least squares method. It should moreover be noted that calculation of the bias depends heavily on the number of accelerometer stations considered. For this reason, both methods have been used to calculate (see Figs. 4(a)-(b)) the bias value for the earthquakes that struck the Po plains in Emilia on May 20, M=5.9, and May 29, M=5.8, 2012, for varying distances of the most distant accelerometer station from the epicenter.

As can be seen in Figs. 4(a)-(b), the two methods yield significantly different results for distances over 25-30 km. With the aim of considering a sufficiently large body of recorded data to arrive at a meaningful regression law following the Shakemap® software procedures for shakemap generation (Wald *et al*. 2006), the bias has been calculated using data from all accelerometer stations within a radius of 120 km from the epicenter. Figs. 5(a)-(b) show the recorded data and regression laws for the Emilia earthquakes of May 20, and 29, 2012.

As it is evident from Figs. 4 and 5, the bias values produced by the method of least squares are more heavily influenced by the recordings in the proximity of the epicenter (distances of less than 25-30 km), which are highly variable (high s.d.), while with the method of least absolute deviations, it is the data from the more distant stations that have a preponderant weight, simply because a greater amount of data is available from these sites. The final result is that the bias calculated via the least squares method provides a better evaluation of the shaking parameter value for low epicentral distances, while that calculated with the method of least absolute deviations yields a better estimate for greater epicentral distances. Herein, in conformity with the procedures indicated for shakemap generation with the Shakemap® software (Wald *et al*. 2006), given the considerable dispersion of the recorded data and in order to properly compare the results obtained with the ones obtained by the Shakemap® software (Wald *et al*. 2006) the method of least absolute deviations has been adopted.

It is however important to note that estimation of the shaking parameter, especially in correspondence to the epicenter where maximum parameter values are to be expected, is heavily influenced by the procedure for calibrating the regression curve and is, in any event, affected by the considerable error inherent in the procedure itself. As described in the following, such error significantly influences the shakemap pattern in the epicentral zone, which is, after all, the most relevant area with regard to identifying potential exclusion zones.

2.4 Creating the phantom points grid

As previously described, the procedure for generating shakemaps calls for interpolating the recorded data in order to create a continuous surface that represents the desired shaking parameter as a function of geographical coordinates. The contour lines of these surfaces represent the shakemaps. However, as accelerometer stations are often distributed non-uniformly throughout the seismic areas, rather wide zones are often left with no data to use in calculating such surfaces. In these zones, direct interpolation can lead to very substantial errors in evaluating the shaking parameter. For this reason, for each seismic event, the data from the accelerometer stations distributed throughout the area have been supplemented with a grid of “phantom” points, for which the shaking parameter values have been calculated by means of the suitably calibrated

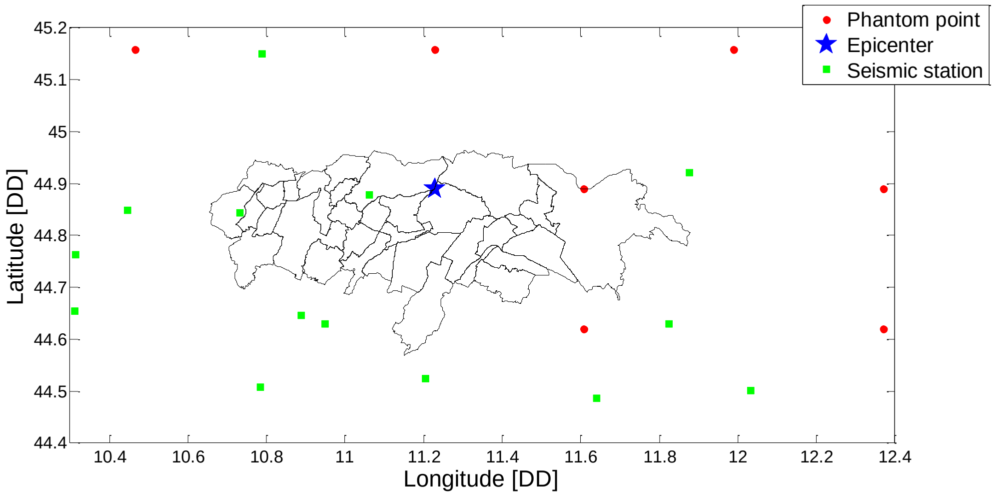


Fig. 6 Positions of active accelerometer stations and phantom points for the earthquake of May 20 2012, M = 5.9

