Improving seismic action assessment: conditional design maps for secondary intensity measures

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ABSTRACT
Vector-valued ground motion intensity measures (IMs) have been the focus of a significant deal of research recently. Proposed measures are mainly function of spectral ordinates which have been shown to be useful in the assessment of structural response. This is especially appropriate in the case of structures following modern earthquake resistant design principles, in which structural damage is mainly due to peak displacements experienced during nonlinear dynamics. On the other hand, there may be cases in which also the cumulative damage potential of the earthquake is of concern, even if it is generally believed that integral ground motion IMs, associated to duration, are less important with respect to peak parameters of the record. For these IMs, it seems appropriate to develop conditional hazard maps; i.e., maps of percentiles of a secondary IM (e.g., duration-related) given the occurrence or exceedance of a primary parameter (e.g., peak acceleration), for which a design hazard map is often already available. In the paper, this concept is illustrated and conditional hazard is developed for a parameter which may account for the cumulative damage potential of ground motion, the so-called Cosenza and Manfredi index (I_D), given peak ground acceleration (PGA). To this aim, a ground motion prediction relationship was retrieved for I_D first. Subsequently, the residuals of PGA and I_D were tested for correlation and for joint normality. Finally, the study obtained analytical distributions of I_D conditional on PGA and on the corresponding design earthquake, in terms of magnitude and distance from hazard disaggregation. As shown by the application to the Campania region (southern Italy), I_D maps conditional on the code design values of PGA may be useful, for example, for a more refined ground motion record selection as an input for nonlinear dynamic analysis of structures.

Keywords: Vector-valued IMs · Cumulative damage · Ground Motion Prediction Relationships

1. INTRODUCTION

Intensity measures (IMs) should allow for a correct and accurate estimation of the structural performance on the basis of the seismic hazard at the construction site. An IM is a parameter which is considered to be a proxy for the potential effect of the ground motion on the structure. Typical ground motion IMs are the peaks of the ground acceleration and velocity, and conventional probabilistic seismic hazard analysis (PSHA) provides the mean annual frequency of exceeding a specified value of one of these parameters at the location of interest. Linear spectral ordinates are also often used as IMs for probabilistic assessment, especially those at the fundamentals period of the structure, $Sa(T_1)$. This is mainly because $Sa(T_1)$, being the response of a linear single degree of freedom system (SDOF), should be, in principle, more correlated with the structural performance with respect to, for example, peak ground acceleration (PGA).
More sophisticated IMs are currently under investigation by many researchers. For example, Baker (2007) discusses vector-valued IMs' potential in terms of *efficiency* in estimating structural response. Most of the proposed vector-valued IMs are comprised of spectral ordinates or other proxies for the spectral shape in a range of periods believed to be of interest for the nonlinear structural behavior. This helps to estimate the peak seismic demand especially in terms of displacements.
Integral signal's parameters, as the *Arias intensity* or *significant ground motion duration*, are possible IMs, but they are considered related more to the cyclic energy dissipation rather than to the peak

structural response. In fact, some studies (e.g., Iervolino et al., 2006) investigated how ground motion duration-related parameters affect nonlinear structural response. It was found that, generally, spectral ordinates are *sufficient* (i.e., duration does not add much information) if one is interested in the ductility demand, while duration-related measures do play a role only if the hysteretic structural response is that to assess; i.e., in those cases in which the cumulative damage potential of the earthquake is of concern. However, in general, the integral ground motion parameters associated to duration are less important with respect to peak IMs, as damages to structures, in general, are more due to displacements, and therefore the former IMs may be considered secondary with respect to the latter. In these cases, it seems appropriate to develop *conditional hazard maps*; i.e., maps of percentiles of the secondary IM given the occurrence or exceedance of the primary parameter for which a design hazard map is often already available by national authorities.

