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Short Note

Conditional Hazard 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 functions 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 caused by peak displacements experienced during nonlinear dynamics. On the other hand, there may be cases in which the cumulative damage potential of the earthquake is also of concern, even if it is generally believed that integral ground-motion IMs, associated with duration, are less important with respect to peak parameters of the record. For these IMs, it seems appropriate to develop conditional hazard maps, that is, 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 this 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 derived 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.

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 considered site. An IM is a parameter, 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 fundamental period of the structure, $\mathrm{Sa}(T_1)$. This is mainly because $\mathrm{Sa}(T_1)$, being the response of a linear single degree of freedom system (SDOF), should be, in principle, more correlated with the structural performance than, for example, peak ground acceleration (PGA).

More sophisticated IMs are currently under investigation by many researchers. For example, Baker (2007) discusses the potential of vector-valued IMs in terms of efficiency in estimating structural response. Most of the proposed vector-valued IMs comprise 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 parameters, as the Arias intensity or significant ground-motion duration, are possible IMs, but they are considered to be related more to the cyclic energy dissipation rather than to the peak structural response. In fact, some studies (e.g., Hancock and Bommer, 2006; 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; whereas duration-related measures do play a role only if the hysteretic structural response is that to assess, that is, in those cases in which the cumulative damage potential of the earthquake is of concern. However, in general, the integral ground-motion parameters associated with duration are less

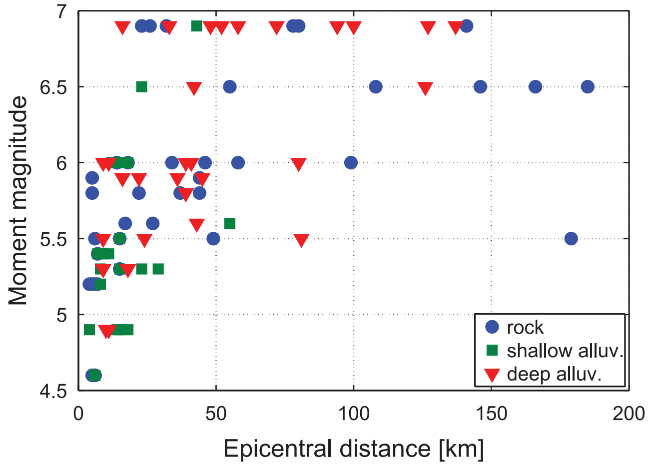

Figure 1. Distribution of the records with respect to moment-magnitude and epicentral distance (M 7).

important with respect to peak IMs because damage to structures in general is caused more by maximum displacement; therefore, the former IMs may be considered secondary with respect to the latter. In these cases, it seems appropriate to develop conditional hazard maps, that is, 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, whereas the secondary is a parameter that may account for the cumulative damage potential (i.e., damage related to the amount of cyclic shaking of the structure); 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 derived for I_D on the basis of an empirical dataset of Italian records already used for other well-known ground-motion prediction equations (GMPEs) proposed in the past by Sabetta and Pugliese (1987, 1996). Subsequently, the residuals of the logarithms 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 fiftieth and the ninetieth) were extracted from the conditional probability density function (PDF) of I_D given PGA and mapped for the Campania region (southern Italy). The selected hazard level for PGA corresponds to a 10% exceedance probability in 50 yr, which is a reference return period for the life-safety limit state of ordinary structures 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, Maddaloni, and Cosenza, 2008; Iervolino *et al.*, 2010). In fact, apart from 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 probabilistically consistent with the hazard of the primary IM.

Ground-Motion Prediction Equation for I_D

I_D has proven to be a good proxy for cyclic structural response (Manfredi, 2001). It is defined in equation (1),

$$I_D = \frac{\int_0^{t_E} a^2(t)\mathrm{d}t}{\mathrm{PGA} \times \mathrm{PGV}} = \frac{I_A}{\mathrm{PGA} \times \mathrm{PGV}}, \qquad (1)$$

where $a(t)$ is the acceleration time-history, t_E is the total duration of the ground-motion recording, and PGV is the

Table 1
Regression Coefficients for PGA, PGV, and I_A (R_{epi})

Y	a	b	c	d	e	h	$\sigma_{\log_{10} Y}$
PGA (cm/s^2)	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 (cm^2/s^3)	0.42	0.92	−1.69	0.24	−0.021*	5.3	0.39

*Coefficient for which 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).