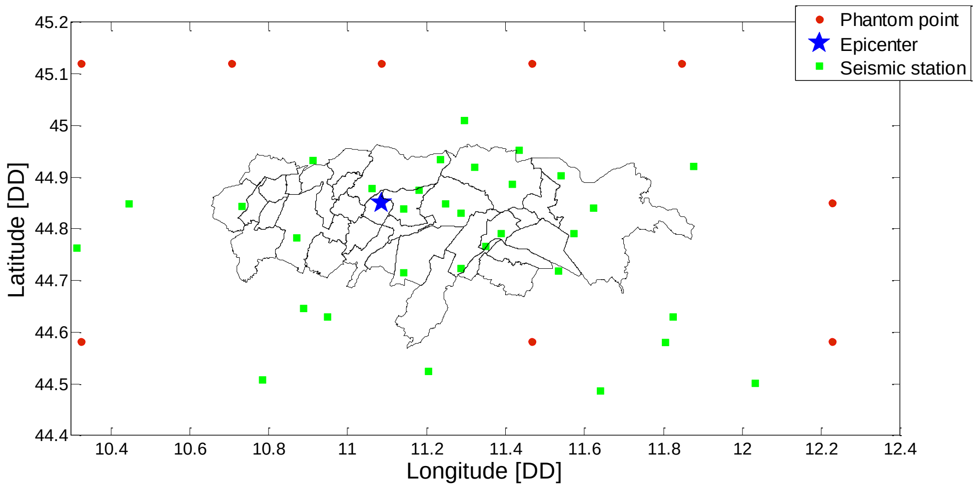


Fig. 7 Positions of active accelerometer stations and phantom points for the earthquake of May 29, 2012, M = 5.8

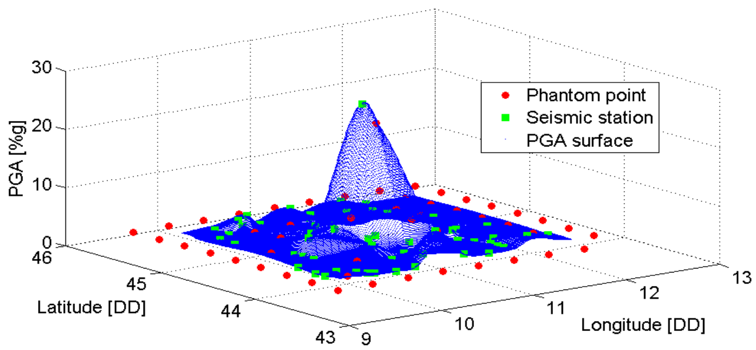
regression law. Thus, by considering both the data recorded directly during the seismic event as well as those calculated via the attenuation law for the phantom points, a grid of points can be obtained on which to base the evaluation, through interpolation, of the continuous surface representing the desired shaking parameter.

As per the procedure for utilizing the Shakemap® software (Wald *et al.* 2006), for each seismic event considered, the phantom points have been prepared on a 30 by 30 km square grid with a phantom point coinciding with the epicenter. Moreover, only phantom points at a distance of over 15 km from the nearest accelerometer station have been considered, with the exception of the epicenter point, which must only be considered if there are no accelerometer stations within 10 km of the epicenter. Figs. 6-7 show the positions of the active seismic stations together with the phantom points for the May 20 and 29, 2012 earthquakes in the Po plains of Emilia. The figures also show the borders of the Emilia region municipalities belonging to therelevant earthquake area as defined by Government.

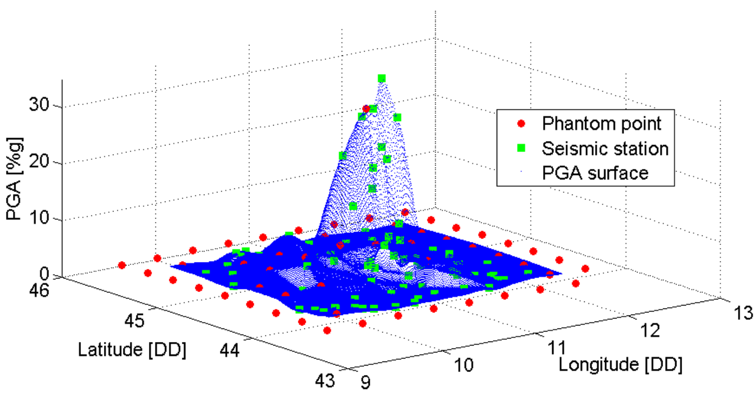
As can be noticed by comparing Figs. 6-7, the amount of accelerometer station data close to the epicenter for the May 20 earthquake is clearly less than for the subsequent earthquake of May 29. Therefore, a greater number of phantom points are needed in the first case to be able to produce the shakemaps in the proximity of the epicenter, with a consequent higher margin of error associated to the uncertainties in estimating the shaking parameter via the attenuation law.

