



A COMPARISON OF ITALIAN SEISMICITY RATES BASED ON SMOOTHED AND AREA SOURCE MODELLING METHODOLOGIES

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ABSTRACT

The aim of this study is the comparison of the seismicity of the Italian region computed using two alternative modelling approaches: smoothed and area source modelling. Historically, hazard studies in Italy adopted traditional area source approaches, in which fixed boundary seismogenic zones are defined and uniform seismicity parameters are estimated within each zone. However, alternative seismic source models are also available, such as smoothed seismicity methods, in which no specific definition of seismogenic zones is required.

Based on the most recent Italian earthquake catalogue, CPTI11, this study computes exceedance rates according to the two aforementioned methodologies and compares them. Results are also compared to historical rates computed from the older catalogue CPTI04. Such a comparison is particularly meaningful given that CPTI04 is currently at the base of the official Italian hazard maps.

Differences and similarities in terms of geographical distribution and exceedance rates due to the different methodologies and different catalogues are discussed. Specific focus is given to the most populated and industrialized areas of the country, where most of the exposure is located. Possible applications of the findings are also presented, with emphasis on seismic risk applications, in which seismicity rates are at the base of artificial event-set generation.

INTRODUCTION

Italian seismicity has been largely investigated in the literature and several studies have given estimation of recurrence rates and distribution of earthquake activity across the country over the past decades. Most notably, current official seismic hazard, at the base of national earthquake design codes, is represented by the research project of INGV in 2004 (Gruppo di Lavoro, 2004).

The study by Gruppo di Lavoro (2004) was based on the 2004 version of the “Catalogo Parametrico dei Terremoti Italiani” (CPTI04) and a seismogenic zonation of Italy called ZS9. The Gruppo di Lavoro (2004) was a very detailed and thorough study, explicitly incorporating different sources of epistemic uncertainties (such as catalogue completeness, max magnitude definition, attenuation relationships, etc.) via a logic tree approach. However, since the completion of such a study, a new earthquake catalogue for Italy has been compiled, representing an amended and more complete version of the CPTI04, called CPTI11.

A detailed description of the new features of the CPTI11 is offered by Rovida et al. (2011). Differences to the CPTI04 are notable. In particular the epicentre of some events has been moved and the magnitude assignment of several historical events has changed. In general several low intensity

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earthquakes are now characterized with a smaller magnitude and some high-intensity earthquakes have been assigned with a larger magnitude. Moreover, while CPTI04 came already declustered of aftershocks, the CPTI11 is a “raw” catalogue, including all fore and aftershocks, allowing the researcher/professional to decluster the catalogue with the preferred technique.

It is therefore clear that CPTI11 represents a significant improvement over the CPTI04, the implications of which in terms of seismicity rates need to be understood. Towards this aim, the study presented in this paper looks at the seismicity rate distribution across the country computed using the CPTI11 catalogue and compares them to the CPTI04 rates. This first objective of the work is presented in the “Area Source Modelling” paragraph.

The main body of the study by Gruppo di Lavoro (2004) was based on area source modelling, i.e. based on a fixed seismogenic zonation in which the exceedance rates and distribution probability of the events within the zone is constant. Such an approach is “traditional” and widely adopted in most of the seismic hazard studies on the Italian region (Albarelo et al., 2000, Stucchi et al., 2011). However, it must be recognized that other techniques are also available, which are seeing an increasing application depending on the specific characteristic of the studied region (see for example SHARE project (Giardini et al. 2013) which adopts different source models in a logic tree fashion).

An alternative to the area source is the so called smoothed seismicity modelling. Smoothed seismicity is an approach based on the assumption that future earthquakes are more likely to occur at locations where historical earthquakes have happened, but it does not make assumptions on the boundaries of seismic sources of homogeneous seismicity (as in the area source methodology). Both methodologies have pros and cons, and no methodology can be labelled as more appropriate or “advanced” a priori, but they are both extremely useful to gauge the epistemic uncertainty related to the choice of a specific seismic source method. Towards this aim this paper recalculates Italian seismicity rates using the smoothed seismicity approach as well as using the newly generated CPTI11 catalogue. This second objective of the work is presented in the “Smoothed Seismicity Modelling” section.

Finally, all results obtained using the two different catalogues (CPTI11 and CPTI04) and the two different source methodology (area source and smoothed seismicity) are compared and discussed in the “Comparisons” section.