Table 2
Regression Coefficients for PGA, PGV, and I_A (R_{jb})

Y	a	b	c	d	e	h	$\sigma_{\log_{10} Y}$
PGA (cm/s^2)	1.44	0.27	−0.87	0.16	−0.016*	5.8	0.18
PGV (cm/s)	−1.02	0.48	−0.91	0.15	0.10	3.6	0.22
I_A(cm^2/s^3)	0.76	0.79	−1.50	0.27	0.097*	3.8	0.38

*Coefficient for which 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).

peak ground velocity. Therefore, the numerator of I_D is proportional to the Arias Intensity and it will be referred to as I_A.

The best candidates to be ground-motion intensity measures are those for which hazard analysis is easy to compute, which requires a 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). A representation in terms of magnitude, distance, and site conditions is given in Figure 1 (see Data and Resources section).

The empirical predictive equations for the logarithms of the terms appearing in the definition of I_D (the generic dependent variable is indicated as Y) were fitted by regression using the same functional form of Sabetta and Pugliese (1996), equation (2),

$$\log_{10} Y = a + bM + c\log_{10}(R^2 + h^2)^{\frac{1}{2}} + dS_1 + eS_2 + \varepsilon_{\log_{10} Y}, \quad (2)$$

as a function of moment-magnitude (M or M_w); source-to-site distance (closest distance to fault surface projection, R_{jb}, and epicentral distance, R_{epi}, both expressed 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 (OLS) regressions is implicitly assumed to be Gaussian with zero mean and a standard deviation $\sigma_{\log_{10} Y}$.

The estimates for the coefficients[1] for PGA, PGV, and I_A, obtained using OLS regression[2], are given in Table 1 (R_{epi}) and Table 2 (R_{jb}). The estimated standard deviations of the respective residuals[3] are also given in those tables. h values were not estimated and assumed to be coincident to those provided by Sabetta and Pugliese (1996); see also Iervolino, Giorgio, *et al.* (2008).

The Shapiro and Wilk (1965) test, based on the considered sample, was used to check the assumption of normal distribution for $\varepsilon_{\log_{10}\mathrm{PGA}}$, $\varepsilon_{\log_{10}\mathrm{PGV}}$, 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 logarithms 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 not to constrain c to the geometrical spreading theoretical value in any of the regressions because data seem not to support such a choice (see also Stafford *et al.*, 2009). Moreover, moment magnitude was used herein, whereas local magnitude and surface-wave magnitude were 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, whereas in this study all the regression analyses were performed, arbitrarily using the horizontal component featuring the largest PGA. To fit all GMPEs for PGA, PGV, and I_A on the same ground-motion component is useful for directly deriving a model for I_D. In fact, in order to obtain a GMPE for the logarithms 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 logarithm of I_D is given by the logarithm of I_A minus the logarithms of PGA and PGV. This leads to the expression of equation (3),

$$\log_{10} I_D = a + bM + \log_{10}\left(\frac{(R^2 + h_1^2)^{c_1}(R^2 + h_2^2)^{c_2}}{(R^2 + h_3^2)^{c_3}}\right)^{\frac{1}{2}} + dS_1 + eS_2 + \varepsilon_{\log_{10} I_D}, \quad (3)$$

in which subscripts 1, 2, and 3 refer to PGA, PGV, and I_A, respectively. The coefficients of equation (3) are listed in Tables 3 and 4 for the two distance metrics considered. For I_D, results of the magnitude coefficient (b) and the soil coefficients (d) and (e) were close to zero[4]; a statistical test could be performed to check the statistical significance of these coefficients.