Herein, for illustration purposes, the primary intensity measure considered is PGA, while the secondary is a parameter which may account for the cumulative damage; the chosen cyclic response-related measure is the so-called *Cosenza and Manfredi index* (I_D) (Manfredi, 2001). To show the concept of conditional hazard, a ground motion prediction relationship had to be retrieved for I_D on the basis of an empirical dataset of Italian records already used for other well known ground motion prediction equations proposed in the past by Sabetta and Pugliese (1987, 1996). Subsequently, the residuals of the logs of PGA and I_D were tested for correlation and for joint normality. The study obtained distributions of I_D conditional on PGA and the corresponding design earthquake in terms of magnitude and distance from hazard disaggregation. Two percentiles (i.e., the 50^{th} and the 90^{th}) were extracted from the conditional probability density function (PDF) of the I_D given the PGA and mapped for the Campania region (in southern Italy). The selected hazard level for PGA corresponds to 10% exceedance probability in 50 years, which is a reference return period for the life-safety limit state of ordinary constructions internationally.

The application to a case study region shows that the conditional hazard analysis may prove useful to complement the available acceleration hazard with maps providing suitable values of secondary IMs, to match in ground motion record selection (e.g., Iervolino and Cornell 2005; Iervolino et al., 2008a; Iervolino et al., 2010). In fact, apart selecting seismic input for nonlinear dynamic analysis reflecting the design peak values of motion (e.g., PGA or spectral ordinates), one can benefit from this kind of information and consider records featuring values of the secondary IM conditionally consistent with the hazard of the primary IM.

2. GROUND MOTION PREDICTION FOR AN INTEGRAL IM

I_D has proven to be a good proxy for cyclic structural response (Manfredi, 2001). It is defined in Eqn. 2.1 where a(t) is the acceleration time-history, t_E is the total duration of the seismic event, and PGV is the peak ground velocity. Therefore, the numerator of I_D is proportional to the Arias Intensity and it will be referred to as I_A.

$$I_D = \frac{\int_0^{t_E} a^2(t)dt}{PGA \cdot PGV} = \frac{I_A}{PGA \cdot PGV} \qquad 2.1$$

The best candidates to be ground motion intensity measures are those for which hazard analysis is easy to compute, which requires a ground motion prediction equation (GMPE) to be available. Therefore, a GMPE was developed for I_D. The dataset used consists of 190 horizontal components from 95 recordings of Italian earthquakes used by Sabetta and Pugliese (1987, 1996). For the purposes of the present study the records were obtained by the *European Strong-motion Database* (ESD), whose URL is http://www.isesd.cv.ic.ac.uk (Ambraseys et al., 2000; Ambraseys et al., 2004). The dataset in terms of magnitude, distance, and, site conditions is given in Figure 1a.

The empirical predictive equations for the logs of the terms (the generic one is indicated as Y) appearing in the definition of I_D were fitted by regression using the same functional form of Sabetta and Pugliese (1996), Eqn. 2.2, as a function of moment magnitude (M), epicentral distance (R, in km), and recording site geology. In this form, *h* is a fictitious depth, the dummy variables S_1 and S_2 refer to the site classification and take the value of 1 for shallow and deep alluvium sites, respectively, and zero otherwise. The residual, $\varepsilon_{\log_{10}Y}$, is a random variable which in ordinary least squares regressions, is implicitly assumed to be Gaussian with zero mean and a standard deviation $\sigma_{\log_{10}Y}$.

$$\log_{10}Y = a + b\ M + c\ \log_{10}\left(R^2 + h^2\right)^{\frac{1}{2}} + d\ S_1 + e\ S_2 + \varepsilon_{\log_{10}Y} \qquad 2.2$$

The estimates for the coefficients[1] for PGA, PGV and I_A, obtained using the ordinary least-squares regression, are given in Table 1. In the same tables also the estimated standard deviations of the respective residuals, are also given. *h* values were not estimated and assumed to be coincident to those provided by Sabetta and Pugliese (1996); see also Iervolino et al. (2008b).

Table 1. Regression coefficients for PGA, PGV and I_A.