2.5 Generating the surface representing the shaking parameter

Once the recorded data have been corrected for local site effects (i.e., referred to an equivalent rigid soil, as discussed in Section 2.2) and the shaking parameter values calculated via the attenuation law have been added where necessary, a surface representing the shaking parameter can be created through interpolation. More in particular, such surface has been calculated on a



(a)



(b)

Fig. 8 PGA surfaces for the earthquake of: (a) May 20, 2012, M = 5.9 and (b) May 29, 2012, M = 5.8.

square grid, with each side equal to 0.0083 decimal degrees (DD) (corresponding, in the considered region, to about 660 m), through cubic interpolation in such a way as to provide the values of the initial shaking parameter in correspondence to the accelerometer station coordinates and the considered phantom points. The surface obtained represents the values of the shaking parameter in rigid soil. Figs. 8(a)-(b) show the surface representing the calculated PGA for the May 20 and 29 earthquakes in the Po plains of Emilia.

In order to consider the actual soil conditions, the shaking parameter values have been amplified by the coefficients in Table 2 according to the shear wave velocity, V_{S30}, and the value of PGA, as expressed by Eq. (5).

$$PGA_{RealSoil} = PGA_{RigidSoil} \cdot Fa(V_{S30}, PGA_{RigidSoil}) \tag{5}$$

It should be noted that direct application of Eq. (5) does not in general provide the exact values recorded at the accelerometer stations during a seismic event, which have been corrected for the soil effects via Eq. (1). An iterative procedure can be applied to limit such error, though it should also be noted that, within the range of shaking parameters relevant to the current analysis, the error associated with such direct use of Eq. (5) is actually quite negligible. By way of example, Table 3 shows the data recorded by the accelerometer stations, together with those calculated through the described procedure, and the associated error for the stations nearest to the epicenter of the May 29 earthquake, of magnitude 5.8. From Table 3, it can be noticed that the error is about 5% in the range of PGA greater than 0.15g, where the Fa factor is about equal to 1 (see Table 2), but is however less than 10% also for all the other stations considered.

Table 3 Error associated with calculation of PGAs, shown for the May 29 earthquake, M= 5.8

					Recorded data	Data calculated through MATLAB procedure	
Station ID		Lon [DD]	Lat [DD]	V_{S30} [m/s]	PGA [% g]	PGA [% g]	**Error**
MRN	1	11.06	44.88	230	29.6	30.2	2.3%
SAN0	2	11.14	44.84	230	22.4	23.9	6.6%
T0802	3	11.18	44.88	230	30.3	30.8	1.7%
T0800	4	11.25	44.85	230	33.7	33.2	-1.4%
SMS0	5	11.24	44.93	230	18.3	19.4	5.7%
FIN0	6	11.29	44.83	230	23.4	24.9	6.1%
RAV0	7	11.14	44.72	230	8.4	8.5	2.1%
MOG0	8	10.91	44.93	230	24.5	25.8	5.4%
CRP	9	10.87	44.78	230	17.3	18.2	4.8%
T0805	10	11.32	44.92	230	24.6	25.9	5.2%
CNT	11	11.29	44.72	230	29.6	30.2	2.2%
T0803	12	11.35	44.77	230	12.1	12.5	3.1%
SERM	13	11.30	45.01	230	1.5	1.6	1.2%
SAG0	14	11.39	44.79	230	8.1	8.2	1.9%
BON0	15	11.42	44.89	230	3.6	3.6	2.2%
NVL	16	10.73	44.84	230	5.5	5.6	1.5%
MDN	17	10.89	44.65	230	5.2	5.3	1.2%
MODE	18	10.95	44.63	230	4.5	4.5	1.3%
FIC0	19	11.43	44.95	230	7.5	7.7	1.9%
T0821	20	11.54	44.90	230	2.0	1.8	-9.7%

2.6 Generating the shakemaps

Once the surfaces representing the desired shaking parameter have been generated, the corresponding shakemaps are obtained by tracing the contour lines of the surfaces themselves. Figs. 9-10 show the shakemaps generated for the earthquakes that occurred in Emilia on May 20 and 29, 2012.

It is interesting to note that strict application of the procedure proposed by Wald *et al.* (1999) and adapted by the INGV for the Italian territory (Michelini *et al*. 2008) yields PGAs at the epicenter of the earthquake of May 20 that are considerably lower than that recorded at the nearest accelerometer station. This is due to the fact that, because of the presence of an accelerometer station at less than 15 km from the epicenter, the phantom point in correspondence to such station has not been considered. Fig. 11 shows the shakemap resulting for the May 20 earthquake when the presence of the epicentral phantom point is instead considered.

Considering the greater consistency of the shakemaps with the predictions of the attenuation laws, in the following the presence of the epicentral phantom point will be taken into account in all calculations.

