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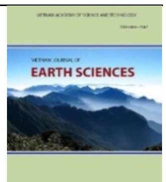

Seismogenic nodes as a viable alternative to seismogenic zones and observed seismicity for the definition of seismic hazard at regional scale

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ABSTRACT

A fixed increment of magnitude is equivalent to multiply the seismic moment by a factor γ_{EM} related to the partial factor γ_q acting on the seismic moment representing the fault. A comparison is made between the hazard maps obtained with the Neo-Deterministic Seismic Hazard Assessment (NDSHA), using two different approaches: one based on the events magnitude, listed in parametric earthquake catalogues compiled for the study areas, with sources located within the seismogenic zones; the other uses the seismogenic nodes identified by means of pattern recognition techniques applied to morphostructural zonation (MSZ), and increases the reference magnitude by a constant amount tuned by the safety factor γ_{EM}.

Using γ_{EM}=2.0, in most of the territory the two approaches produce totally independent, comparable hazard maps, based on the quite long Italian catalogue. This represents a validation of the seismogenic nodes method and a tuning of the safety factor γ_{EM} at about 2.

Keywords: Seismogenic nodes; Seismogenic zones; Maximum Credible Earthquake; Neo Deterministic Seismic Hazard Assessment; Eurocodes.

1. Introduction

In the original formulation of NDSHA (Neo Deterministic Seismic Hazard Assessment; Panza et al., 2001; 2012), physics-based computer computation was combined with a comprehensive geologic and geophysical overview of the regional tectonic setting and earthquake history to solve, in a first approximation, the fundamental problems posed by an adequate description of the physical process of earthquake occurrence (which in the real earth is a tensor phenomenon). It examines the largest scenario event physically possible, usually termed Maximum Credible Earthquake (MCE). At a given site the cellular magnitude of this event M_{design} can be tentatively, until proven

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otherwise, set equal to the maximum observed or estimated magnitude M_{max}, plus some multiple of its accepted global standard deviation σ_M. In areas where information on faults and other input data are sparse, the historical data together with morphostructural analysis are relied upon to estimate this maximum magnitude (e.g. Parvez et al., 2017; Hassan et al., 2017; Rugarli et al., 2019). The NDSHA approach overcomes one of the key drawbacks of PSHA from the observational point of view: the need to have as much as possible a complete catalogue for minor earthquakes (e.g. M<4). This condition is hardly met in many instances, mostly in historically not so active tectonic regions, where minor earthquakes may have occurred but were not observed. NDSHA requires satisfactory completeness for moderate earthquakes (M≥5) that rarely may elude observations.

According to Chebyshev's theorem for a very wide class of probability distributions, no more than a certain fraction of values can be more than a certain distance away from the mean. Specifically, no more than $1/k^2$ of a distribution's values can be more than k standard deviations away from the mean (or equivalently, at least $1-1/k^2$ of the distribution's values are within k standard deviations of the mean). If k=2, then at least 75% of the values fall within $2\sigma_M$ and if k=3 at least 89% of the values fall within an interval of $3\sigma_M$ centered on the mean.

The factor k can be considered a tunable safety factor that may be applied coherently with the safety factors used in structural engineering, e.g. naming it γ_{EM} (EM = Earthquake Magnitude).

So $M_{design}=M_{max}+\gamma_{EM}\sigma_M$, where it is currently assumed σ_M=0.2−0.3, and it is proposed to use γ_{EM}=1.5−2.5. Since the design value M_{design} is determined by adding a further tunable increment to the maximum estimated value M_{max} (not the mean), it must be considered an envelope-evaluated at the best of our present-day knowledge. Incidentally we observe, for example, that the application of the upper limit of the "tunable safety factor" $\gamma_{EM}\sigma_M$ to the Maximum observed magnitude (M_{max} = 7.5) in southern California, within the time interval 1932–2011 (Chiou and Miao, 2013), we obtain $M_{design}=M_{max}+\gamma_{EM}\sigma_M \approx 8.2$; this result is well in agreement with the estimates by Kijko (2004), where $M_{max} \approx 8.3$ and by Field et al. (1999), wherein $M_{max} \approx 8.0$.

2. Safety factors

In the mechanical systems currently used by engineers to evaluate the safety of the structures, the semi-probabilistic or partial safety factors paradigm has emerged as a reference in the last 40 years. In the following, reference will be made to the so called Eurocode 0 (CEN EN-1990:2002), which is a standard accepted worldwide, because the paradigm is described in detail. This standard is the basis of all the other Eurocodes, referring to actions (EN 1991), concrete structures (EN 1992), steel structures (EN 1993), seismic design (EN 1998) and so on.

Both the applied actions and the resistances are usually evaluated statistically, and characteristic values are computed. Characteristic values are values that, assuming some distribution of probability, have a given low probability to be exceeded (the actions), or to be unreached (the material resistances), in a given reference period or after some production process.

Among the existing actions, Eurocode 0 enlists also the so-called accidental actions, among which earthquakes are to be considered. An accidental action is defined in Eurocode 0 (CEN EN-1990:2002, par.1.5) as

"an action, usually of short duration but of significant magnitude, that is unlikely to occur on a given structure during the design working life

NOTE 2 Impact, snow, wind and seismic actions may be variable or accidental actions, depending on available information on statistical distribution".