AREA SOURCE MODELLING

Area source modelling is a classical method for the representation of the earthquake generation mechanism, dating back to the early work by Cornell (1968). The method is currently still widely used in seismic hazard studies thanks to its simplicity and its applicability also in those regions where the exact location of faults is unknown. The current Italian seismic hazard at the base of national seismic design code is based on area source modelling, and the geometry of the seismogenic zonation is the ZS9 version, depicted in figure 1. The zones in the ZS9 zonation are 36 in total, covering most of the territory.



Figure 1 – Italian seismogenic zones as defined by the ZS9 zonation (base map from open street map)

From the geometry of the seismogenic sources and the earthquake catalogue, earthquake exceedance rates of each seismogenic zone can be computed. In the next sections the elaboration of the two earthquake catalogues used in this study, CPTI11 and CPTI04, is presented and the calculation of the exceedance rates of each is discussed.

CPTI11 Catalogue

The CPTI11 represent a significant step forward compared to the previous versions of the catalogue in terms of completeness and reliability. Compared to CPTI04 the magnitude of several events has been reassigned, resulting in a magnitude decrease for several low intensity events and a magnitude increase for some large intensity event. Also, the CPTI11 comes as “raw”, i.e. all events of which there is a trace in the historical records is included in the database, with no prior declustering done by the researchers who compiled the catalogue.

A “raw” catalogue allows for a greater flexibility as the user can choose the preferred declustering method and eventually assess the uncertainty correlated to the specific declustering choices. For this study the Gardner and Knopoff (1974) declustering technique was adopted (referred to as G-K hereafter), which represents an improvement compared to the magnitude-independent, fixed-time and fixed-space method used in the generation of the CPTI04 catalogue. The G-K method, instead, searches for foreshocks and aftershocks on the basis of fixed time and distance windows, which however are proportional to the magnitude of an event. The distance window is centered on the mainshock and the time windows for foreshock or aftershock can be selected to be identical or different (the former is usually set to be shorter). Table 1a shows the parameters adopted in the declustering of the CPTI11 by this study.

The resulting declustered catalogue is represented in figure 2, where the seismogenic zonation ZS9 is also depicted. Clearly the ZS9 geometry follows quite closely the distribution of the most significant earthquakes, even though a remaining low-intensity activity is also located outside of the ZS9 zones.

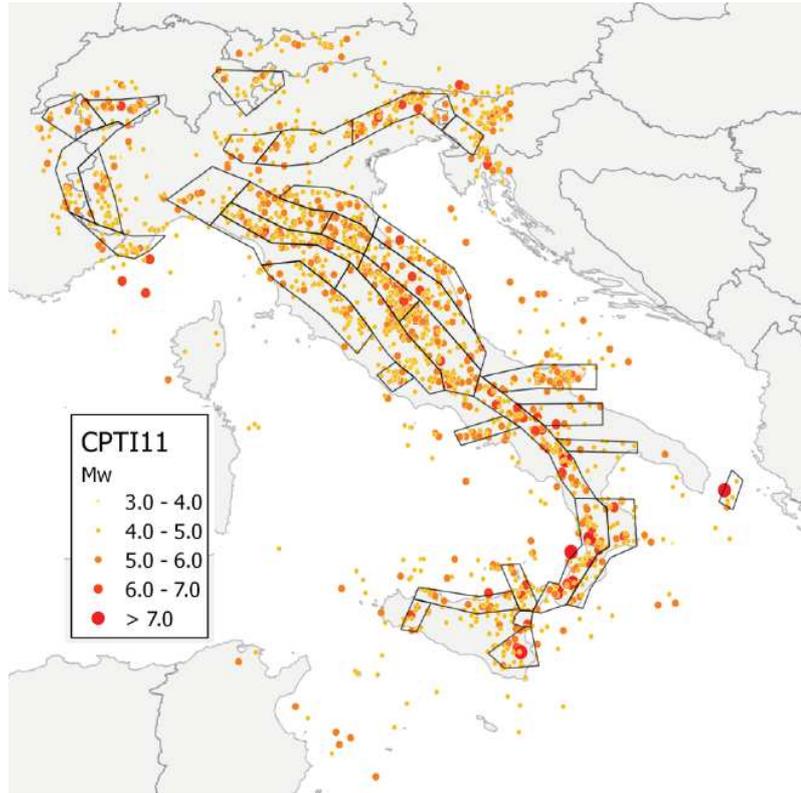


Figure 2 – Declustered CPTI11 catalogue superimposed to the ZS9 seismogenic zonation

Before estimating rates of seismicity, it is necessary to define the period of completeness by magnitude bins. Different completeness periods might be estimated for each of the seismogenic zone, as it was done by Gruppo di Lavoro (2004). However, for the sake of simplicity in this work we favoured a geographically homogeneous selection of completeness periods by magnitude bin across the whole country. Table 1b reports the magnitude bins and their respective completeness period. To ensure consistency, magnitude bins are the same as Gruppo di Lavoro (2004) and the completeness period is equal to the most recent amongst all seismogenic zone completeness periods identified by Gruppo di Lavoro (2004), as they proved to be matching quite well the completeness periods of CPTI11.

