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SEISMIC GROUND MOTION MODELLING AND DAMAGE EARTHQUAKE SCENARIOS A BRIDGE BETWEEN SEISMOLOGISTS AND SEISMIC ENGINEERS

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Abstract

The input for the seismic risk analysis can be expressed with a description of "groundshaking scenarios", or with probabilistic maps of perhaps relevant parameters.

The probabilistic approach, unavoidably based upon rough assumptions and models (e.g. recurrence and attenuation laws), can be misleading, as it cannot take into account, with satisfactory accuracy, some of the most important aspects like rupture process, directivity and site effects. This is evidenced by the comparison of recent recordings with the values predicted by the probabilistic methods.

We prefer a scenario-based, deterministic approach in view of the limited seismological data, of the local irregularity of the occurrence of strong earthquakes, and of the multiscale seismicity model, that is capable to reconcile two apparently conflicting ideas: the Characteristic Earthquake concept and the Self Organized Criticality paradigm.

Where the numerical modeling is successfully compared with records, the synthetic seismograms permit the microzoning, based upon a set of possible scenario earthquakes. Where no recordings are available the synthetic signals can be used to estimate the ground motion without having to wait for a strong earthquake to occur (pre-disaster microzonation). In both cases the use of modeling is necessary since the so-called local site effects can be strongly dependent upon the properties of the seismic source and can be properly defined only by means of envelopes.

The joint use of reliable synthetic signals and observations permits the computation of advanced hazard indicators (e.g. damaging potential) that take into account local soil properties. The envelope of synthetic elastic energy spectra reproduces the distribution of the energy demand in the most relevant frequency range for seismic engineering. The synthetic accelerograms can be fruitfully used for design and strengthening of structures, also when innovative techniques, like seismic isolation, are employed.

For these reasons the skill of seismology to estimate realistic ground motions at a particular site should be fully exploited by seismic engineers. In fact, even if recently strong motion records in near-fault, soft soil, or basin conditions have been obtained, their number is still very limited to be statistically significant for seismic engineering applications.

1. Introduction

Earthquakes, like many other natural disasters, have both immediate and long-term economic effects. Within a fraction of a minute, single earthquakes can inflict damage to houses, businesses, government buildings, and infrastructures. A single earthquake may trigger a global ecological catastrophe, cause up to thousands of casualties and global economic depression: the disruption of commerce will affect the rate of economic growth, inflation, productivity and trade balance.

Case studies of seismic hazard assessment techniques indicate the limits of the currently used methodologies, deeply rooted in engineering practice, based on a probabilistic approach. The probabilistic analysis supplies indications that can be useful but not sufficiently reliable to characterize the seismic hazard.

The mathematical modelling, with different degrees of complexity, based on probabilistic concepts cannot fill in the gap due to the lack of knowledge about the physical process behind an earthquake, at the most it can supply some guidelines. Moreover, it may loose validity in dealing with uncertainties that are so large that may not be quantifiable in a meaningful sense (Chandler et al., 2001) as it happens in low to moderate seismicity regions, or regions lacking historical and instrumental earthquake data.

For a given zone, the mathematical modelling of the occurrence of seismic events and of the related values of probability are derived from empirical data that may fail to describe adequately the reality.

When constructing appropriate earthquake-resistant structures, design and construction should not be such that in extreme events no damage occurs but rather an acceptable level of damage takes place as a function of the corresponding performance expectations (operational, safe-life, etc.).

Therefore the realistic definition of hazard in scenario-like format should be accompanied by the determination of advanced hazard indicators as, for instance, damaging potential. Such a determination, due to the limitation of the available strong ground motion records, requires resorting to broad band synthetic seismograms that allow us to perform realistic waveform modelling for different seismotectonic environments. The modelling takes into account source properties, like dimensions, directivity, duration, lateral heterogeneity's along the path and local site features. Such a procedure is a must since it has been proven both experimentally (e.g. Wang and Nisimura, 1999) and theoretically (Romanelli and Vaccari 1999; Field et al., 2000; Panza et al., 2001) that the so-called local site effects can be strongly dependent upon the characteristics of the seismic source generating the seismic input. At present, only from a careful performance of modelling experiments it is possible to realistically account for effects such as long duration pulses, shaking duration, temporal distribution of pulses, amplitude and, connected to them, the linear and nonlinear structural response in terms of strength, energy and displacement.