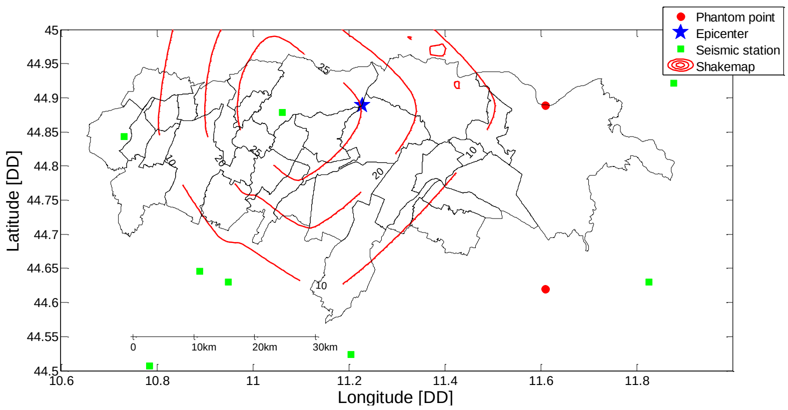


Fig. 9 Shakemap for the earthquake of May 20 2012, M = 5.9

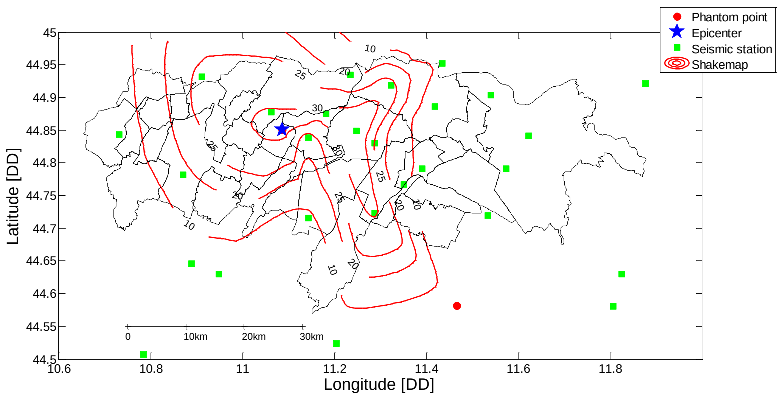


Fig. 10 Shakemap for the earthquake of May 29, 2012, M = 5.8

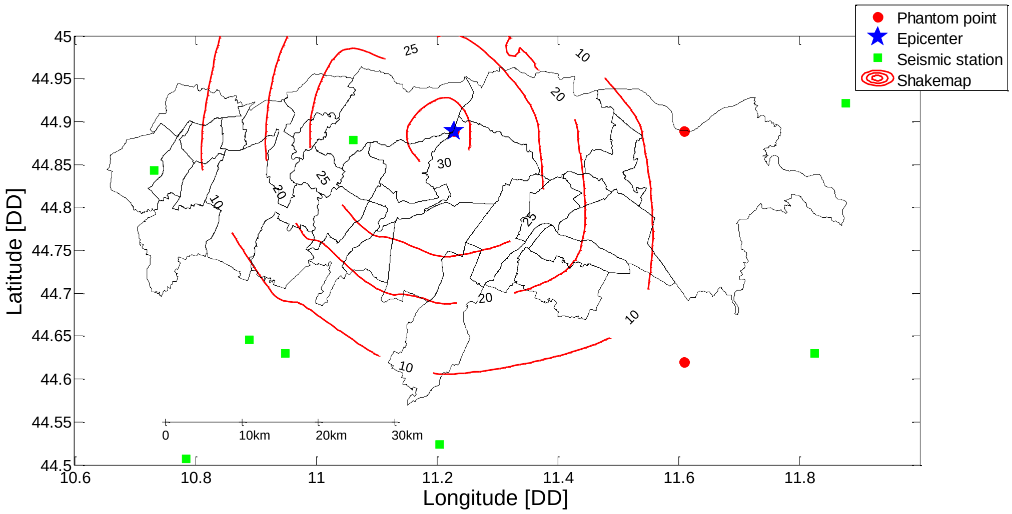


Fig. 11 Shakemap for the May 20, 2012 earthquake (M = 5.9) considering the phantom point at the epicenter

3. Analysis of the sensitivity of results obtained via the procedure and a comparison with the results obtained by the INGV

As described in the foregoing, calibration of the attenuation law, which makes it possible to generate the shakemaps in correspondence to the zones for which accelerometer station data are lacking, is heavily influenced by the hypotheses on which the calculations are based. The most important of these concerns calculation of the bias, which can in general be done via the method of least squares or by minimizing the sum of the absolute distances of the regression curve with the recorded data (i.e., method of least absolute deviations). The two methods lead to very different results that have a particular influence on determination of the epicentral shaking parameter and, consequently, the shape of the shakemaps in correspondence to the epicenter itself. From Fig. 4 it is evident that the attenuation curve calibrated through the least squares method yields a better approximation of the data recorded in the epicentral zone, as it is characterized by a smaller number of available samples, but also greater dispersion. To the contrary, using the method of least absolute deviations, the bias calculation is more heavily influenced by the data recorded at greater distances from the epicenter, for which the number of recorded data points is larger. The risk in using this second method, however, lies in the fact that it has a tendency to provide values of the epicentral shaking parameter that in some cases may be significantly lower than the values recorded at the nearest accelerometer stations. For the sake of comparison, Figs. 12-13 show the shakemaps for the Emilia earthquakes of May 20 and 29, 2012 calculated via the two methods. It is clearly evident that the results are practically coincident in the areas characterized by a high density of accelerometer stations, but differ considerably in correspondence to the epicenter.