Table 1 – (a) G-K parameters for the declustering of the CPTI11, (b) completeness periods adopted for the CPTI11

Mw	Distance [km]	Time [decimal years]
4	30.07	0.11
4.5	34.68	0.21
5	39.99	0.39
5.5	46.12	0.73
6	53.19	1.37
6.5	61.33	2.43
7	70.73	2.52
7.3	77.04	2.57

(a)

Mw bin	Completeness
4.76 +/- 0.115	1895
4.99 +/- 0.115	1895
5.22 +/- 0.115	1787
5.45 +/- 0.115	1787
5.68 +/- 0.115	1787
5.91 +/- 0.115	1787
6.14 +/- 0.115	1530
6.37 +/- 0.115	1530
6.6 +/- 0.115	1530
6.83 +/- 0.115	1530
7.06 +/- 0.115	1530
7.29 +/- 0.115	1530

(b)

CPTI04 Catalogue

The CPTI04 catalogue (<http://emidius.mi.ingv.it/CPTI04/>) processed by INGV contains 2550 mainshock events occurred in the period between 217 B.C and 2002 A.D. The CPTI04 catalogue is the end result of a large effort from many scientists to produce a unified catalogue for hazard assessment in Italy. This catalogue comes already declustered and the declustering was done using a simple magnitude-independent technique that removed less energetic events that occurred within 90 days from the main event and with an epicentre located within 30km from the epicentre of the main event.

To compute CPTI04 rates in this work, the same completeness periods adopted by Gruppo di Lavoro (2004) have been implemented. The Gruppo di Lavoro (2004) computed completeness periods not only by Magnitude bins, but also by seismogenic zone. Moreover, Gruppo di Lavoro (2004) provided two alternative estimates of completeness periods, one solely based on the observation of rate trends (called “statistical completeness”), and the other based on the integration of completeness periods with historical considerations (called “historical completeness”).

For the full list of all completeness periods by Mag bin and by zone please refer to the original publication by Gruppo di Lavoro (2004).

SMOOTHED SEISMICITY MODELLING

The smoothed seismicity methodology recognizes that future earthquakes are more likely to occur at locations where historical earthquakes have happened but it does not make assumptions on the boundaries of seismic sources of homogeneous seismicity, as it is done in the ZS9 source zonation. In this work the procedure proposed by Frankel (1995) has been implemented to compute the smoothed seismicity rates.

The basic concept behind the smoothed seismicity approach is the independent evaluation of seismicity rates in each individual cells of a fine grid covering the entire territory. However, the length and the completeness of current catalogues are way too small to provide any stable indication of the true occurrence rate in each cell of the grid. Smoothed seismicity approaches attempt to mitigate this limitation by smoothing the seismicity of the cells containing events across adjacent cells using a 2 dimensional Gaussian kernel (as proposed by Frankel, 1995). A large standard deviation of the 2D kernel (e.g., 50km or more) tends to favour a smooth trend while a peaky kernel with a small standard deviation (e.g., 20 km or less) tends to generate a bull’s-eye activity rate pattern around the locations where past events occurred.

The main advantage of this approach is the removal of subjectivity in selecting the geometry of seismogenic zones, even though it must be recognized that an important degree of subjectivity is still present in the selection of the width of the smoothing kernel. Moreover the method is based on the concept that future earthquakes are located close to past earthquakes, not allowing for “surprise” events far from past quakes. A complete discussion on the advantages and disadvantages of each methodology is beyond the scope of this paper, but it must be recognised that smoothed seismicity provides an alternative view of the local seismicity, removing some sources of uncertainty and introducing some others.

This study applies the smoothed seismicity approach on a 0.1deg by 0.1deg grid, providing a and b values of the Gutenberg-Richter relationship in each cell of the grid. It is noted here that the 10^a value is equal to the annual rate of earthquakes per year with magnitude greater than zero. The standard deviation of the smoothing kernel has been put equal to 30km and truncated at three standard deviations from the centre. To evaluate the 10^a values on land all events of the declustered CPTI11 catalogue within a buffer of 100km from the coast and the Italian borders have been used.