The normal distribution of I_D (i.e., of the residual of the GMPE) should follow from the normality of the logarithms of PGA, PGV, and I_A. Nevertheless, normality of the previously mentioned parameters was based on a hypothesis test; therefore, it may be prudent to also test the normality of the logarithm of I_D. So, the normality of the residual of equation (3) was tested, and such a hypothesis could not be rejected at 0.05 significance level.

[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 with them could be dropped from equation (2).

[2]A more refined model accounting for interevent and intraevent variability (e.g., Joyner and Boore, 1993) was also used for the regressions on the considered database; however it did not change significantly the estimates of coefficients and variances with respect to those obtained with OLS. This is consistent with Sabetta and Pugliese (1996) who also could not find sufficient evidence supporting the use of fitting methods other than OLS.

[3]These, still consistent with Sabetta and Pugliese (1996), may be considered small with respect to more recent GMPEs. In fact, Bindi *et al.* (2009) calibrated a new model for Italy with the same functional form, on the new Italian Accelerometric Archive (ITACA) in which estimated standard deviations are larger. However, this does not affect the scope of this study, that is, illustrating the concept of conditional hazard maps.

[4]It may sound odd that an intensity measure is insensitive to magnitude; however, from equation (1) it emerges that I_D is an integral intensity measure (numerator) normalized by peak measures (denominator). In fact, it has proven to be well correlated with the equivalent number of cycles of an SDOF, which is a structure response measure made of hysteretic energy divided by a quantity related to the peak response (Manfredi, 2001), that is, an engineering demand parameter normalized by peak response. In the following text, however, the dependence of I_D on M has been kept in symbols for completeness.

Table 3
Regression Coefficients for I_D (R_{epi})

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

*Coefficient for which 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).

Table 4
Regression Coefficients for I_D (R_{jb})

Y	a	b	c_1	c_2	c_3	d	e	$\sigma_{\log_{10} Y}$
I_D	0.35	0.039*	0.87	0.91	1.50	−0.039*	0.0082*	0.19

*Coefficient for which 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).

A plot of I_D versus epicentral distance is given in Figure 2, where the typical increasing trend with distance of duration-related measures is shown (Manfredi *et al.*, 2003).

Joint Normality and Conditional Distributions of the Logarithms 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 logarithms of the pair was tested. In fact, if the vector mentioned previously 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 were used to test multivariate normality of the vector made of $\varepsilon_{\log_{10}\mathrm{PGA}}$ and $\varepsilon_{\log_{10} I_D}$. Results of the bivariate normality tests developed by Mardia (1985) are given in Tables 5 and 6. With a given significance level of 0.05, the multivariate skewness and kurtosis result as nonsignificant.

The residuals of the prediction relationships for the logarithms of PGA and I_D have also been tested for correlation in order to compute $f(\log_{10} I_D | \log_{10}\mathrm{PGA})$, that is, the conditional PDF of the logarithm of I_D given the logarithm of PGA. The estimated correlation coefficient (r) between $\varepsilon_{\log_{10}\mathrm{PGA}}$ and $\varepsilon_{\log_{10} I_D}$ (equal to −0.25 considering R_{epi}) has been tested via a t-test assuming as the null hypothesis H_o: $\rho = 0$ (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 equation (4),

$$f(\log_{10} I_D, \log_{10}\mathrm{PGA}|M,R) = \frac{e^{-\frac{1}{2(1-\rho^2)}\left[\frac{(\log_{10} I_D-\mu_{\log_{10} I_D|M,R})^2}{\sigma^2_{\log_{10} I_D}} - \frac{2\rho(\log_{10} I_D-\mu_{\log_{10} I_D|M,R})(\log_{10}\mathrm{PGA}-\mu_{\log_{10}\mathrm{PGA}|M,R})}{\sigma_{\log_{10} I_D}\sigma_{\log_{10}\mathrm{PGA}}} + \frac{(\log_{10}\mathrm{PGA}-\mu_{\log_{10}\mathrm{PGA}|M,R})^2}{\sigma^2_{\log_{10}\mathrm{PGA}}}\right]}}{2\pi\sigma_{\log_{10} I_D}\sigma_{\log_{10}\mathrm{PGA}}\sqrt{1-\rho^2}}. \tag{4}$$