2. General problems in seismic hazard assessment

The typical seismic hazard problem lies in the determination of the ground motion characteristics associated to future earthquakes, both on regional and on local scale. The input for the subsequent seismic risk analysis can be expressed in various ways, e.g. with a description of the groundshaking severity due to an earthquake of a given distance and magnitude ("groundshaking scenario"), or with probabilistic maps of relevant parameters describing the ground motion. For example, the historically most used parameter in engineering analysis for the characterization of the seismic hazard is the PGA

(Peak Ground Acceleration), which is a single-value indicator commonly used in seismic hazard assessment. Actually, it is recognized that PGA alone can not describe adequately all the effects associated to the ground shaking, since the frequency content and the duration of a seismic wavetrain can play a decisive role. Although it has been understood that the characteristics of the ground motion such as its amplitude, frequency content and duration are relevant to estimate its damaging potential, some of these characteristics have often been ignored.

A more adequate definition of the seismic ground motion due to an earthquake with a given magnitude and source-to-site distance, can be done following two main approaches. The first one (denoted as the engineering approach) is based on the analysis of the available strong motion databases, collected by existing seismic networks, and on the grouping of those accelerograms that contain similar source, path, and site effects (e.g. Decanini and Mollaioli, 1998). A fundamental step in this approach involves the estimation of realistic source-to-site transfer functions.

The second approach (the seismological approach) is based on modelling techniques, developed from the knowledge of the seismic source process and of the propagation of seismic waves, that can realistically simulate the ground motion associated with the given earthquake scenario (Panza et al., 1996; Field et al., 2000). The ideal procedure is to follow the two complementary ways, in order to validate, for the different areas to be investigated, the numerical modelling with the available recordings (e.g. Decanini et al., 1999; Panza et al., 2000a,b). In the last decades the number of the recorded strong motions has considerably increased, especially for North America, Japan and Taiwan, but the installation and maintenance costs make the deployment of a dense seismic network in each earthquake prone area a too expensive operation. For most of the European seismic zones strong motion data are very scarce and most of the available data for destructive events are only the macroseismic intensities. In these cases synthetic signals, to be used as seismic input in a subsequent engineering analysis, must be produced (immediately and at a very low cost/benefit ratio) taking into account the source characteristics, the path and the local geological and geotechnical conditions and must be validated against observed intensities.

As a result, we suggest a scenario-based, deterministic approach in view of the limited seismological data and of the multiscale seismicity model formulated by Molchan et al. (1997). Accordingly to this model only the ensemble of events that are geometrically small, compared with the elements of the seismotectonic regionalization, can be described by a log-linear FM relation. This condition, largely fulfilled by the early global investigation by Gutenberg and Richter (e.g. see Fig. 49 of Båth, 1973), has been subsequently violated in many investigations. This violation has given rise to the Characteristic Earthquake (CE) concept (Schwartz and Coppersmith, 1984) in opposition to the Self-Organized Criticality (SOC) paradigm (Bak and Tang, 1989). The multiscale model implies that, in order to apply the probabilistic approach the seismic zonation must be made at several scales, depending upon the self-similarity conditions of the seismic events and the linearity of the log FM relation, in the magnitude range of interest.

Moreover, the macroseismic observations made in correspondence of the destructive events of the last century have clearly evidenced the influence of other two fundamental aspects in the characterization of the damage distribution: the near-surface geological and topographical conditions. This observation highlights the large spatial variability of the destructive potential of earthquake ground motion. Since most of the anthropised areas are settled in correspondence of sedimentary basins (e.g. river valleys), a realistic definition of the seismic input that takes into account the site response has become one of the most relevant tasks in the seismic engineering analysis. The soft surface layering often controls local amplification of the ground motion. The impedance contrast between the soft surface soils and the underlying bedrock leads to the trapping of the seismic energy, and the relatively simple onset of vertical resonance can be transformed into a complex resonance's pattern, strongly dependent on the characteristics of the sub-surface layers and the bedrock configuration.