The length of the complete catalogue, however, is too short for a robust evaluation of cell specific b values. Therefore, more robust estimates of the G-R b value were obtained by working at a country scale. For the estimation of the b -value the declustered CPTI11 catalogue was “filtered” using only the events inside Italy and a least square method was used for the regression. The minimum magnitude class used was $M_w=4.76 \pm 0.115$. The regression was made considering the events in each magnitude-specific completeness interval and counting the number per magnitude bin. The final estimate of the b value is 1.05.

The results of the smoothed seismicity approach are shown in figure 3, where the values in the cells represent the maximum likelihood estimates of 10^a above the minimum earthquake threshold selected, which is 4.465 for figure 3a and 5.105 for figure 3b.

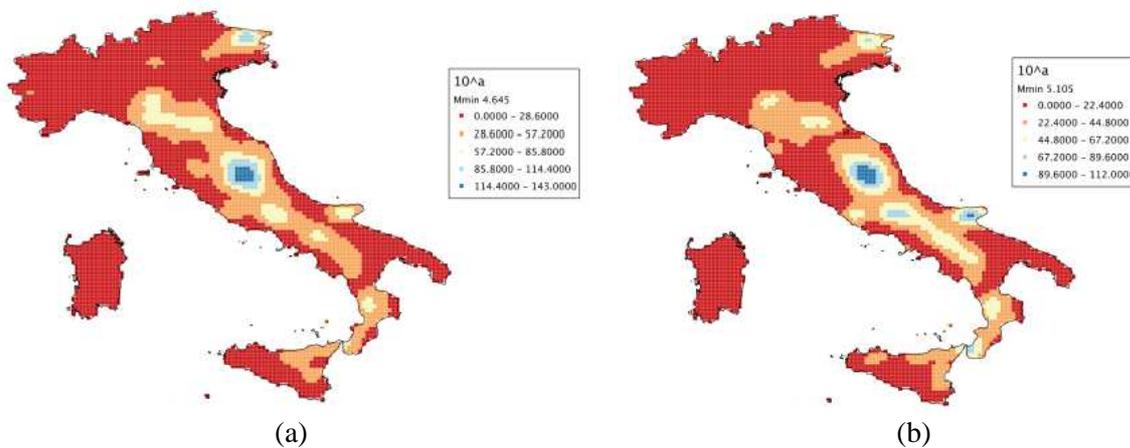


Figure 3 – Smoothed seismicity 10a exceedance rates in each cell of the grid for the two threshold magnitude: (a) 4.465 and (b) 5.105

By not contemplating events with a magnitude lower than Mw 5.105 (figure 3b), many clusters of seismicity with smaller magnitudes are not considered in areas where events with magnitude as large as Mw 5.105 or larger has never been observed in the recent past but they could potentially occur. When using a minimum magnitude of Mw 4.645, on the other hand, the coverage is more complete spatially but in some areas the rates are lower and in others higher than those observed in the, rather short, completeness periods of the historical catalogue.

The differences between the two different results are better represented in figure 4, where the ration between the smoothed seismicity results with the two different minimum magnitudes is plotted.

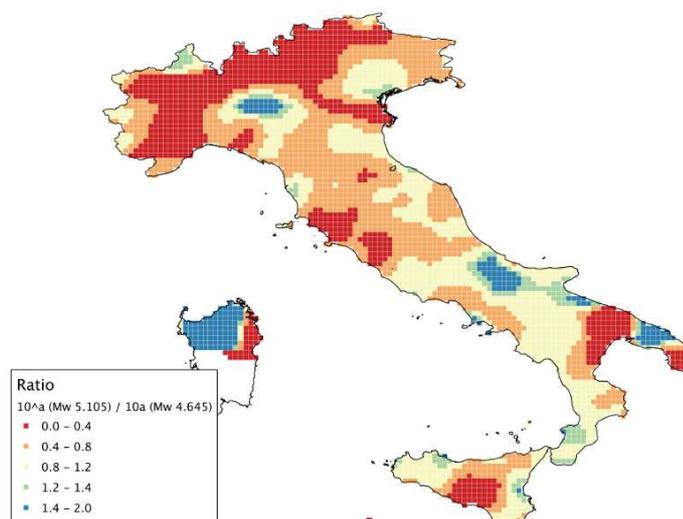


Figure 4 – Ratio between smoothed seismicity rate computed with the two different threshold values of Mw=4.465 and Mw=5.105