Eurocode 0 is aware that it is not always possible to have reliable statistics referring to actions. For these cases it admits that the characteristic value of variable actions is expressed as (Eurocode 0, CEN EN-1990:2002, par. 4.1.2(7))

"A nominal value, which may be specified in cases where a statistical distribution is not known".

In Eurocode 0 (CEN EN-1990:2002, par. 1.5) a nominal value is defined as a

"value fixed on non-statistical bases, for instance on acquired experience or on physical conditions".

For seismic action, which is a special accidental action unless otherwise stated, Eurocode 0 requires that (Eurocode 0, CEN EN-1990:2002, par. 4.1.2(9)) the design value

"design value A_{Ed} should be assessed by the characteristic value A_{Ek} or specified for individual projects".

Gulvanessian et al. (2002) underline that:

"Note that some variable actions may not have a periodical character similar to climatic or traffic actions and the above concepts of reference period and return period may not be suitable. In this case the characteristic value of a variable action may be determined in a different way, taking into account its actual nature".

As it has been much debated elsewhere (e.g. PAGEOPH Topical Volume 168, "Advanced Seismic Hazard Assessment" (2011) and references therein; Wyss et al., 2012; Bela, 2014), the use of historically tuned statistical indices for seismicity, based on the erroneous concept of "return period" and Poisson's statistical distributions, is rootless and unsafe, and, in particular, NDSHA does not use such assumptions. However, Eurocode 0 allows that for individual projects, which are one of the intrinsic abilities of NDSHA, design values may be otherwise specified.

It must be underlined that for variable actions, the code allows for the use of nominal values as characteristic values, that is, values that are notionally agreed because considered safe. In what follows it will be shown that the use of a maximum reference magnitude increased by a constant term $\gamma_{EM}\sigma_M$ is deeply rooted within the standard Eurocode procedures, and it is not an erratic tentative procedure.

Using the currently accepted Eurocode paradigm, in order to get the design value for variable actions, a further safety factor, named γ_q, is applied to the characteristic value of an action Q_k, so that the design value for the action is $Q_d=\gamma_q Q_k$. Usually, for the so-called ultimate limit states, and for typical actions like those of wind or snow, γ_q=1.5. As it has been seen, Q_k may also be a nominal value.

The mechanism of fault slip giving rise to seismic waves that, after propagation from source to site, will load the structures as accidental actions, is governed by several parameters, among which are mainly important, for displacement dislocation at the fault, the forces exchanged between the two sides of the slipping fault that can be represented exactly by a double couple, with seismic moment M_0 (Burridge and Knopoff, 1964). In considering seismicity, at a given fault, the idea to get the characteristic seismic moment value by a statistical distribution must be abandoned due to the lack of data. The missing characteristic seismic moment acting at the fault is replaced with the estimated or maximum seismic moment M_0 acting at a given fault, that is a nominal value using the Eurocode nomenclature. The seismic moment M_0 at the fault is chosen according to what follows, in NDSHA:

(1) The seismic moment M_0 considered is a reasonable lower estimate of the worst that might physically happen when only seismogenic nodes are used, since, by definition, they accommodate earthquakes

with a magnitude above a fixed threshold (Gorshkov et al., 2002; 2004; Peresan et al., 2015) (this is the NDSHA suggested procedure when no historical catalogues are available or they are not considered sufficiently complete).

(2) The seismic moment M_0 considered is the maximum in the parametric catalogue if only the catalogue and seismogenic zones are used (this is the original, chronologically first NDSHA).

(3) The seismic moment considered is the maximum between parametric catalogue and seismogenic nodes, all within seismogenic zones, if are all used at the same time (this is NDSHA as suggested in regions where catalogues are available).

The seismic moment applied at the fault is one of the main input of NDSHA, at a given source. Then, by also controlling other parameters, NDSHA is able to fully simulate waves induced in the earth-mechanical system along the path from source to the bedrock at the site, and with site specific analyses, the path from the bedrock at the site to the surface at the site.

In other words, the seismic moment M_0 acts, within the framework of NDSHA, as a variable action whose (usually maximum) value is estimated in order to compute some mechanical effects caused by it. The analogy with what is done by structural engineers with their systems is strict, in theoretical sense.

The moment magnitude M_w is related to the seismic moment acting at the fault M_0 by the well-known Hanks-Kanamori formula (Hanks and Kanamori, 1979), where the seismic moment is measured in Nm:

$$M_W = \frac{2}{3}\left[\mathrm{Log}(M_0) - 6\right]$$

If the same rule used by Eurocode 0 for variable actions is applied to the seismic moment acting at the fault M_0, which acts as an input action Q_k, we get

$$M_{W,design} = \frac{2}{3}\left[\mathrm{Log}(\gamma_q M_0) - 6\right]$$

which leads to

$$M_{W,design} = \frac{2}{3}\left[\mathrm{Log}(\gamma_q M_0) - 6\right] = M_W + \frac{2}{3}\mathrm{Log}(\gamma_q)$$

So in order to factor the seismic moment which acts as a mechanical force applied to the system, the magnitude related to it should be increased by a fixed increment, namely

$$\Delta M = \frac{2}{3}\mathrm{Log}(\gamma_q)$$

If we set this increment equal to σ_M times a new safety factor γ_{EM}, we get

$$\gamma_{EM}\sigma_M = \frac{2}{3}\mathrm{Log}(\gamma_q)$$

Assuming σ_M=0.2 and γ_{EM} in the range 1.5−2.5 (e.g. Rugarli et al., 2019) we get that γ_q can be defined in the integer range γ_q=3–6. The high values, when compared to the current 1.5 used for more friendly actions like wind or snow, or passing vehicles, are the counterpart of the much higher uncertainness related to earthquakes. In fact γ_q=3–6 is well consistent with the variation that may affect M_0, as determined, for the same event, by different agencies and methods (e.g. Panza and Saraò, 2000; Saraò et al., 2001; Guidarelli and Panza, 2006; Chu et al., 2009).