Another parameter that heavily influences the resulting shakemaps is the distance from the epicenter of the furthest accelerometer station used in calculating the bias. As already underlined in the foregoing and as can be seen in Figs. 4-5, such calculation is greatly influenced by the epicentral distance in question. Figs. 14 to 17 show the shakemaps for different levels of PGA,

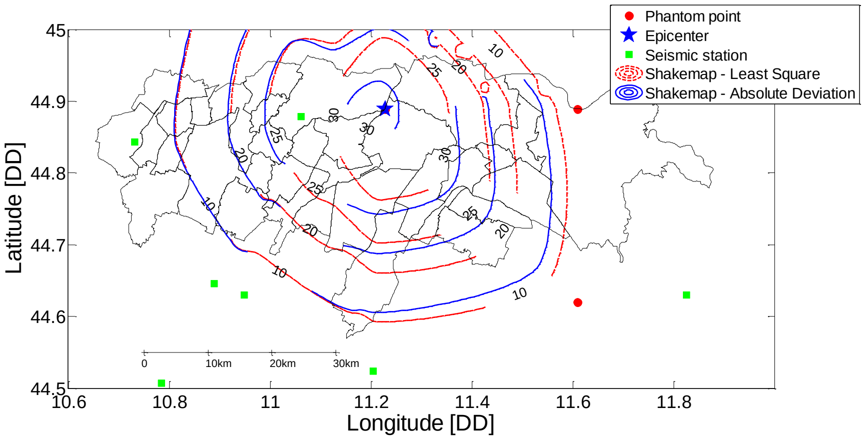


Fig. 12 Comparison of the shakemaps for the earthquake of May 20, 2012, M = 5.9

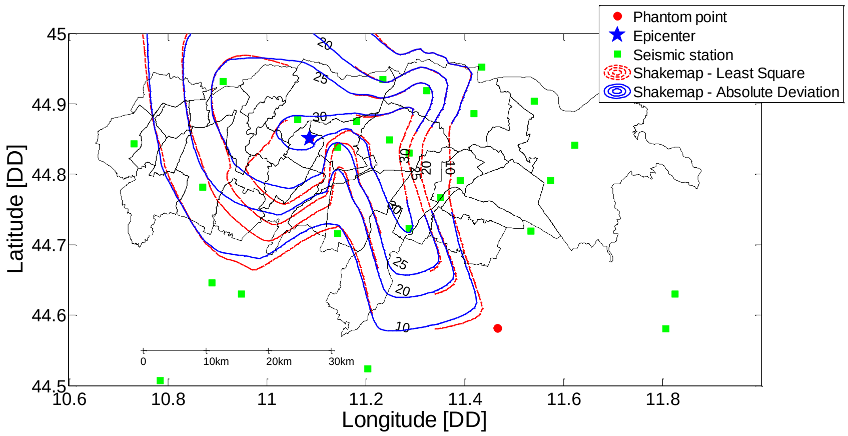


Fig. 13 Comparison of the shakemaps for the earthquake of May 29, 2012, M = 5.8

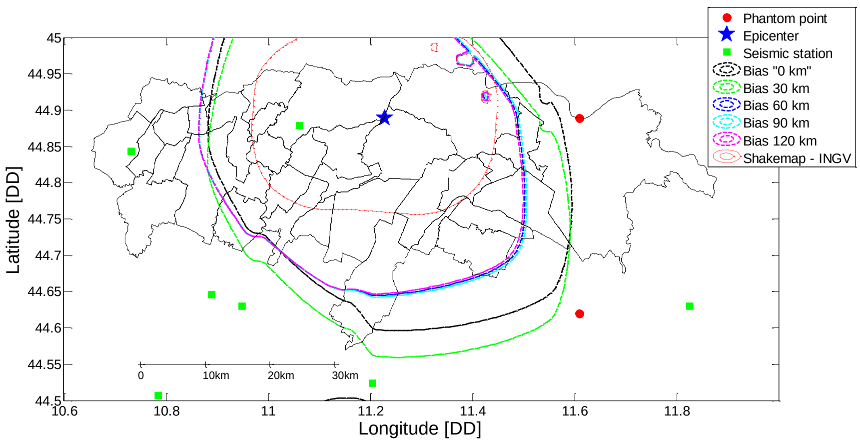


Fig. 14 Shakemaps for PGA = 0.15g, calculated with different bias values for the May 20, 2012 earthquake, M = 5.9