Y	*a*	*b*	*c*	*d*	*e*	*h*	$\sigma_{\log_{10}Y}$
PGA [cm/s²]	1.12	0.34	-0.89	0.16	-0.065*	5.0	0.19
PGV [cm/s]	-1.27	0.55	-0.95	0.14	0.036*	3.9	0.25
I_A *[cm²/s³]*	0.42	0.92	-1.69	0.24*	-0.021*	5.3	0.39

The Shapiro-Wilk test (1965), based on the considered sample, was used to check the assumption of normal distribution for $\varepsilon_{\log_{10}PGA}$, $\varepsilon_{\log_{10}PGV}$ and $\varepsilon_{\log_{10}I_A}$. Results of the tests, not reported here for the sake of brevity, indicate that the null hypothesis of normality cannot be rejected, assuming a 0.05 significance level, for the logs of all the parameters considered.
The results of the regression are slightly different from those obtained by Sabetta and Pugliese (1996), but these discrepancies are expected. Despite the work of Sabetta and Pugliese (1996), it was decided to not constrain *c* to the *geometrical spreading* theoretical value in any of the regressions, because data seem to not support such a choice (see also Stafford et al., 2009). Moreover, moment magnitude was used herein, while local magnitude and surface-wave magnitude was used by the mentioned researchers. In addition to that, the records used come from different databases and therefore may have been subjected to different processing. Finally, Sabetta and Pugliese (1996) used the component featuring the largest value of the parameter of interest separately for each regression, while in this study all the regression analyses (for PGA, PGV and I_A) were performed, arbitrarily, using the horizontal component featuring the largest PGA. In fact, to fit GMPEs for different IMs all on the same ground motion component is useful for the model for I_D.
In order to obtain an attenuation relation for the logs of I_D as a function of M, R and local site conditions it is possible to derive its coefficients as linear combinations of those for $\log_{10}PGA$, $\log_{10}PGV$ and $\log_{10}I_A$ as the log of I_D is given by the log of I_A minus the logs of PGA and PGV. This leads to the expression of Eqn. 2.3, in which subscripts 1, 2 and 3 for *c* coefficient and *h* refer to PGA, PGV and I_A, respectively.

$$\log_{10}I_D = a + bM + \log_{10}\left(\frac{\left(R^2 + h_1^2\right)^{c_1}\left(R^2 + h_2^2\right)^{c_2}}{\left(R^2 + h_3^2\right)^{c_3}}\right)^{\frac{1}{2}} + dS_1 + eS_2 + \varepsilon_{\log_{10}I_D} \qquad 2.3$$

The coefficients of Eqn. 2.3 are listed in Table 2. For I_D, the magnitude coefficient (*b*) and the soil coefficients (*d*) and (*e*) resulted close to zero; a statistical test could performed to check the statistical significance of these coefficient.

[1] Note that for some of the coefficients, those marked with an asterisk in the tables, the null hypothesis of being equal to zero could not be rejected at 0.05 significance level using a *Student's T-Test* (Mood et al., 1974), which means the variables associated to them could be dropped from Equation (2).

Table 2. Regression coefficients for I_D.

Y	a	b	d	c_1	c_2	c_3	e	$\sigma_{\log_{10} Y}$
I_D	0.58	0.034*	-0.068	-0.89	-0.95	-1.69	0.0077	0.19