So when the estimated magnitude at a fault is increased by a constant value, this is equivalent to factoring the seismic moment acting at the fault, exactly as a structural engineer following the format of partial safety factor method would do.

3. Validation of the safety factor

NDSHA's aim is to supply an envelope value, in other words a value that should not be exceeded, therefore it is immediately falsifiable: if an earthquake occurs with a magnitude M_{eq}, larger than that indicated by NDSHA's M_{design}, then $\Delta M = M_{eq}\text{-}M_{max} > \gamma_{EM}\sigma_M$ and γ_{EM} should be increased. Given the way M_{design} is defined, however, this is expected to be a rare condition.

γ_{EM} should similarly be increased, should recorded peak ground motion values (e.g. PGA) on the bedrock at the occurrence of an earthquake M_{eq} after the compilation of NDSHA maps, exceed within error limits those values given in these same maps. By way of improving usefulness and applicability of future strong ground motion recordings, this would suggest to possibly install additional stations over stiff soils, so as to avoid the local amplifications due to site effects. Today the majority of the strong ground motion stations of, for instance, the Italian net, are sited over soft soils (ITACA release 2.3 - http://itaca.mi.ingv.it/).

The selection of the multiplier γ_{EM} to be applied to the standard deviation cannot be proved by equations, and it would be misleading to try to do so. Therefore the choice of its value is partly heuristic, or rule-of-thumb. Nonetheless, should this heuristic be falsified by natural experiments, this multiplier can be gradually reset to the minimum safe value. This is what has already been done with all the safety factors used in engineering: (i) the γ=1.5 safety factor for material limit stresses was used well before the availability of reliable statistical measures; and (ii) the semi-probabilistic methods used in structural engineering are de facto tuned to confirm these already validated-by-experience values (Rugarli et al., 2019).

4. Tuning of γ_{EM} in Italy

Italy is the country with the longest parametric earthquake catalogue based upon both historical and instrumental data. As it is well known the loglinear Gutenberg-Richter relation (GR) represents a law only at global scale (Båth, 1973; Kosobokov and Mazhkenov, 1994; Molchan et al., 1997).

Considering the loglinear GR relation as a law, the used Italian earthquake catalogue can be considered sufficiently complete (e.g. Vorobieva and Panza, 1993) at national scale, starting from year 1000, for events with magnitude M such that $M_{tr}<M<M_{up}$ that is, for Italy, 5.0<M<7.5. Indeed, hazard maps given by NDSHA for Italy, based on magnitude range 5.0<M<7.5, envelope the standard national PSHA maps at the base of the national seismic code (e.g. Zuccolo et al., 2011).

The magnitude M_{tr}=5 is the lower magnitude threshold used for NDSHA computations (Panza et al., 2001). The upper magnitude M_{up} is related to the specific of Italian territory.

Completeness according to GR means that:
(1) in the catalogue the number of occurred but missed earthquakes having $M>M_{tr}$, that is the completeness threshold (in our case M_{tr}=5.0), is minor;
(2) the information content of the catalogue cannot exclude the occurrence, in Italy, of a future event with $M>M_{up}$=7.5.

Naturally, completeness does not obviously imply ubiquitous representativeness of the real earthquake hazard and this imposes special care in the definition of MCE. "As far as the laws of mathematics refer to reality, they are not certain; and as far as they are certain, they do not refer to reality" (Albert Einstein, Geometry and Experience-an expanded form of an Address to the Prussian Academy of Sciences in Berlin on January 27th, 1921).

Via the GR law, the extension of the region to be considered and the interval of magnitudes are related, as the sources in all the magnitude range must be so small, when compared to the region extent, to be considered as points: GR law is only valid when considering a region sufficiently extended.

Having a catalogue that might be considered complete in a given area and for a given magnitude interval, implies having some root in assuming that the still not experienced faults are a small number, otherwise major, not minor differences between the expected and the historically recorded number of events could be estimated, should GR law be considered valid.

If this is true, then the catalogue is a useful tool to tune the safety factor γ_{EM} in a procedure where only seismogenic nodes are used, and not the catalogue itself or the related seismogenic zones.

In this way the catalogue is used as a huge set of experiments, to be tested against some possibly assumed safety factors γ_{EM}. Full independency between the map considered summing a given constant $\gamma_{EM}\sigma_M$ to the magnitude of seismogenic nodes, and the results of the catalogue, is preserved. The two sets are totally independent.

4.1. Hazard map based on seismogenic zones and parametric earthquake catalogue

This map is the map used as target value, i.e. the map has been considered equivalent to a set of experimental results, during 1000 years. This is a unique-worlwide set of data. However, the experimental macroseismic intensities, and then the magnitudes and derived M_0, are necessarily affected by high uncertainness, that should be considered when using them.