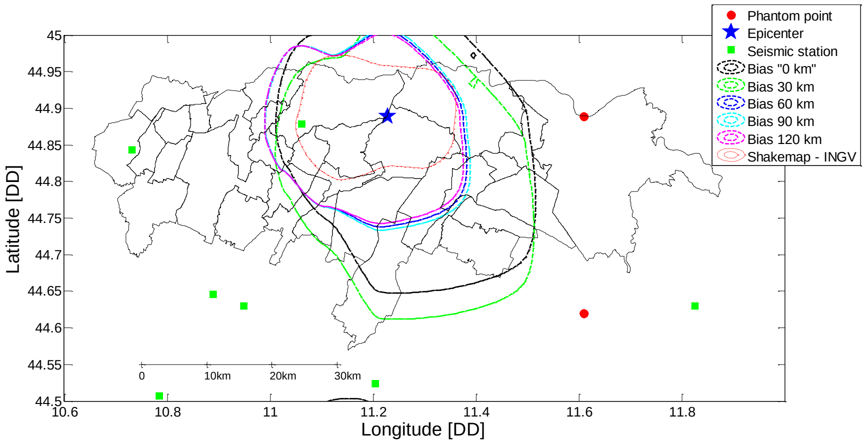


Fig. 15 Shakemaps for PGA = 0.25g, calculated with different bias values for the May 20, 2012 earthquake, M = 5.9

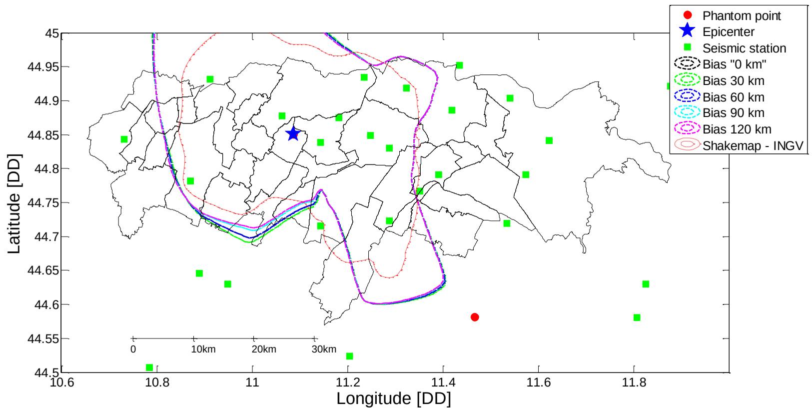


Fig. 16 Shakemaps for PGA = 0.15g, calculated with different bias values for the May 29, 2012 earthquake, M = 5.8

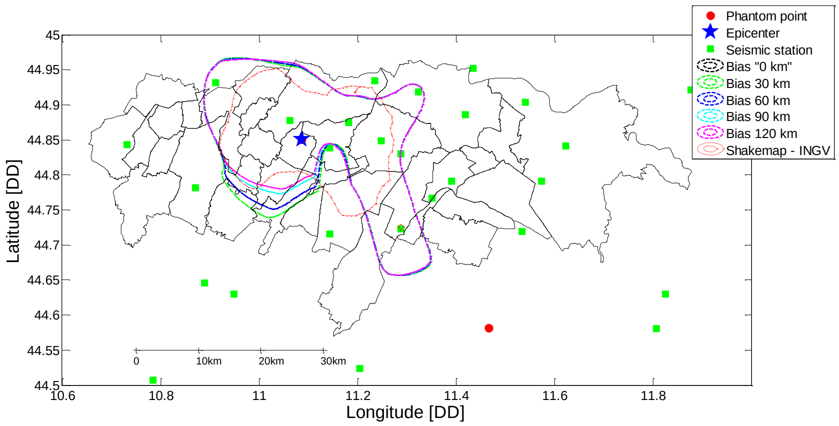


Fig. 17 Shakemaps for PGA = 0.25g, calculated with different bias values for the May 29, 2012 earthquake, M = 5.8