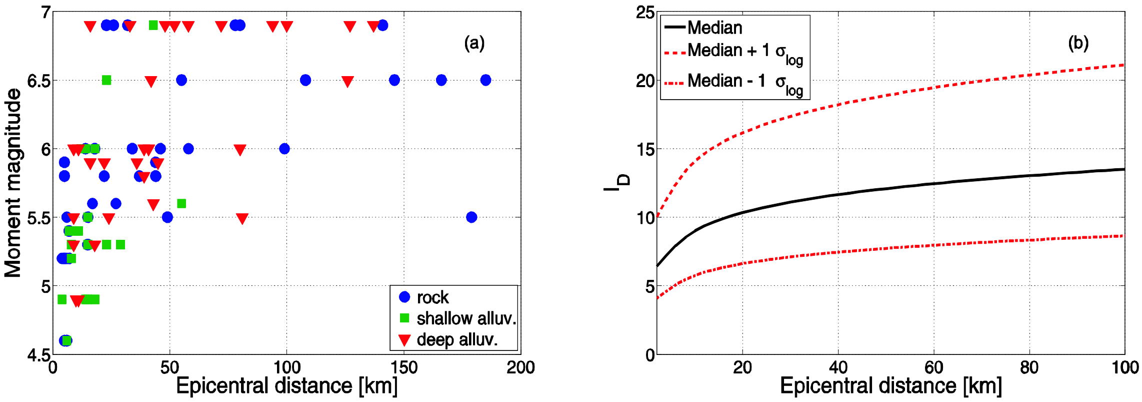

Figure 1. (a); Distribution of the strong-motion records with respect to moment-magnitude and epicentral distance; (b) Plot of I_D as a function of epicentral distance.

The normal distribution of I_D (i.e., of the residual of the GMPE) should follow from the normality of the logs of PGA, PGV and I_A. Nevertheless, normality of the above parameters was based on a hypothesis test, therefore it may be prudent to also test the normality of the log of I_D. So, the normality of the residual of Eqn. 2.3 was tested and such a hypothesis could not be rejected at 0.05 significance level.
A plot of I_D versus epicentral distance is given in Figure 1b where the typical increasing trend with distance of duration-related measures is shown (Manfredi et al., 2003).

3. JOINT AND CONDITIONAL DISTRIBUTIONS OF THE LOGS OF I_D AND PGA

As this study aims to investigate the joint and conditional distributions of PGA and I_D, the joint normality of logs of the pair was tested. In fact, if the vector above can be considered normally distributed, all the possible marginal and conditional distributions obtained from the joint distribution are still Gaussian. The skewness and kurtosis' tests of Mardia (1985) were used to test multivariate normality of the vector made of $\varepsilon_{\log_{10}\mathrm{PGA}}$ and $\varepsilon_{\log_{10}\mathrm{I_D}}$. With a given significance level of 0.05, the multivariate skewness and the multivariate kurtosis result non-significant.
The residuals of the prediction relationships for the logs of PGA and I_D have been also tested for correlation in order to compute $f(\log_{10} I_D \mid \log_{10}\mathrm{PGA})$, that is, the conditional PDF of the logs of I_D given the logs of PGA. The estimated correlation coefficient (r) between $\varepsilon_{\log_{10}\mathrm{PGA}}$ and $\varepsilon_{\log_{10}\mathrm{I_D}}$ (equal to -0.25) has been tested for statistical significance using a Student-T statistic (Mood et al., 1988) and assuming as the null hypothesis H_o: ρ = 0 (ρ is the "true" correlation coefficient), which has been rejected at 0.05 significance level. Then, the joint distribution of $\log_{10} I_D$ and $\log_{10}\mathrm{PGA}$ may be defined by the bivariate normal PDF of Eqn. 3.1.

$$f(\log_{10} I_D, \log_{10}\mathrm{PGA}|M,R) = \frac{e^{-\frac{1}{2(1-\rho^2)}\left[\frac{\left(\log_{10} I_D-\mu_{\log_{10} I_D|M,R}\right)^2}{\sigma^2_{\log_{10} I_D}}-\frac{2\rho\left(\log_{10} I_D-\mu_{\log_{10} I_D|M,R}\right)\left(\log_{10}\mathrm{PGA}-\mu_{\log_{10}\mathrm{PGA}|M,R}\right)}{\sigma_{\log_{10} I_D}\sigma_{\log_{10}\mathrm{PGA}}}+\frac{\left(\log_{10}\mathrm{PGA}-\mu_{\log_{10}\mathrm{PGA}|M,R}\right)^2}{\sigma^2_{\log_{10}\mathrm{PGA}}}\right]}}{2\pi\sigma_{\log_{10} I_D}\sigma_{\log_{10}\mathrm{PGA}}\sqrt{1-\rho^2}} \quad 3.1$$