The magnitude smoothing procedure applied by NDSHA for regional scale computations (Panza et al., 2001) is a first step aimed at a conservative earthquake hazard estimate. Figure 1 shows the earthquake sources defined within the ZS9 seismic zones (Meletti et al., 2008), before (left) and after (right) the smoothing window of three cells has been applied to the magnitude values reported in the CPTI04 parametric catalogue (CPTI04 Working Group, 2004), discretized into 0.2° × 0.2° cells. No magnitude increment $\gamma_{EM}\sigma_M$ has been applied to this map.

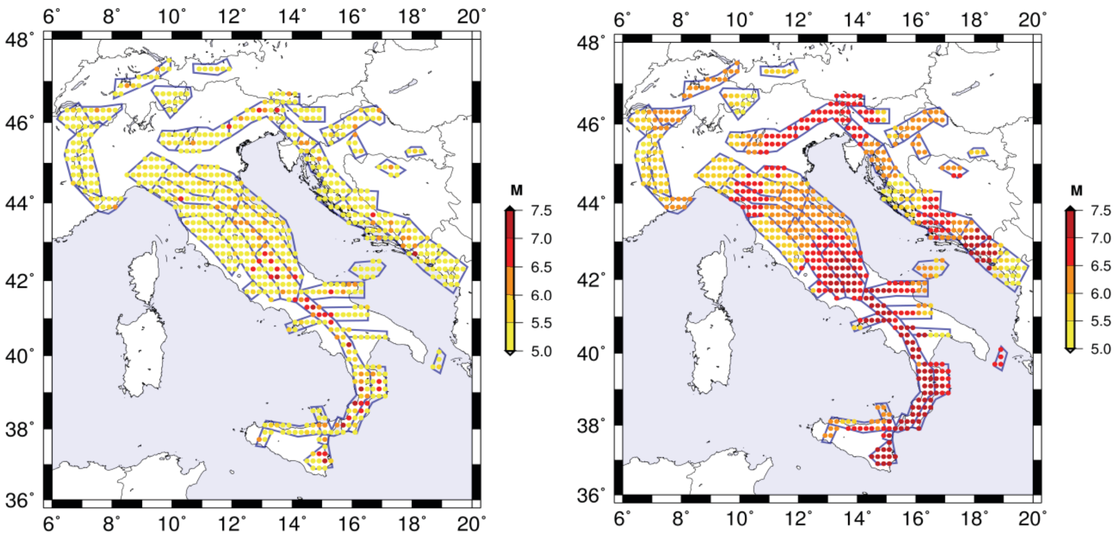

Figure 1. Earthquake sources used for the computation of the synthetic seismograms, which are at the base of the NDSHA maps at regional scale (γ_{EM}=0). For our study area, the sources are located within the seismogenic zones defined by ZS9 (Meletti et al., 2008), with additions by A.A. V.V. (2000). Left: distribution obtained from the unperturbed magnitudes available in the CPTI04 (CPTI04 Working Group, 2004) earthquake catalogue, discretized into 0.2° × 0.2° cells. Right: distribution obtained after the smoothing procedure has been applied

The NDSHA map of Design Ground Acceleration (DGA) based on the smoothed magnitude distribution is shown in Fig. 2. It corresponds to Model 3 of Panza et al. (2012), but for sake of simplicity, the Size Scaled Point Source model (SSPS) has been used here instead of the Size and Time Scaled Point Source one (STSPS) (Panza et al., 2012). The computations have been carried out with the cutoff frequency of 1 Hz. NDSHA allows for computations of synthetic seismograms with higher cutoff frequency, when an adequate representation of the source rupturing mechanism and of the medium along the paths from sources to sites are available. The possibility to perform the computation with 10 Hz cutoff frequency for multiple realisations of the rupturing process obtained using different finite faults models is given by Fasan et al. (2016), but, as a rule, we use this possibility in smaller scale studies. At regional scale the available knowledge well justifies the use of DGA, as shown by the major events occurred in Italy since 2009 (Rugarli et al., 2019).

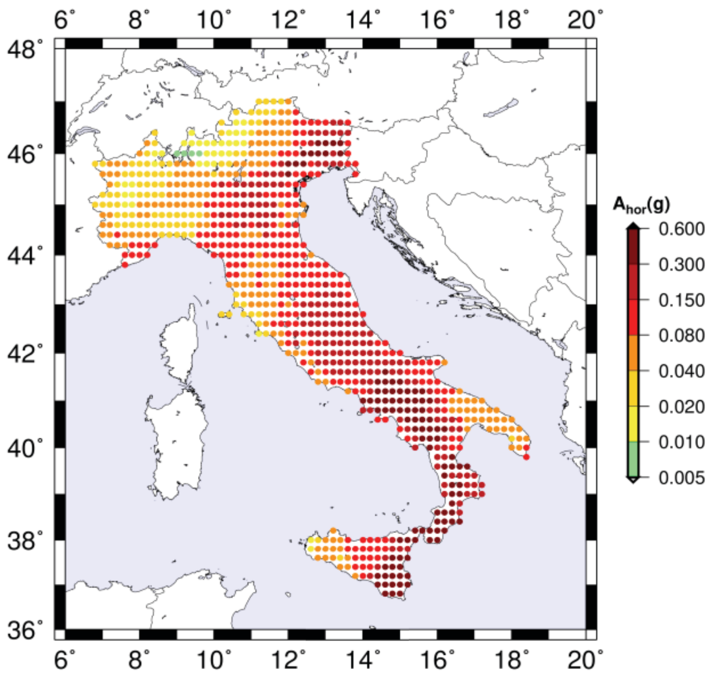

Figure 2. Horizontal DGA map computed using the earthquake sources obtained after smoothing the unperturbed discretized magnitude of catalogue CPTI04 (Fig. 1, right). This may be considered as the map got by a 1000 years lasting set of experiments