COMPARISONS OF DIFFERENT METHODOLOGIES AND CATALOGUES

The seismicity rates in Italy have been computed according to different methodologies and using different catalogues. In particular, the following results data has been produced:

- Exceedance rate by seismogenic zone using CPTII 1

- Exceedance rate by seismogenic zone using CPTI04 (2 alternative rates available depending on the statistical or historical completeness)
- Exceedance rate by grid cell (smoothed seismicity approach) using CPTI11

An initial and interesting discussion is represented by the comparison of seismicity rates between CPTI11 and CPTI04 using the same area source modelling methodology. The results of the comparison are presented in figure 5, which shows the ratio of cumulative annual rates for events greater than 4.645. For the generation of figure 5 only, the CPTI04 rates have been computed using the same country-wide completeness period as the CPTI11, rather than the historic and statistical completeness by Gruppo di Lavoro (2004), to ensure consistency.

In general a decrease of rates going from CPTI04 to CPTI11 can be observed. Most of the variability is limited to +/-25% (yellow and light orange), with some important exceptions such as some of the west coast zones, showing a much sharper decrease.

It should be noted that this ratio is computed using the exceedance rate of earthquakes with $M_w > 4.645$ and it is therefore driven by small magnitude events and it is not representative of the variation of high intensity events. From a risk perspective, however, the comparison is still very meaningful since generally the average annual loss (AAL) is mostly driven by medium/small events, generating small losses but much more frequently. It is therefore possible to expect that a seismic loss estimation which used the CPTI11 rather than CPTI04 as basis of the artificial event set might results in a smaller AAL loss (even though specific portfolio distribution will also have a strong influence).

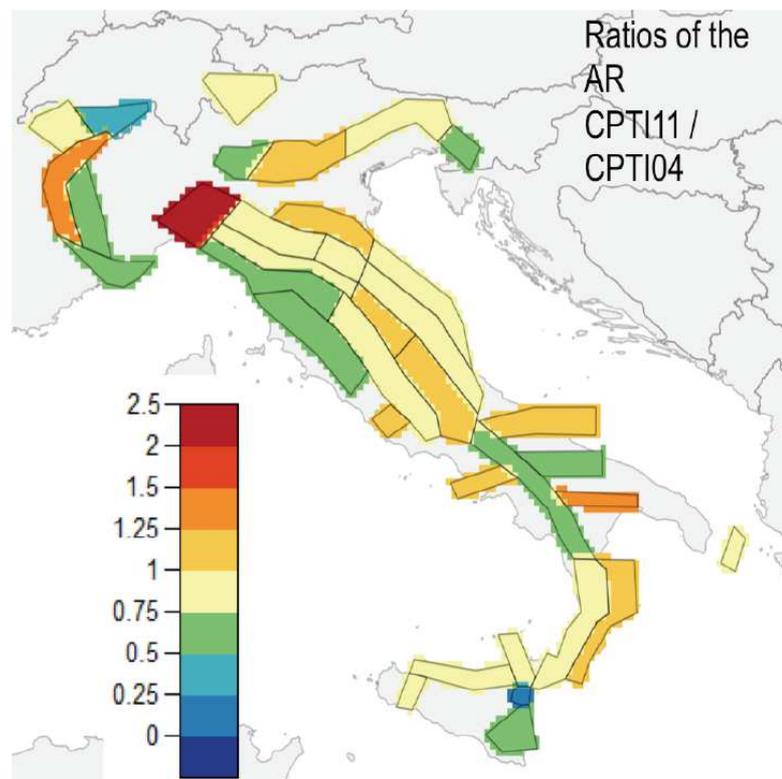


Figure 5 – Ratios between exceedance rate for $M_w = 4.645$ computed using CPTI11 and CPTI04

The overall countrywide comparison for all magnitudes is offered in terms of Gutenberg-Richter plot in figure 6. The figure includes all results produced for this work, area source modelling and smoothed seismicity. The CPTI04 H and S values refer to the historical and statistical completeness respectively. The country wide values of the area source models is equal to the sum of the exceedance rates of the all seismogenic zones, while the smoothed seismicity values is obtained from the sum of all grid a values.