In Eqn. 3.1 $\mu_{\log_{10} I_D|M,R}$ and $\sigma_{\log_{10} I_D}$ are the mean and the standard deviation of $\log_{10} I_D$ respectively;

i.e., Eqn. 2.3. $\mu_{\log_{10}PGA|M,R}$ and $\sigma_{\log_{10}PGA}$ are the mean and the standard deviation of $\log_{10}PGA$ respectively; i.e., Eqn. 2.2. The variance-covariance matrix, Σ, for $\varepsilon_{\log_{10}PGA}$ and $\varepsilon_{\log_{10}I_D}$ is reported in Eqn. 3.2.

$$\Sigma = \begin{pmatrix} 0.034 & -0.0087 \\ -0.0087 & 0.036 \end{pmatrix} \qquad 3.2$$

Because of bivariate normality, the conditional PDF for one of the variables given a known value of the other, is normally distributed. The conditional mean ($\mu_{\log_{10}I_D|\log_{10}PGA,M,R}$) and standard deviation of $\log_{10}I_D$ ($\sigma_{\log_{10}I_D|\log_{10}PGA}$) given that $\log_{10}PGA = z$ are given in Eqn. 3.3.

$$\begin{cases} \mu_{\log_{10}I_D|\log_{10}PGA,M,R} = \mu_{\log_{10}I_D|M,R} + \rho\sigma_{\log_{10}I_D} \dfrac{z-\mu_{\log_{10}PGA|M,R}}{\sigma_{\log_{10}PGA}} \\ \sigma_{\log_{10}I_D|\log_{10}PGA} = \sigma_{\log_{10}I_D}\sqrt{1-\rho^2} \end{cases} \qquad 3.3$$

Because the joint distribution of I_D and PGA depends on the I_D attenuation and from the PGA attenuation, therefore also on magnitude and distance, to obtain the conditional distribution of the logs of I_D conditional on PGA only, the marginalization in Eqn. 3.4 is required.

$$f\left(\log_{10}I_D \mid \log_{10}PGA\right) = \int_M \int_R f\left(\log_{10}I_D \mid \log_{10}PGA, M, R\right) f\left(M, R \mid \log_{10}PGA\right) dm\, dr \qquad 3.4$$

It is easy to recognize that the $f\left(M,R \mid \log_{10}PGA\right)$ term in Eqn. 3.4 is the PDF of M and R given the occurrence of $\log_{10}PGA$; i.e., the result of disaggregation of seismic hazard (e.g., Bazzurro and Cornell, 1999). As an approximation of the integral in Eqn. 3.4, for example, the modal values M* and R* (i.e., those corresponding to the maxima of the joint M and R distribution from disaggregation) may be plugged in Eqn. 3.3; i.e., Eqn. 3.5.

$$\mu_{\log_{10}I_D|\log_{10}PGA,M,R} \approx \mu_{\log_{10}I_D|M^*,R^*} + \rho\sigma_{\log_{10}I_D} \frac{z-\mu_{\log_{10}PGA|M^*,R^*}}{\sigma_{\log_{10}PGA}} \qquad 3.5$$

4. CASE-STUDY APPLICATION

An example of the possible use of the results obtained is given in Figure 2. Figure 2b shows the PGA values on rock (expressed in fractions of *g*) with a 10% exceedance probability in 50 years (return period, T_R, equal to 475 years which is the reference for life-safety limit states in structural design at an international level) in the Campania region (southern Italy) according to the classical seismic hazard analysis procedure (see for example Convertito et al., 2009). This map was computed discretizing the region in a regular grid of nodes with spacing of about 2 km (2700 points in total).
Sources were modeled as the seismogenic zones of Figure 2a (Meletti et al., 2008) which have been used to compute the official Italian hazard data produced by the *Istituto Nazionale di Geofisica e Vulcanologia* or INGV (available at http://esse1.mi.ingv.it/). Source features, from Barani et al. (2009), are given in Table 3 where α is the seismicity rate, that is, the mean annual rate of occurrence of the earthquakes between M_{min} and M_{max} for the zone, and *b* is the corresponding parameter of the Gutenberg-Richter.