4.2. Hazard map based on seismogenic nodes

The morphostructural zonation (MSZ) technique (Gelfand et al., 1972, Gorshkov et al., 2003) detects the morphostructural nodes that are formed at the intersections of morphostructural lineaments. Among those nodes, pattern recognition techniques (Gelfand et al., 1976; Alekseevskaya et al., 1977, Gorshkov et al., 2003; Peresan et al., 2011) allows the identification of the seismogenic nodes, i.e. the nodes where strong events may nucleate.

Accordingly with Talwani (1988, 1999), who proposed a model that demonstrates that intersecting faults provide a location for stress accumulation, large intraplate earthquakes are connected with intersections of lineaments. The relationship between earthquakes and intersections for plate boundaries and rift structures has been evidenced by Hudnut et al. (1989) and Girdler and McConnell (1994), respectively; King (1986) suggests that fault intersection zones provide locations for the initiation and ending of ruptures. The non-randomness of earthquake nucleation at the nodes is proved statistically by a specifically designed method (Gvishiani and Soloviev, 1981).

Recent estimations of the validity of the worldwide recognition results of earthquake-prone areas are given by Gorshkov and Novikova (2018) who report a global score of about 86%. Such a value confirms earlier investigations about the percentage of post-publication earthquakes falling in the recognized seismogenic nodes (Soloviev et al., 2014; Peresan et al., 2015).

The sufficient validity of the methodology for identifying areas capable of strong earthquakes is proven and, at the same time, the idea about nucleating strong earthquakes at the nodes is confirmed, as recently empirically observed by Walters et al. (2018) in the 2016 Central Italy seismic sequence. Such validation is very important since the model of seismogenic nodes is mathematically rigorous, based upon objective, but not error-free morphostructural data.

Gorshkov et al. (2002; 2004) compiled a morphostructural map for the Italian territory assuming that future strong events will occur at the intersection of lineaments and evaluated the seismic potential of each node for two magnitude thresholds: M_{sz}≥6.0 and M_{sz}≥6.5. The nodes prone to earthquakes with M_{sz}≥6.0 are identified with the pattern recognition algorithm "CORA-3" (Gelfand et al., 1972; 1976; Gorshkov et al., 2003). The nodes with larger earthquakes potential are identified by the criteria of high seismicity derived by Kossobokov (1983) from pattern recognition in the Pamirs-Tien Shan region.

For recognition purposes, the node conventionally used is a circle of radius R=25 km surrounding each point of intersection of lineaments. The value R=25 km is not arbitrarily selected here but comes from the MSZ method rules, tested at global scale (Gelfand et al., 1972). For any study area the volume occupied by known active faults is, by definition (Alekseevskaya et al., 1977, Gelfand et al., 1972), a subspace of that occupied by nodes. As shown by Gorshkov and Novikova (2018), for any studied area 86% of post-publication events on the maps showing the recognized seismogenic nodes fall within the recognized seismogenic nodes. For the magnitude range considered here, the radius is roughly comparable with the size of the earthquake sources (e.g. Wells and Coppersmith, 1994).

In Fig. 3 the earthquake sources are shown that, ignoring both the ZS9 seismic zones and the CPTI04 catalogue, are obtained considering only the seismogenic nodes.

The reference magnitude used for the earthquake at a seismogenic node, is a lower bound of the earthquake magnitude threshold, M_{sz}, identified for that node as a result of recognition (Gelfand et al., 1972; 1976).

In Fig. 3 the shown magnitude is M_{sz} incremented by ΔM=0.5, i.e. $2\sigma_M$ (e.g Båth, 1973, p. 111). To the published information (Gorshkov et al., 2002; 2004) a few nodes with M_{sz}=5.0, identified in the western Po plain using "CORA-3", have been considered (Peresan et al., 2015), again after raising by 0.5 their magnitude. The corresponding map of DGA is given in Fig. 4.