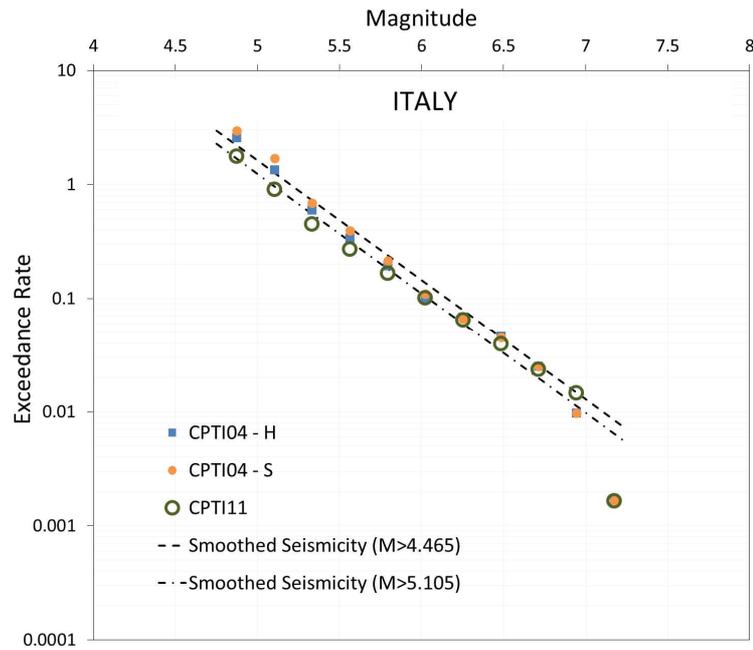


Figure 6 – magnitude versus exceedance rate values computed using seismogenic zones and smoothed seismicity method for the CPTI04 and CPTI11 catalogues (H and S refer to historical and statistical completeness)

The difference between the rates obtained using CPTI11 and CPTI04 can be noticed in figure 6 as well, particular for magnitude values smaller than about 6. For larger magnitudes the values are similar with the exception of the $M_w=7$ rates, where CPTI11 is larger than CPTI04. The smoothed seismicity country-wide rates are in line with the other values.

The variability between different methodologies increases if regional values are observed, rather than countrywide values.

Figure 7 shows three zones where the discrepancy between the smoothed seismicity and the other approaches is significant. The rates are quite similar for small magnitudes but then to diverge for higher intensity events.

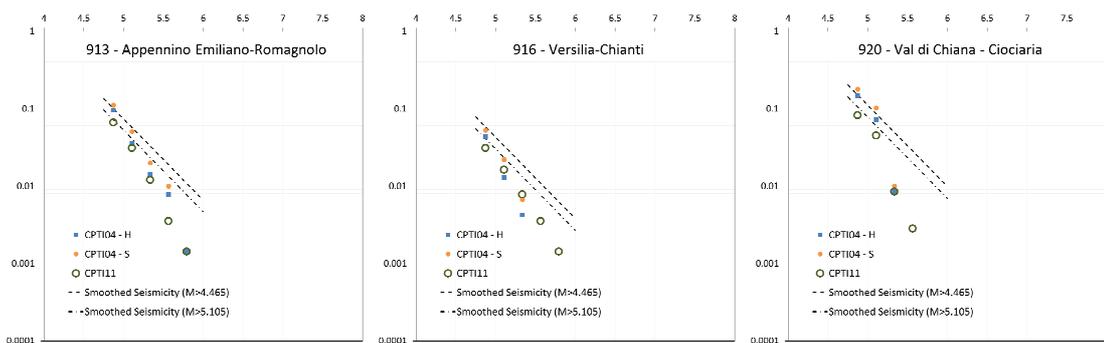


Figure 7 – Example of zones in which the smoothed seismicity rates are larger than “area source” rates

The variability between smoothed seismicity rates and the other rates, however, is opposite in some other zones. Figure 8 shows three zones where the discrepancy is particularly evident: rates are similar at small magnitudes, while diverge at larger magnitude, with smoothed seismicity rates being significantly lower than area source rates.

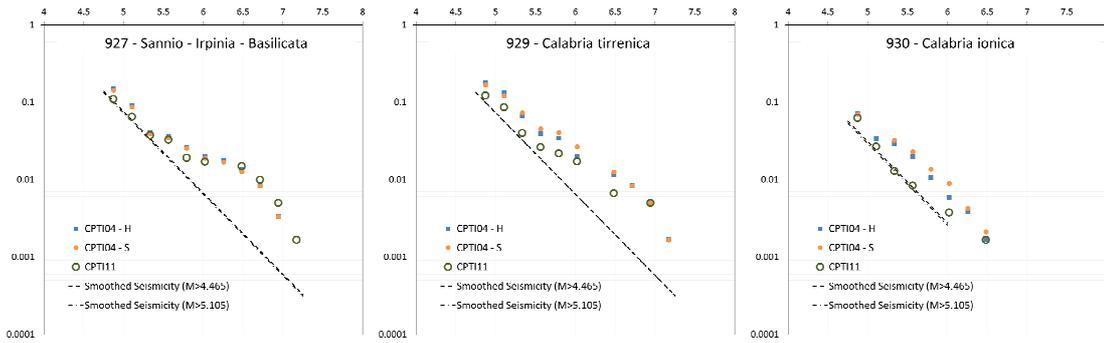


Figure 8 – Example of zones in which the smoothed seismicity rates are smaller than “area source” rates.