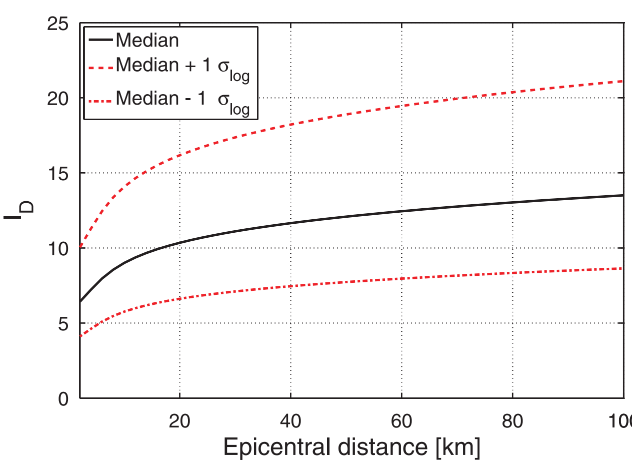

Figure 2. Plot of I_D as a function of epicentral distance (M 7).

In equation (4) $\mu_{\log_{10}\mathrm{PGA}|M,R}$ and $\sigma_{\log_{10} I_D}$ are the mean and the standard deviation of $\log_{10} I_D$, respectively; that is, equation (3). $\mu_{\log_{10}\mathrm{PGA}|M,R}$ and $\sigma_{\log_{10}\mathrm{PGA}}$ are the mean and the standard deviation of $\log_{10}\mathrm{PGA}$, respectively; that is, equation (2). The covariance matrix, Σ, for $\varepsilon_{\log_{10}\mathrm{PGA}}$ and $\varepsilon_{\log_{10} I_D}$ is reported in equation (5), for R_{epi},

$$\Sigma = \begin{pmatrix} \sigma^2_{\log_{10}\mathrm{PGA}} & \rho\sigma_{\log_{10}\mathrm{PGA}}\sigma_{\log_{10} I_D} \\ \rho\sigma_{\log_{10}\mathrm{PGA}}\sigma_{\log_{10} I_D} & \sigma^2_{\log_{10} I_D} \end{pmatrix} = \begin{pmatrix} 0.036 & -0.009 \\ -0.009 & 0.036 \end{pmatrix}. \tag{5}$$

Figure 3a shows an example of joint distribution of I_D and PGA for a M 7 event and for a site characterized by an epicentral distance of 50 km. Figure 3b shows the contours of

Table 5
Tests for Joint Normality of the Logarithms of PGA and I_D (R_{epi})

	Mardia's Test of Skewness	Mardia's Test of Kurtosis
Test statistic	2.21	−0.86
Critical value at 0.05 significance level	9.49	±1.64

Table 6
Tests for Joint Normality of the Logarithms of PGA and I_D (R_{jb})

	Mardia's Test of Skewness	Mardia's Test of Kurtosis
Test statistic	0.94	−0.94
Critical value at 0.05 significance level	9.49	±1.64

the joint distribution of I_D and PGA for different magnitude values (for a site at epicentral distance equal to 50 km). From Figure 3b, it is evident that projecting on the I_D axis the bivariate distribution contours, a similar shape of the marginal distributions is obtained regardless of the magnitude values, which reflects the fact that the marginal I_D distribution appears to be very weakly dependent on magnitude.