The most traditional empirical techniques for the estimation of site effects are based on the computation of the spectral ratio between the signal (or a portion of it, e.g. a single phase) recorded at the sedimentary site and a reference one, preferably recorded at a nearby bedrock site (Borcherdt, 1970). Quite often a signal recorded on bedrock is not available close to the investigated sites, so that directional effects due to the source could become relevant. Even in the favorable condition that such a reference site exists, unless well isolated single phases are used, the spectral ratios are not completely free from source influences (e.g. Romanelli and Vaccari, 1999). Some techniques have been proposed that are non-reference-site dependent (e.g. Boatwright et al., 1991).

An alternative approach, originally applied by Langston (1979) for crustal and upper mantle studies, is based on the measurement of the spectral ratio between the horizontal and vertical components of motion. The method is based on the assumption, not always fulfilled, that the propagation of the vertical component of motion (in general only S-waves are considered) is not perturbed by the uppermost surface layers, and can therefore be used to remove source and path effects from the horizontal components. Anyway, this method produced unsatisfactory results, as verified in recent severe earthquakes.

As a matter of fact, local site effects can be strongly dependent upon the characteristics of the seismic source (e.g. Romanelli and Vaccari, 1999). Therefore, the use of synthetic seismograms is fundamental even when relevant observational data are available, in order to explore the local responses that may correspond to sources that are different from the known ones.

The wide use of synthetic signals allows us to easily construct scenarios based on ground motion descriptors, strictly linked with energy and displacement demands (Decanini and Mollaioli, 2001).

3. Shortcomings of the probabilistic approach

The probabilistic analysis of the seismic hazard determines the probability rate of exceeding, over a specified period of time, various levels of ground motion. It is basically conditioned by the definition of the seismogenic zones, which is affected by serious uncertainties. Within each of them the seismogenic process is frequently assumed to be rather uniform, however the uncritical assumption of homogeneity can introduce significant errors in the estimate of the seismic hazard in a given site. For a recent extreme example concerning the Italian territory reference can be made to the 17 July 2001 (M_b=4.9; M_s=4.0, NEIC), event which occurred in NorthEast Italy outside the defined seismogenic zones (Meletti et al., 2000), thus in a region not considered for hazard analysis.

The multiscale seismicity model supplies a formal framework that describes the intrinsic difficulty of the probabilistic evaluation of the occurrence of earthquakes (Molchan et al., 1997). The problem is chiefly due to the difficulty to properly choose the size of the region to analyze, so that it is large enough to guarantee the applicability of the Gutenberg-Richter law and related concepts. In order to apply the probabilistic approach, the seismic zonation must be made at several scales, depending upon the self-similarity conditions of the seismic events and the linearity of the log frequency-magnitude (FM) relation, in the magnitude range of interest.

The difficulty to evaluate the occurrence of the earthquakes (log FM relations) and the propagation of their effects (attenuation laws), as well as the parameters characterizing the destructive potential of the ground motion leads to a probabilistic estimate of the seismic hazard that could represent a gross approximation of the reality. When the multiscale seismicity model is applied to analyze the seismicity, the time dependence of seismicity becomes unimportant. In fact, the classical Poisson hypothesis (seismic events are time independent) can hardly be accepted if the considered seismic events are those associated to a specific source (where there are processes of storage and release of energy). The Poisson hypothesis can be physically acceptable when the considered area is large enough to contain a great number of sources.

To deal with the time dependence of seismicity, that is relevant only if we consider a very small number of seismic sources, the concept of renewal process has been introduced (Esteva, 1970; Araya and Der Kiureghian, 1988; Hagiwara, 1974; Savy et al., 1980). Accordingly with the renewal process models a memory is introduced so that each event, with some probability, depends from the previous one. In these models the intercurrence time between two events does not follow an exponential distribution, thus the probability of occurrence of an earthquake is not constant with time. Assuming that the seismic crisis is over or during a seismic sequence, the occurrence of the events is interpreted using mixed functions of the density of probability, obtained with the combination of two different functions. These functions depend upon the seismogenetic properties of the sources and upon the time evolution of the sequences; therefore they differ from place to place. Such models rely upon several assumptions that to be verified require the availability of observations that often are not available or are insufficient, and this makes it difficult, if not impossible, the calibration of the distribution functions. The application of the renewal process model requires the evaluation of the time elapsed from the last event. Such an evaluation can be impossible if the length of the catalogue is smaller than the storage and release time interval and palaeoseismological data are not available, or when a linear source does not correspond to a single fault but to a system of several faults almost parallel. In the latter case the occurrence of severe seismic events, within close epicentral zones and during short time intervals, could not be analyzed resorting to criteria based on the existence of seismic gaps.