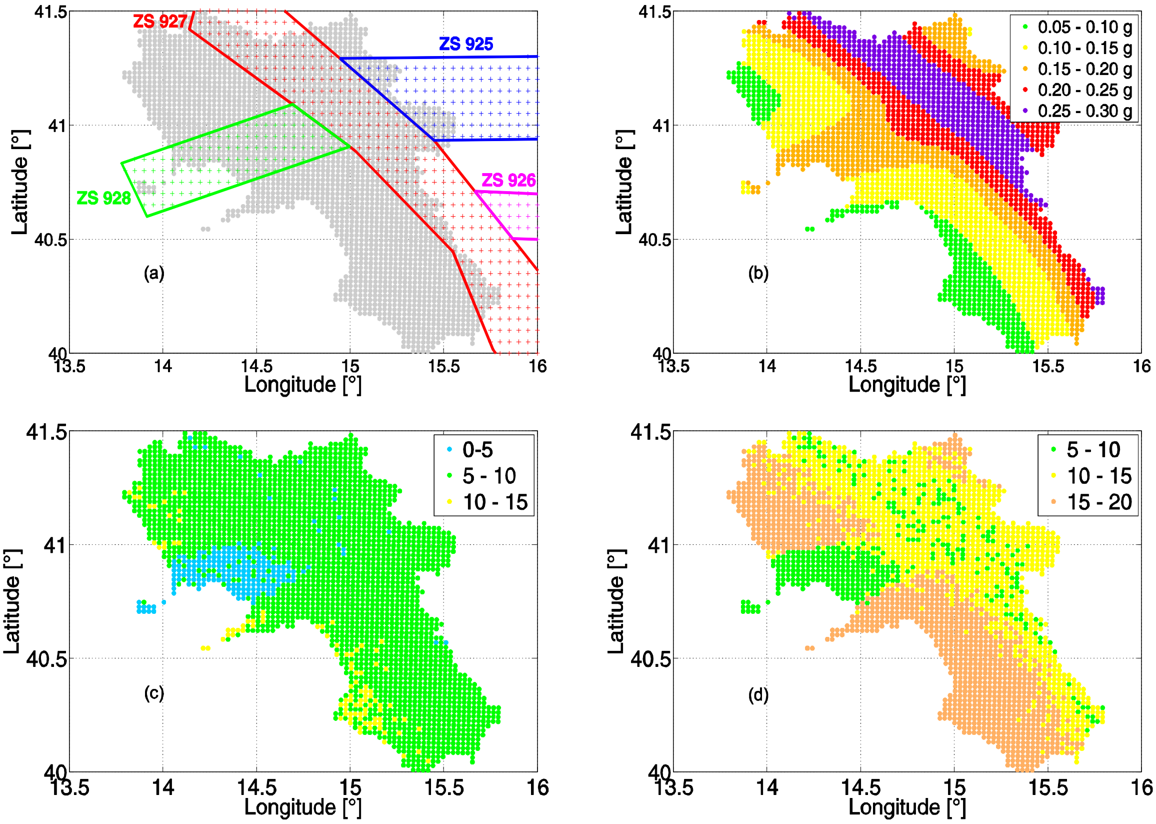

Figure 2. (a) Seismic zones considered in the analysis; (b) 475 years return period PGA on rock hazard map for the Campania region (southern Italy); (c) hazard map in term of I_D with a 50% exceedance probability given PGA of panel (b); (d) hazard map in terms of I_D with a 10% exceedance probability given PGA of panel (b).

Figure 2c and Figure 2d show the maps of seismic hazard in terms of I_D given the PGA of Figure 2b. In particular, Figure 2c and Figure 2d are the 50th and 90th percentiles of the conditional I_D PDF, respectively. The conditional I_D maps were obtained using the distribution of parameters in Eqn. 3.3 in which the *z* (log of PGA) values are those of Figure 2b, while the values of magnitude and distance (M* and R*) to plug in the $\mu_{\log_{10}PGA|M,R}$ and $\mu_{\log_{10}I_D|M,R}$ terms of Eqn. 3.3 were obtained by disaggregation of hazard in terms of occurrence of design PGA values (Figure 3). The adopted disaggregation methodology is the same described in Convertito et al. (2009), which is not reported here for the sake of brevity.