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 ($\mu_{\log_{10} I_D|\log_{10}\mathrm{PGA},M,R}$) and standard deviation of $\log_{10} I_D$ ($\sigma_{\log_{10} I_D|\log_{10}\mathrm{PGA}}$), given $\log_{10}\mathrm{PGA} = z$, are reported in equation (6),

$$\begin{cases} \mu_{\log_{10} I_D|\log_{10}\mathrm{PGA},M,R} = \mu_{\log_{10} I_D|M,R} + \rho\sigma_{\log_{10} I_D}\frac{z-\mu_{\log_{10}\mathrm{PGA}|M,R}}{\sigma_{\log_{10}\mathrm{PGA}}} \\ \sigma_{\log_{10} I_D|\log_{10}\mathrm{PGA}} = \sigma_{\log_{10} I_D}\sqrt{1-\rho^2} \end{cases}. \tag{6}$$

Because the joint distribution of I_D and PGA depends on I_D and PGA GMPEs, and therefore also on magnitude and distance, to obtain the conditional distribution of the logarithms of I_D conditional on PGA only, the marginalization in equation (7) is required:

$$f(\log_{10} I_D|\log_{10}\mathrm{PGA}) = \int_M\int_R f(\log_{10} I_D|\log_{10}\mathrm{PGA},M,R) \times f(M,R|\log_{10}\mathrm{PGA})\mathrm{d}m\mathrm{d}r. \tag{7}$$

It is easy to recognize that the $f(M,R|\log_{10}\mathrm{PGA})$ term in equation (7) is the PDF of M and R given the occurrence of $\log_{10}$ PGA; that is, the result of disaggregation of seismic hazard (e.g., Bazzurro and Cornell, 1999). As an approximation of the integral in equation (7), 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 equation (6); that is, equation (8):

$$\mu_{\log_{10} I_D|\log_{10}\mathrm{PGA}} \approx \mu_{\log_{10} I_D|M^*,R^*} + \rho\sigma_{\log_{10} I_D}\frac{z-\mu_{\log_{10}\mathrm{PGA}|M^*,R^*}}{\sigma_{\log_{10}\mathrm{PGA}}}. \tag{8}$$

Illustrative Application

An example of the possible use of the results obtained is given in Figure 4. Figure 4b shows the PGA values on rock (expressed in fractions of g) with a 10% exceedance probability in 50 yr (return period, T_R, equal to 475 yr) in the Campania region according to the classical seismic hazard analysis procedure (see, e.g., 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).

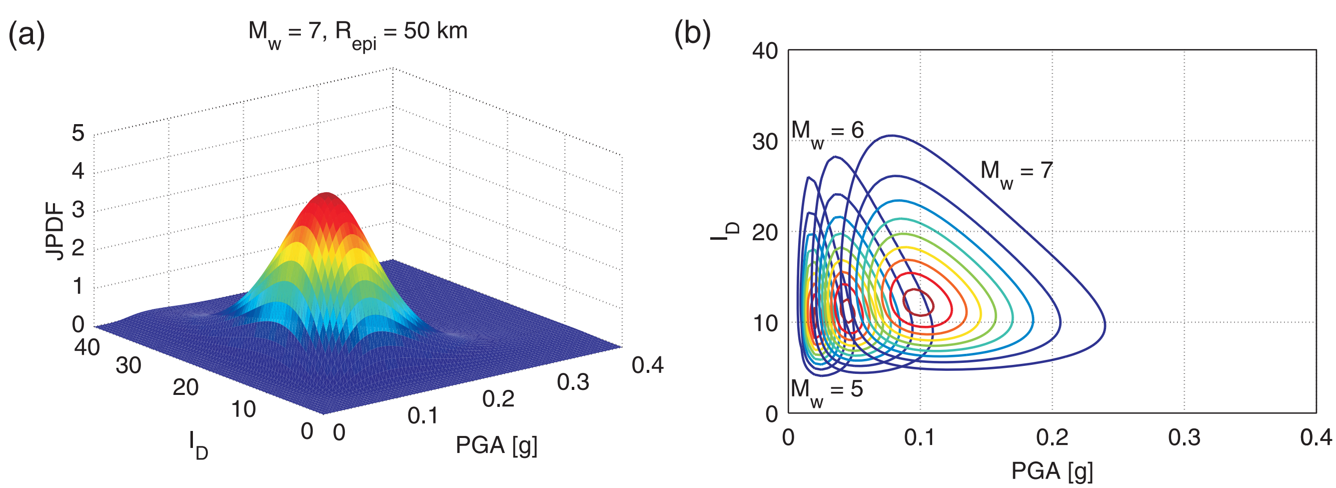

Figure 3. (a) Example of joint distribution of PGA and I_D for an M 7 event and for a site at 50 km from the source in terms of epicentral distance. (b) Contours of joint distribution of PGA and I_D for different M values (R_{epi} = 50 km).