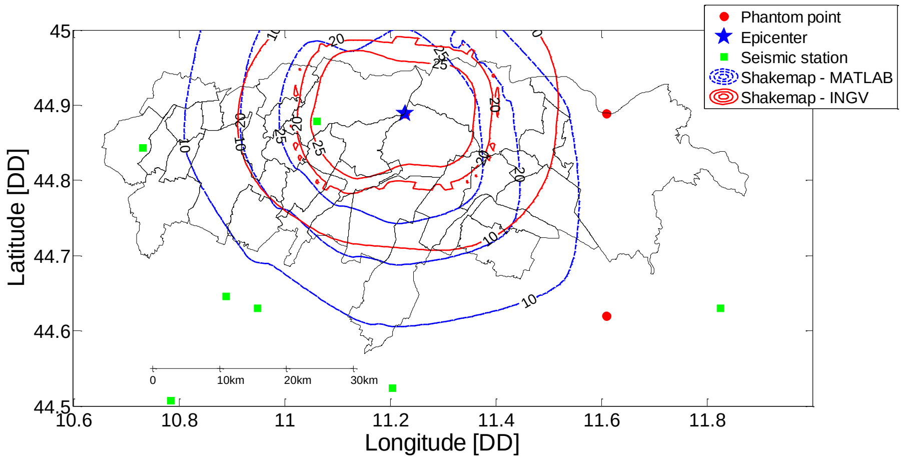


Fig. 18 Comparison of the shakemaps for the May 20, 2012 earthquake, M = 5.9

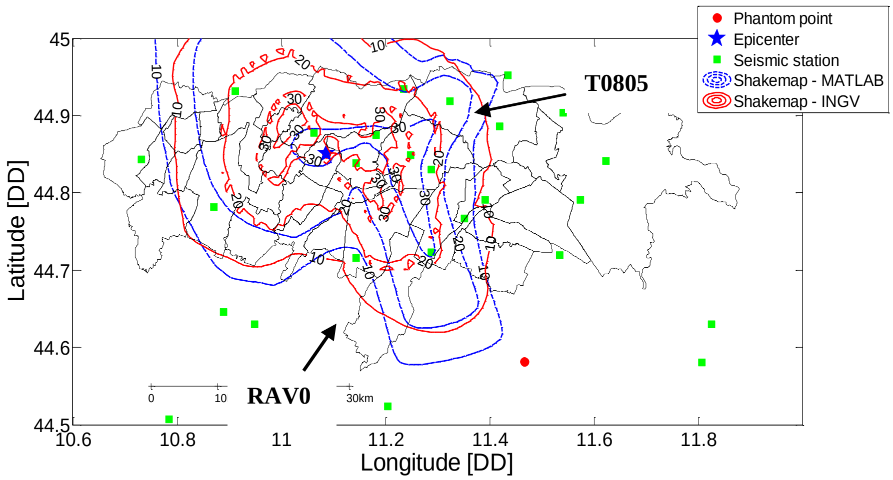


Fig 19 Comparison of the shakemaps for the May 29, 2012 earthquake, M = 5.8

calculated using varying values of the maximum station distance from the epicenter, in particular, 30, 60, 90 and 120 km. For the sake of comparison, the same graphs also include the case in which the bias is calculated starting with the nearest accelerometer station ("0 km"), as well as the corresponding contour lines calculated using the data provided by the INGV.

Once again in this case, the influence of the considered parameter is clearly important when the recorded data are scarce (May 20 earthquake), while it is negligible when the available recorded data is richer (May 29 earthquake), with the exception of the areas with low densities of accelerometer stations, one of which is immediately discernible in the figures in the area just south of the epicenter of the May 29 earthquake.

For the sake of comparison, Figs. 18-19 show the results obtained via the procedure described in the foregoing and the results published by the INGV on the Website *http://shakemap.rm.ingv.it/shake/archive/*. The resulting maps for the May 20 earthquake of

Table 4 Error in PGA calculation for the May 29, 2012 earthquake of magnitude 5.8

					Recorded data	Data calculated using INGV data		Data calculated through MATLAB procedure	
Station ID		Lon [DD]	Lat [DD]	V_{S30} [m/s]	PGA [% g]	PGA [% g]	Error	PGA [% g]	Error
MRN	1	11.06	44.88	230	29.6	28.66	3.1%	30.2	2.3%
SAN0	2	11.14	44.84	230	22.4	29.92	33.4%	23.9	6.6%
T0802	3	11.18	44.88	230	30.3	30.77	1.5%	30.8	1.7%
T0800	4	11.25	44.85	230	33.7	29.55	12.3%	33.2	1.4%
SMS0	5	11.24	44.93	230	18.3	20.45	11.5%	19.4	5.7%
FIN0	6	11.29	44.83	230	23.4	21.84	6.9%	24.9	6.1%
RAV0	7	11.14	44.72	230	8.4	11.78	40.9%	8.5	2.1%
MOG0	8	10.91	44.93	230	24.5	22.68	7.3%	25.8	5.4%
CRP	9	10.87	44.78	230	17.3	17.71	2.2%	18.2	4.8%
T0805	10	11.32	44.92	230	24.6	18.67	24.3%	25.9	5.2%
CNT	11	11.29	44.72	230	29.6	25.45	13.9%	30.2	2.2%
T0803	12	11.35	44.77	230	12.1	12.61	4.3%	12.5	3.1%
SERM	13	11.30	45.01	230	1.5	3.83	149.2%	1.6	1.2%
SAG0	14	11.39	44.79	230	8.1	8.67	7.7%	8.2	1.9%
BON0	15	11.42	44.89	230	3.6	6.07	70.0%	3.6	2.2%
NVL	16	10.73	44.84	230	5.5	5.67	2.9%	5.6	1.5%
MDN	17	10.89	44.65	230	5.2	5.16	0.8%	5.3	1.2%
MODE	18	10.95	44.63	230	4.5	4.81	7.2%	4.5	1.3%
FIC0	19	11.43	44.95	230	7.5	7.16	5.1%	7.7	1.9%
T0821	20	11.54	44.90	230	2.0	2.29	16.4%	1.8	9.7%