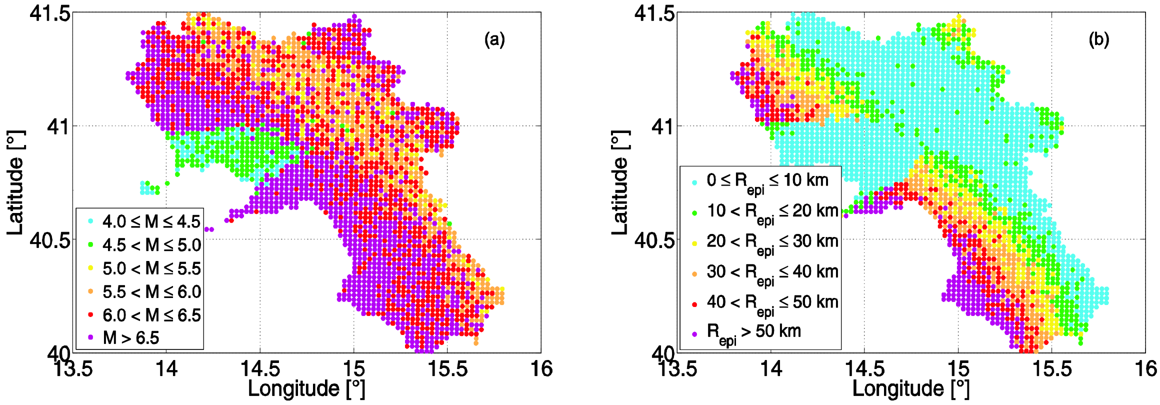

Figure 3. Modal values of magnitude and epicentral distance from disaggregation of seismic hazard in terms of PGA (given in Figure 2b) used to compute the conditional distribution of I_D (whose percentiles are in Figure 2c and Figure 2d).

Table 3. Parameters of the selected seismogenic zones shown in Figure 2a.

Zone	α [events/year]	*b*	M_{min}	M_{max}
925	0.071	0.508	4.3	7.0
926	0.061	1.017	4.3	5.8
927	0.362	0.557	4.3	7.3
928	0.054	1.056	4.3	5.8

5. CONCLUSIONS

There are situations in which more than one ground motion parameter has to be taken into account in seismic structural assessment. For example, although it is generally believed that integral ground-motion parameters are secondary for structural demand assessment in respect to peak quantities of ground motion, sometimes the cumulative damage potential of the earthquake is also of concern. For these cases it could be useful to have a distribution of secondary intensity measures conditional on the primary parameter used to define the seismic action on structures (e.g., accelerations). Such distribution can complement the hazard curves or maps produced for the primary IM. This approach has the advantages of vector-valued seismic hazard analysis without the computational effort required by PSHA for vectors of IMs. To explore such a concept, in this paper the distribution of a parameter which may account for the cumulative damage potential of ground-motion, conditional to peak ground acceleration (PGA), was investigated. The chosen secondary measure is the so called Cosenza and Manfredi index (I_D). A ground-motion prediction relationship has been retrieved for the log of I_D on the basis of an empirical dataset of Italian records already used for well known prediction equations proposed in the past by other researchers. Subsequently, the residuals of prediction relationships have been tested for correlation and for joint normality. The study allowed to obtain analytical distributions of I_D conditional on PGA and the corresponding design earthquake in terms of magnitude and distance from hazard disaggregation. Results of the study have been used to compute the distribution of I_D conditional on PGA with a return period of 475 years for each node of a regular grid having about 2 km spacing and covering the territory of the Campania region (in southern Italy). The presented conditional hazard maps provide information on the values of I_D which, for example, should be taken into account along with the hazard in terms of PGA at the site, for ground motion record selection for nonlinear dynamic analysis of structures.

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