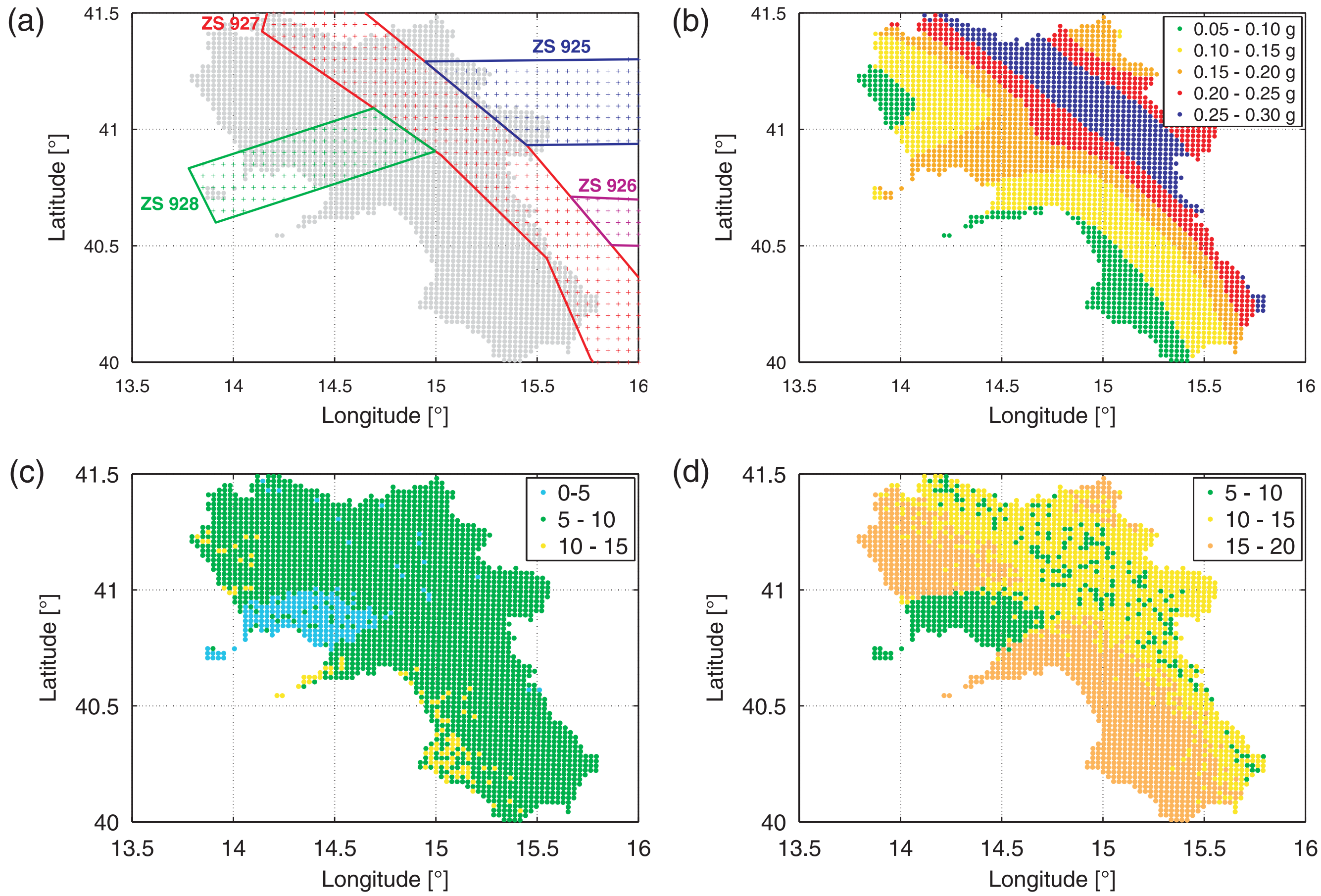

Figure 4. (a) Seismic zones considered in the analysis; (b) 475 yr return period PGA on rock hazard map for the Campania region (southern Italy); (c) hazard map in term of I_D with a 50% exceedance probability given PGA of panel (b); (d) hazard map in terms of I_D with a 10% exceedance probability given PGA of panel (b).