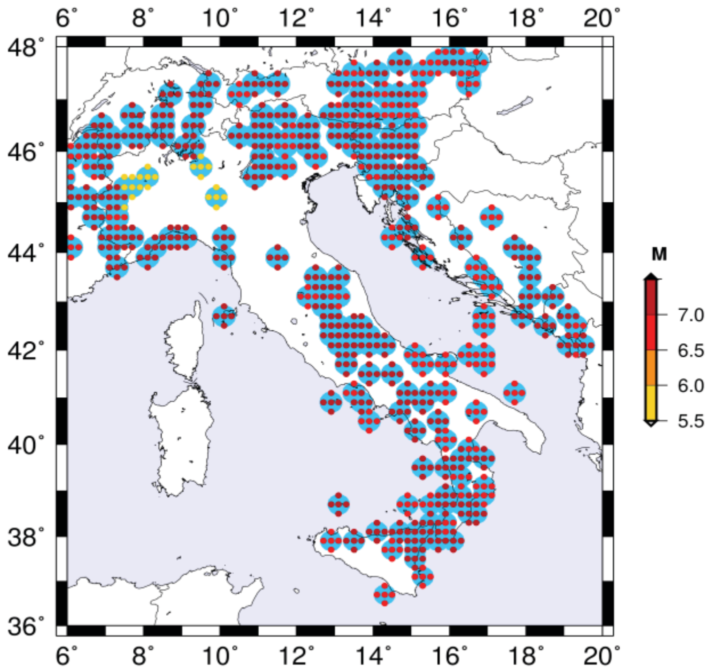

Figure 3. Earthquake sources used for the computation of synthetic seismograms, defined within the seismogenic nodes, with magnitude M_{sz} increased by 0.5, i.e. $\Delta M=\gamma_{EM}\sigma_M=0.5$. The info coming from the historical catalogue of seismicity is here deliberately neglected, to evaluate the hazard forecasting capability supplied by the seismogenic nodes, identified by morphostructural zonation (MSZ) and pattern recognition

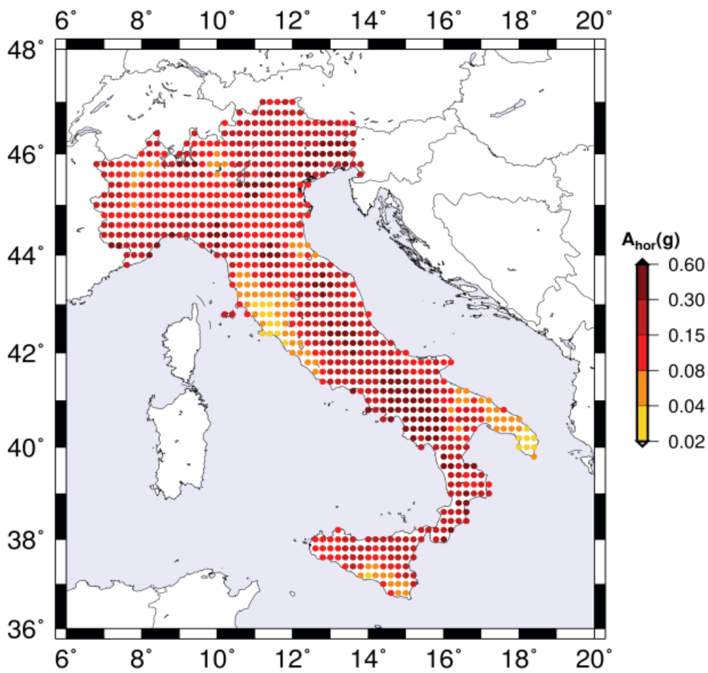

Figure 4. Horizontal DGA map computed using the earthquake sources defined within the seismogenic nodes (see Fig. 3), with magnitude M_{sz} incremented by 0.5, i.e. $\Delta M=\gamma_{EM}\sigma_M=0.5$

5. Discussions

In Fig. 5 the ratio between the values of DGA given in Fig. 2 (sources defined processing the magnitudes found in the historical catalogue of seismicity CPTI04) and those in Fig. 4 (sources defined within the seismogenic nodes and using γ_{EM}=2.0) is shown.

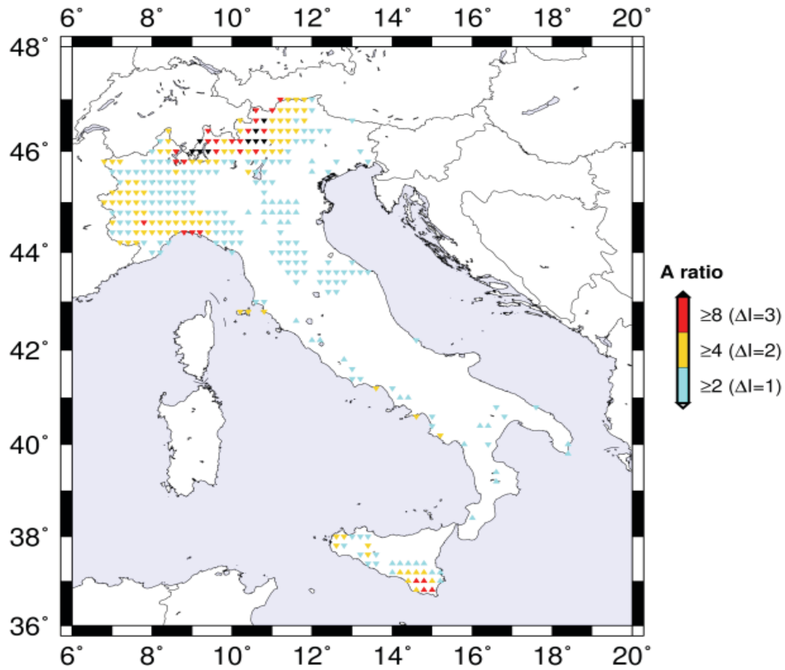

Figure 5. Map of the ratios between the Design Ground Acceleration (DGA) values given in Fig. 2 and Fig. 4. The upward triangles indicate larger values obtained considering the CPTI04 earthquake catalogue, while the downward triangles indicate larger values obtained considering the sources associated with the seismogenic nodes, whose magnitude has been increased by 0.5, i.e. $\Delta M=\gamma_{EM}\sigma_M$=0.5