Finally figure 9 compares the rates computed using the CPTI11 events located outside the seismogenic zones and the sum of the smoothed seismicity rates of all the cells located outside ZS9 zones. Again a certain discrepancy can be observed, with the smoothed seismicity rates being larger than the historical rates from CPTI11.

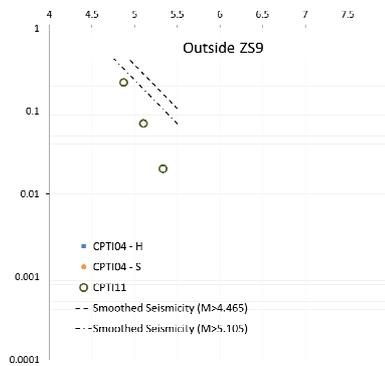


Figure 9 – Comparison of smoothed seismicity and area source rates for the part of the territory not covered by seismogenic zones.

It can be detected a pattern within the discrepancies between smoothed seismicity rates and the area source rates, related to the geographical location of the zones: the zones that experience larger smoothed seismicity rates at large magnitudes are in the north of the country, while the opposite happens in the south. The reason for such a geographical correlation of the rate discrepancy is to be sought in the relative frequency of large earthquake to small earthquakes and its variability across the country.

The relative frequency of small to large earthquakes is governed by the b value of the Gutenberg-Richter formula, which in the application of the smoothed seismicity approach in this work takes a single value representative of the average relative frequency of the entire Italian territory, equal to 1.05.

In the area source modelling, instead, rates are computed individually in each seismogenic zone and therefore the relative frequency of small to large earthquakes varies from zone to zone. In their work, Gruppo di Lavoro (2004) computed the best fit for the Gutenberg-Richter b value to the historical rates, and indeed it was found that in general b value in the northern part of Italy was larger than in the southern part. The distribution of the b -values calculated by Gruppo di Lavoro (2004) is represented in figure 10, where it is shown how b values larger than 1 are mostly located in the north (yellow and orange zones), and b values smaller than one are mostly located in the south (light and dark blue zones).