Sources were modeled as the seismogenic zones of Figure 4a (Meletti *et al.*, 2008), which have been used to compute the official Italian hazard data produced by the Istituto Nazionale di Geofisica e Vulcanologia (see Data and Resources section). Because of the use of seismogenic zones, GMPEs in terms of R_{epi} were used in hazard analysis.

Source features, from Barani *et al.* (2009), are given in Table 7, 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 relationship.

Figure 4c,d shows the maps of seismic hazard in terms of I_D given the PGA of Figure 4b. In particular, Figure 4c,d

Table 7
Parameters of the Selected Seismogenic Zones Shown in Figure 4a

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

are the fiftieth and ninetieth percentiles of the conditional I_D PDF, respectively. The conditional I_D maps were obtained using the distribution of parameters in equation (6) in which z (logarithms of PGA) values are those from Figure 4b, whereas the values of magnitude and distance (M^* and R^*) to plug in the $\mu_{\log_{10}\mathrm{PGA}|M,R}$ and $\mu_{\log_{10} I_D|M,R}$ terms of equation (8) were obtained by disaggregation of hazard in terms of occurrence of design PGA values (Fig. 5). The adopted disaggregation methodology is the same described in Convertito *et al.* (2009).

As a site-specific example, Figure 6 represents the complementary cumulative density functions of I_D conditional on PGA for the sites of S. Angelo dei Lombardi (latitude: 40.8931°, longitude: 15.1784°) and Ponticelli (latitude: 40.8516°, longitude: 14.3446°) in the Campania region. These two sites have been selected based on the fact that S. Angelo dei Lombardi is located in the epicentral area of the 23 November 1980 Irpinia earthquake, and Ponticelli is the construction site of one of the largest seismically isolated structures in Europe (Di Sarno *et al.*, 2006). The five chosen scenarios, in terms of M and R (Table 8), refer to the mean values obtained from disaggregation of seismic hazard for PGA for different probabilities of occurrence in 50 yr

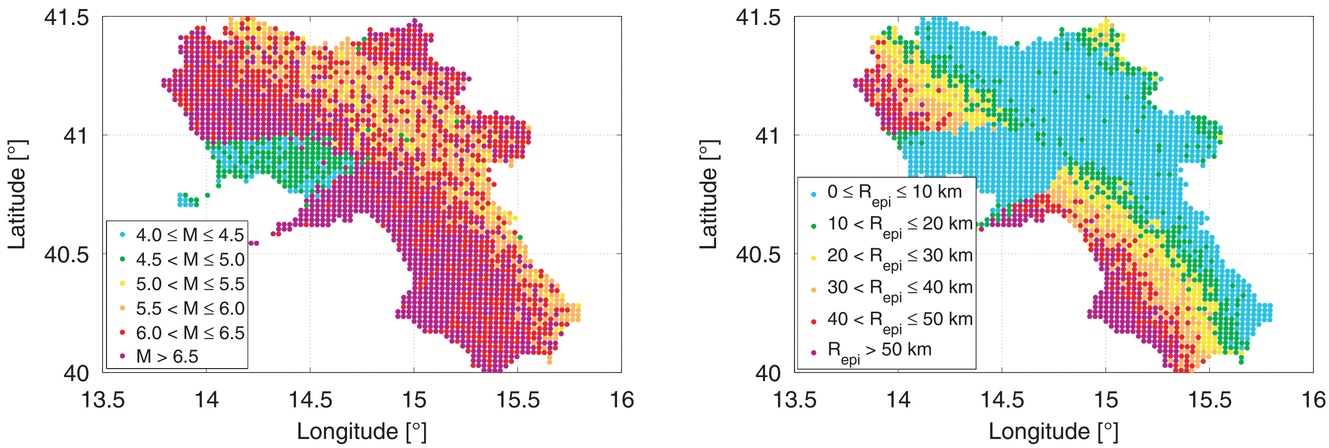

Figure 5. Modal values of magnitude and epicentral distance from disaggregation of seismic hazard in terms of PGA given in Figure 4b and used to compute the conditional distribution of I_D whose percentiles are in Figure 4c,d.