It must be kept in mind that in the figure real differences are those greater than 2; a factor of 2 is comparable with the resolving power of the available experimental data about *M*, essentially all based on Macroseismic Intensity (I_{MCS}). Several empirical relationships have been proposed to convert the abundant information about intensity of historical events into magnitude. A possible set of values appropriate for the Mediterranean region is proposed by D'Amico et al. (1999). In fact, any intensity scale is discrete and therefore it has unit incremental steps; intermediate values are not defined. Typical discrete ranges of hazard values (units of g) are in geometrical progression (close to 2), consistent with the real resolving power of the worldwide available experimental data (e.g. Cancani, 1904; Lliboutry, 2000). More details on relations involving macroseismic intensity, peak values of ground motion and magnitude are given in Panza et al. (2014).

The regions of continental Italy and Sicily not occupied by triangles are those where the two maps match in terms of intensity; the match can still be considered satisfactory in correspondence of the light blue triangles *(*Δ*I*=1) when considering the error threshold intrinsically related to macroseismic intensity I_{MCS}.

From Fig. 5 it is evident that for

$\Delta M=\gamma_{EM}\sigma_M=0.5$, or equivalently $\gamma_{EM}=2.0$, the hazard at the bedrock, defined only considering seismogenic nodes, safely and reliably envelopes peak values observed in the last millennium almost everywhere in Italy. We believe this is a remarkable result, considering that the two maps are totally independent one another. The maps shown in Fig. 2 and Fig. 4 do match almost everywhere, i.e. the difference between them in terms of acceleration leads to no difference in terms of intensity (DGA ratio lower than 2 in Fig. 5). There are two exceptions:

(1) a few locations in southeastern Sicily;

(2) Central Alps

that will be now discussed.

The space distribution of a few locations in southeastern Sicily nicely mirrors the portion of the Africa plate occupied by the Hyblaean Mountains, south of the Apennines arcuate thrusts front (e.g. Carminati and Doglioni, 2012; Doglioni and Panza, 2015); there a larger value of $\Delta M=\gamma_{EM}\sigma_M=0.5$ seems to be necessary. This increment, while keeping $\gamma_{EM}=2.0$, can be consistently obtained assuming for σ_M the upper bound of the range estimated by Båth (1973) for instrumental magnitudes, and nowadays routinely confirmed by global estimates of M supplied for the same earthquake by different Agencies. However, a test done with $\Delta M=\gamma_{EM}\sigma_M=0.6$ still underestimates the ground shaking obtained using the historical catalogue in southeastern Sicily.

The large differences that can be read in the map for southeast Sicily, and that could be explained by the possibly natural discrepancy between the distribution of earthquake sources within the seismogenic zones, on one side, and the seismogenic nodes, on the other, can hardly be attributed to the local mechanical properties.

It must be considered the high uncertainness of the historical catalogue when evaluating macroseismic intensity of specific events. When just one event is determinant, this is particularly true, because a single possible error might directly impact the mapped final result (of Fig. 2).

The use of a $\sigma_M \gg 0.3$ seems to be appropriate in this particular case. Indeed for the 1693 M=7.4 event, that seems to control the hazard in the zone, $\sigma_M=0.7$ can be assumed, a typical value for magnitudes derived from I_{MCS} according to D'Amico et al. (1999), also on account of the proximity of the epicentral area to the sea. This means that the uncertainness embedded in σ_M may be increased to 0.7 instead of using the normal 0.2−0.3, for the particular nodes referring to the region where the 1693 event was recorded, still being within the error limit acceptable.

Therefore it is consistent to add to M_{sz} a value of $\Delta M=\gamma_{EM}\sigma_M=1.4$ and thus consider a magnitude value 7.4 in the computation of DGA using the earthquake sources defined within the two southeasternmost seismogenic nodes in the area (nodes 142 and 145 in Gorshkov et al., 2002). In such a way, i.e. within experimental errors, the underestimates in southeastern Sicily, shown in Fig. 5 fade away as shown in Fig. 6.

The minimum error affecting the experimental I_{MCS} is, by definition, one degree, as well confirmed empirically for 55 damaging earthquakes occurred in Italy since 461, as shown by the detailed analysis made by Kronrod et al. (2002). Therefore it can be concluded that, within errors, the hazard assessed considering only the seismogenic nodes envelopes (exceeds or equals) the one assessed considering CPTI04 catalogue and ZS9 seismic zonation, and almost everywhere does indeed match it.

On the other side, $\Delta M=\gamma_{EM}\sigma_M=0.5$ leads to some diffused overestimation in Northern Italy, with a relevant peak in Central Alps, that remains outstanding even using of $\Delta M=\gamma_{EM}\sigma_M=0.4$. Values of $\Delta M=\gamma_{EM}\sigma_M>0.6$, required to eliminate the hazard underestimation in southeastern Sicily, would of course imply much larger overestimations elsewhere, with the largest discrepancies obviously in the Central and Western Alps.