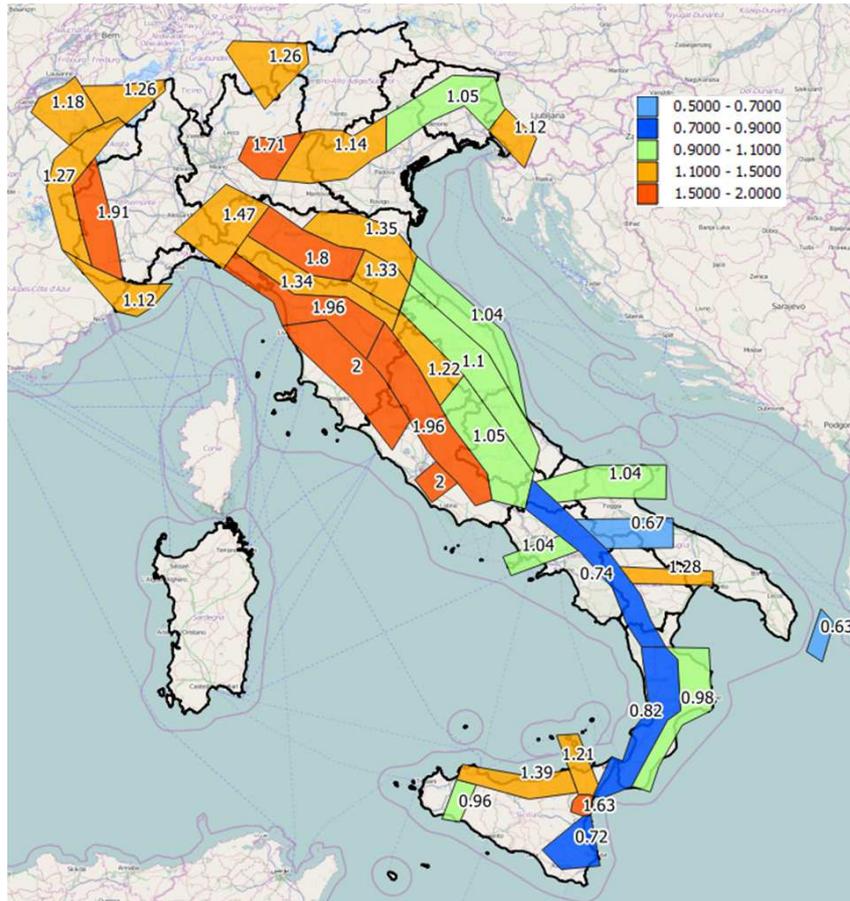


Figure 10 – b values of the Gutenberg-Richter curve as computed by Gruppo di Lavoro (2004) using the historical completes option.

CONCLUSIONS

In this work Italian seismicity rates have been computed using two different catalogues, CPTI04 and CPTI11, and two different methodologies, area source modelling and smoothed seismicity modelling, with the aim of estimating the uncertainties and variability correlated to such factors.

Comparing the historical rates computed with the two catalogues within each seismogenic zones it was found that:

- The rates computed with the CPTI11 are generally lower than the rates computed with CPTI04, with few notable exceptions.
- The difference, however, is generally limited and falls in the +/- 25% range with few notable differences, where the reduction is more drastic. Very few zones see an increase larger than 25%.

The difference between the CPTI11 and CPTI04 rates are certainly to be sought in the composition of the catalogues themselves, knowing that the magnitude of historical earthquakes has been reassigned in several cases. Part of the difference, however, is also to be related to a different declustering technique adopted for the two catalogues. While the CPTI04 was declustered using a magnitude-independent technique, the CPTI11 has been declustered in this study using the Gardner and Knopoff (1974) method, which is likely to have removed a larger number of aftershocks, especially after high energy quakes.

The comparison between the smoothed seismicity and the area source modelling rates identified the following important differences and similarities between the results of the methodologies:

- Country-wide the rates obtained from the smoothed seismicity method and the area source modelling are in good agreement (as expected, since the two approaches are based on the same catalogues)

- Regionally, however, important discrepancies arise. The following observations could be made comparing the rate by each zone of the ZS9:
 - In some zones in the north the large magnitude rates predicted by smoothed seismicity are larger than the historical rates computed within the same seismogenic zones
 - In some zones in the south the large magnitude rates predicted by smoothed seismicity are smaller than the historical rates computed within the same seismogenic zones
 - Some discrepancies between smoothed seismicity rates and historical rates outside seismogenic zones also exist

Given the intrinsic differences between area source and smoothed seismicity modelling, rate estimates were expected to have a certain degree of disagreement. However, it is interesting to notice that the divergence between the two approaches has a spatial pattern. This is due to the variation across the Italian of the relative frequency of small to large earthquakes: the smoothed seismicity method, as implemented in this specific study, is not able to reflect this variability since it adopted a single b value across the whole country.

This comparison highlights an important characteristic of the smoothed seismicity modelling, i.e. the necessity to compute an average b value over a large portion of the territory, which needs to be carefully considered in an application over the Italian territory. Provided that the relative frequency distribution of small to large events across the Italian territory as shown by the historical rates of CPTI04 and CPTI11 is realistic and not generated by an artificial bias in the catalogue generation (e.g. lack/duplication of records, too few events in the zones, etc.), the adoption of a single b value in a smoothed seismicity approach might lead to significantly different results in some areas and not be entirely appropriate. However, such a choice might also fall into the bigger discussion of the regional variability of b values, which sees some studies supporting a constant value, equal to 1, at both large and small scale (see for example Kagan, 2002) and some others who allow for a variable b values depending on the tectonic regime, stress state and materials (see for example Schorlemmer et al., 2005 or Shanker and Sharma, 1998). A thorough discussion on the topic is however outside the scope of this study and requires a more extensive research.

The selection of the two alternative solutions (area source modelling with variable b value and smoothed seismicity with constant b value) should be considered with special care also in the case of seismic loss estimations. The seismicity rates as computed in this paper are often used as basis for the generation of artificial event set to be adopted in seismic risk applications for the simulation of losses of large portfolios distributed over the territory. The fact that different methodologies predict similar results at a countrywide scale might not be relevant for portfolios not uniformly distributed within the country. Indeed a non-uniform distribution of exposure is often the case, especially in a country like Italy, where the industrial gap between north and south is very large. In this context, this study might provide useful guidance and insight in the evaluation and comparison of different methodologies and catalogues at a regional scale.

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