(corresponding to five values of T_R, from 30 to 2475 yr). The curves of Figure 6 give information on the values of I_D probabilistically consistent with respect to the hazard in terms of PGA at the site.

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 with 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 PGA, was investigated. The chosen secondary measure is the so-called Cosenza and Manfredi index. A ground-motion prediction relationship has been derived for the logarithm 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 the obtaining of 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 yr 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.

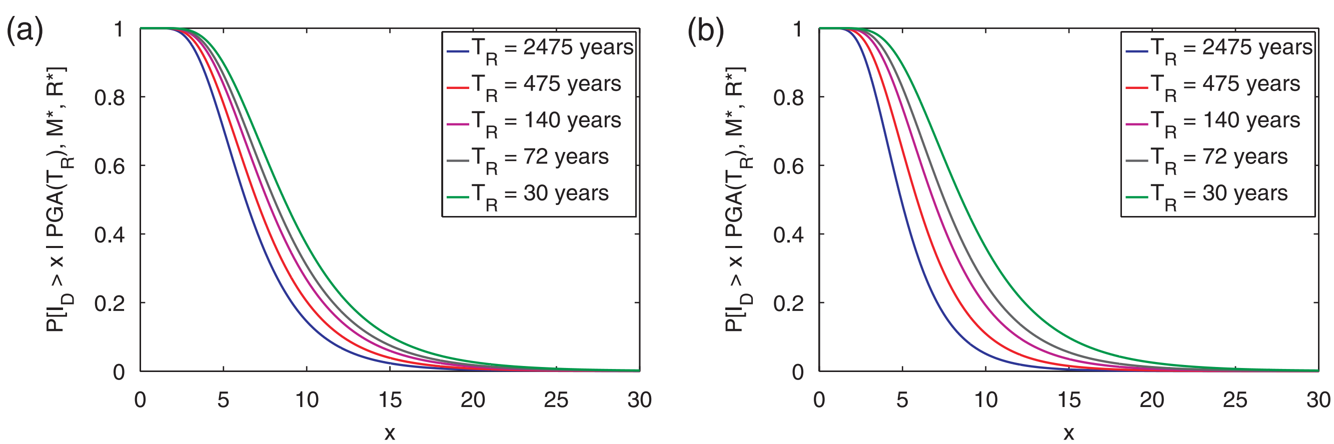

Figure 6. Probability of exceedance of I_D given PGA for five scenarios for (a) S. Angelo dei Lombardi, and (b) Ponticelli.

Table 8
Considered Scenarios for S. Angelo dei Lombardi and Ponticelli

	S. Angelo dei Lombardi			Ponticelli		
T_R (yr)	M^*	R^* (km)	PGA (g)	M^*	R^* (km)	PGA (g)
2475	6.4	5.8	0.51	5.1	5.1	0.28
475	6.0	8.4	0.26	5.0	9.9	0.17
140	5.8	12.5	0.14	5.2	18.8	0.10
72	5.7	16.1	0.10	5.3	27.3	0.073
30	5.5	23.7	0.060	5.4	42.6	0.046

Data and Resources

For the purposes of the present study, the ground motions and related information were obtained by the European Strong-Motion Database (ESD) available at http://www.isesd.cv.ic.ac.uk (last accessed July 2007; Ambraseys *et al.*, 2000; Ambraseys *et al.*, 2004). Official Italian hazard data produced by the Istituto Nazionale di Geofisica e Vulcanologia (INGV) are available at http://esse1.mi.ingv.it/; last accessed November 2009).

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