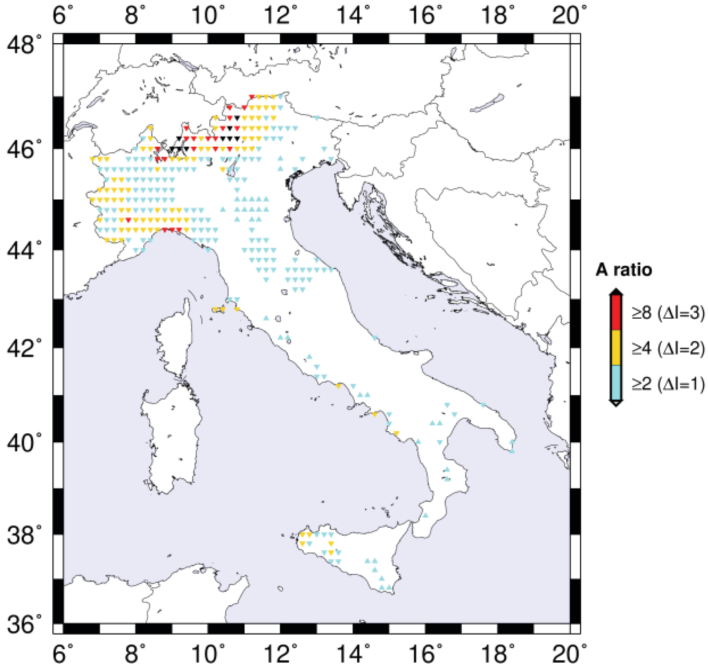

Figure 6. Same as Fig. 5 but with $\Delta M=\gamma_{EM}\sigma_M$=1.4 in southeast Sicily

Thus, it may be argued that part of the observed misfit can be naturally explained by a different level of error affecting empirical *M* determinations. The only exception is limited to the Central Alps, an area where the >1000 years long catalogue CPTI04, even though complete for *M*>5 at national scale (Vorobieva and Panza, 1993), may not fully represent the local seismicity, given that there the occurrence rate (i.e. the normalized count of events in the observation time) of large earthquakes (I_{MCS}>VII) seems to be smaller than 1 event per 1000 years (Magrin et al., 2017; Michetti et al., 2012; Houlié et al., 2018).

This may imply an event of significant magnitude that is not present in today's historical catalogue for this area or could be explained by the occurrence of dislocation creep within a lithosphere with fairly anomalous mechanical and rheological properties (Panza and Raykova, 2008; Malusà et al., 2018).

It must be underlined that the two regions discussed up to this point are very limited when compared to the extension of Italy.

6. Conclusions

When catalogue completeness is barely adequate, probabilistic approaches try to overcome the problem for instance implementing the extreme value method (e.g. Gumbel, 1958; Burton. 1979). Aoudia et al. (2000) showed how to include in NDSHA the evidences coming from paleoseismology. Here, considering the seismogenic nodes identified in the Italian territory, it has been shown that incrementing by a constant variation Δ*M* the magnitude considered at a fault, in order to get safe envelope of seismic actions, is totally equivalent to applying a partial safety factor γ_q to the seismic moment at the fault M_0, as normally asked by

Eurocodes and other international standards for typical structural actions ($\Delta M = \frac{2}{3}\mathrm{Log}(\gamma_q)$).

In turn, this is equivalent to applying a γ_{EM} safety factor to the typical standard deviation in the evaluation of earthquake magnitude, σ_M, so as to get the desired magnitude increment $\Delta M=\gamma_{EM}\sigma_M$, constant for each seismic source.

By using as typical value $\gamma_{EM}\sigma_M=0.5$ ($\sigma_M=0.25$, central value of the experimental range 0.2−0.3, and $\gamma_{EM}=2.0$) and NDSHA using only seismogenic nodes, it has been shown that the unique 1,000-year long Italian earthquake catalogue, acting as experimental set, is, within errors, almost everywhere matched or enveloped.

Minor variations are related to possible error in evaluating I_{MCS} of historical events, or in missing seismic events in a very restricted Italian area, with very peculiar mechanical and rheological properties.

The uniqueness of the Italian catalogue allowed us to formulate the model and carry on this pilot study. We had not set up yet a procedure to tune the safety factor γ_{EM}. We tentatively assumed $\gamma_{EM}=2.0$, which implied a $\Delta M=0.4$–0.5 (consistent with global Magnitude standard deviation σ_M) and observed a general agreement with two exceptions. These two exceptions are not expected to imply a change in the safety factor, which ideally should be general, but we have observed that in these regions there are reasons to assume a different standard deviation σ_M.

Future studies, and the application of the methodology to other regions (like India and Egypt, where seismogenic nodes and historical catalogues have been jointly used for hazard assessment-Parvez et al., 2017; Gorshkov et al., 2019), will explain if there is a true need of differentiating and tuning the safety factor, or if it is the reference standard deviation to be assumed, that might possibly change. What we think is relevant, is that there is a general very good agreement, which was not obvious given the totally different nature of the two data-sets. In any case, it must be stressed that in seismicity, lack of data is common, and so it is not surprising a local loss of adequacy of a tentatively assumed safety factor. It may be also accepted, in our view, that due to the differences in the quality and reliability of seismic regions available data, different safety factors are to be assumed. The work of tuning these safety factors will always face, however, the lack of data.

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