Further shortcomings of the probabilistic approach are connected with (1) the choice of the parameters characterizing the destructiveness potential of earthquake ground motion, and (2) the attenuation relationships for the estimation of the ground motion at a site for a given earthquake.

3.1 Characterization of earthquake destructiveness potential

The characterization of seismic motion in earthquake prone areas requires the identification of adequate parameters that characterize accurately the earthquake destructiveness potential. The specification of these parameters in general requires the selection of significant signals for the design of new structures or the seismic safety assessment of existing ones. To define, in general, a design earthquake represents a fundamental step in a seismic hazard analysis. The adoption of inadequate parameters can lead to the definition of a non-realistic design earthquake and, consequently, to the unreliable evaluation of the seismic risk. Recent earthquakes (e.g. Imperial Valley 1979, Loma Prieta 1989, Landers 1992, Northridge 1994, Kobe 1995, Turkey 1999, Taiwan 1999, Greece 1999, Gujarat, 2001) have demonstrated that the seismic hazard evaluation, based prevalently on a probabilistic approach, has underestimated considerably these demands, particularly in near-fault regions.

The quite large number of near-fault records from recent earthquakes indicate that, for a given soil condition, the characteristics of strong ground motion and consequently of the damage potential can vary significantly as a function of the location of the site with respect to the propagation of the rupture. Particularly, in the case of *forward rupture directivity* most of the energy arrives in a single large pulse of motion which may give rise to an amplification of the ground motion at sites toward which fracture propagation progresses (e.g. Bolt, 1983; Panza and Suhadolc, 1987; Heaton et al., 1995). The long-period parts of the signals in forward directivity locations can be energetic due to the development of one or more, unidirectional, long-period pulses. The dynamic response of a structure depends simultaneously on its mechanical properties and on the characteristics of the induced excitation. Therefore it is necessary to investigate if certain properties, which are efficient to mitigate the structure response when subjected to certain inputs, might have an undesirable effect during other seismic inputs. Moreover, the presence of long duration accelerometric pulses in the ground motion constitutes an important factor in causing damage, as it involves the transmission of large energy amounts to the structures in a very short time, with high energy dissipation and displacement demands.

The quantification of the ground motion expected at a particular site, that would drive the structure to its critical response, resulting in the highest damage potential, requires: (a) the identification of the ground motion parameters that characterize the severity and the damage potential of the earthquake ground motion (for a more complete discussion on this topic see the Appendix), and (b) the seismological, geological, and topographic factors that affect them. In this context, energy-based and displacement demand parameters constitute an adequate approach to highlight the damaging potential of these kinds of signals (Decanini and Mollaioli, 1998; Decanini et al., 2000). This necessity is confirmed by the analysis performed by Panza et al. (1999) when seeking for a correlation between maximum observed macroseismic intensity, I, (MCS) and computed peak values of ground motion, like Design Ground Acceleration (DGA), Peak Ground Velocities (PGV) and Peak Ground Displacements (PGD). They do not show any significant improvement in the regression scatter when going from DGA to PGV and PGD. The slope value is always close to 0.3, a value that corresponds to the relation DGA(I-1)/DGA(I)=PGV(I-1)/PGV(I)=PGD(I-1)/PGD(I)=2. Such a value is not contradicted by the numerous empirical relations (see Shteinberg et al., 1993 and references therein) found when considering peak values of ground acceleration.

The large energy demand in the near-field region ($D_f \leq 5$ km), with respect to larger distance ranges, is clearly evidenced in Tab. 1. In the table, a comparison between maximum input energy E_{Imax} and a Seismic Hazard Energy Factor AE_I (Decanini and Mollaioli, 1998) is given for sites located on a soil of intermediate mechanical properties, S2; for different values of interval of magnitude (M) and source-to-site distance (D_f) classes. D_f is defined as the closest distance from the intersection with the free surface of the fault plane, or of its extension to the surface for blind faults.