magnitude 5.9 (Fig. 18) are quite different, probably due to the fewer available recordings and the consequently greater influence of the hypotheses used in calculating the attenuation law, as already underlined in the foregoing. The two shakemaps for the May 29 earthquake, of magnitude 5.8 (Fig. 19), are instead generally in agreement, though it is immediately evident that the map produced using the INGV data does not, in some cases, correspond to the data recorded by the accelerometer stations (e.g. stations RAV0, which reported a PGA value of 8.33% g and station T0805, which recorded a PGA equal to 24.65% g).

With the aim of highlighting such differences, Table 4 shows the data recorded by the accelerometer stations, together with those calculated using the data provided by the INGV (file “grid.xyz.zip” available at *http://shakemap.rm.ingv.it/shake/7223045800/products.html*) and the associated error, for the stations nearest to the epicenter of the May 29 2012 earthquake of magnitude 5.8. To facilitate the comparison, the Table also contains the corresponding results calculated via the procedure described herein (and already presented in Table 3).

4. Conclusions

In the foregoing the procedure for generating the shakemaps used by the Italian National Institute of Geophysics and Volcanology (INGV) has been described. With the aim of analyzing its sensitivity to varying initial hypotheses underlying the calculations used, the procedure has been completely reconstructed, implemented in the MATLAB (MATLAB, 2008) software, and applied to the two major seismic events that struck the Emilia region of Italy on May 20 and 29, 2012, respectively characterized by magnitudes of 5.9 and 5.8. The choice of these seismic events was not arbitrary, but suggested by the provisions of a law specifically aimed at reducing the economic consequences of these seismic events on the region (Decree n. 74 of June 6, 2012, subsequently converted, with modifications, into Parliamentary law n. 122 of August 1, 2012). The law (Article 3, Section 10) specifically calls for using the shakemaps published by the INGV as an instrument for guiding the "Reconstruction and repair of private residences and non-housing properties; aid to enterprises; provisions for simplifying procedures".

An analysis has been conducted of the data recorded by the accelerometer stations present within the affected area, including calibration of the attenuation law for estimating the peak values of the considered shaking parameters. The calibration has been repeated a number of times, varying some of the underlying hypotheses in such way as to evaluate the sensitivity of the resulting shaking map to the aforesaid hypotheses. In particular, the shakemaps have been obtained by calibrating the attenuation law through two different possible methods: the least squares and the least absolute deviations. The results of application of the former have been found to exhibit closer agreement to the data recorded in correspondence to the epicentral zone, while the latter's correspond better to the outlying stations. The influence of the distance of the accelerometer station furthest from the epicenter used for calibrating the law of regression has also been investigated. In particular, 5 cases have been considered, that is, with a maximum station distance equal to: 30, 60, 90 and 120 km, plus the case in which the regression law is calculated using solely the station nearest to the epicenter. The results are shown in Figs. 14, 15, 16 and 17. Lastly, the influence of the presence of an epicentral phantom point was considered, even when excluded by rigorous application of the procedure proposed by the INGV.

The results obtained have highlighted the substantial sensitivity of the resulting shakemaps to the hypotheses underlying calculation of the regression law in correspondence to areas with a low density of accelerometer stations. Similar results were found by (Cultrera *et al*. 2014) that tried to assess the influence of this sensitivity on the exclusion zones defined by the Parliamentary Law no. 122 of August 1, 2012. On the aforementioned work it is then suggested to use the shakemaps for the early emergency managements, while "they fail if used beyond their intrinsic limitations". Also in this case, the main source of uncertainties and limitations can be identified in the correct application of the regression law.

For this reason it is suggested, within this work, to consider, when defining the exclusion zones, only data characterized by a density of accelerometer stations that do not need the calculation of the regression law. Another way to overcome such drawback, currently under development,integrates the data from the accelerometer stations with the information on the damage surveyed immediately after an earthquake. The procedure employs Bayesian updating and represents a significant improvement over the procedure presented here, one which the Authors believe can greatly increase the precision of the overall procedure, merging the data on the seismic events deriving from the acceleration stations and the information on the damaged structures.

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