SOIL S2 $5.4 \leq M \leq 6.2$			
D_f (km)	**$AE_{I(design)}$ cm^2/s**	**$E_{I(max)}$ cm^2/s^2**	**$AE_{I(max)}$ cm^2/s**
$D_f \leq 5$	45000	39000	34568
$5 < D_f \leq 12$	18000	13000	8960
$12 < D_f \leq 30$	10000	7600	5828
$D_f > 30$	3000	480	420
SOIL S2 $6.5 \leq M \leq 7.1$			
D_f (km)	**$AE_{I(design)}$ cm^2/s**	**$E_{I(max)}$ cm^2/s^2**	**$AE_{I(max)}$ cm^2/s**
$D_f \leq 5$	110000	90000	98446
$5 < D_f \leq 12$	75000	41000	31320
$12 < D_f \leq 30$	50000	31000	42683
$D_f > 30$	15000	9400	9836

Table 1. Comparison between AE_I (design and maximum observed) and E_I (maximum observed). Soil S2 (intermediate).

The input energy per unit of mass, $\frac{E_I}{m} = \int \ddot{u}_t du_g = \int \ddot{u}_t \dot{u}_g dt$, has been extensively used for the evaluation of the damage potential of earthquake ground motion (Akiyama, 1985; Uang and Bertero, 1988; Fajfar and Fishinger, 1990; Uang and Bertero, 1990; Bertero and Uang, 1992; Krawinkler 1997; Decanini and Mollaioli, 1998; Decanini and Mollaioli, 2001). The parameter $AE_I = \int_{0.05}^{4.0} E_I(x = 5\%, T)dT$, which represents the area enclosed by the elastic input energy spectrum in the interval of periods between 0.05 and 4.0 seconds, may be considered a global hazard index in energy terms (Decanini and Mollaioli, 1998). In fact it considers the influence of the energy demand in the whole period range. The proposed values of E_I and AE_I were determined from a database of 300 acceleration time histories taken from 37 different seismic events with magnitude ranging from 4 to 8.1 and distance, from the horizontal projection of the causative fault, from 0 to 390 km.

The large difference among the energy parameters in the near-fault ($D_f \leq 5$ km) and at other locations ($5 < D_f \leq 12$ km; $12 < D_f \leq 30$ km; $D_f > 30$ km) has been found for the displacement demand too, as shown in Fig. 1. The largest displacements can be observed on soft soil sites (S3), in the same distance and magnitude range (Fig. 2), as the amplification of ground motions may be significantly affected by the combined effect of the source and of the soil stiffness and thickness.

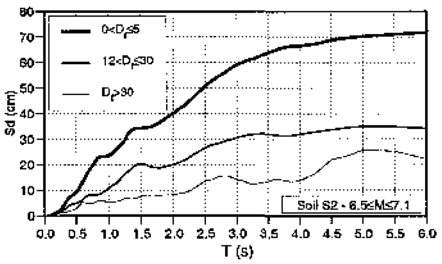

Fig. 1. Mean Displacement Spectra for different source-to-site distance ranges. Intermediate soil class (S2). $6.5 \leq M \leq 7.1$.

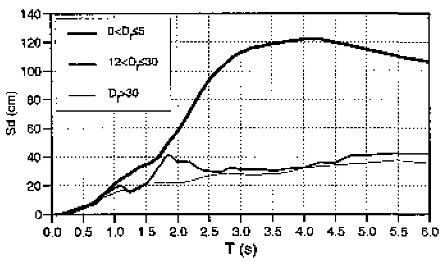

Fig. 2. Mean Displacement Spectra for different source-to-site distance ranges; soft soil (S3); $6.5 \leq M \leq 7.1$.

Each recorded strong ground motion history is a useful addition to the time record database, which increases our choices in selecting acceleration histories for various analyses. The growing database for near-field and soft soil strong motion records, gives the opportunity to enhance the state of knowledge in damage potential evaluation. Anyway, it has been noted that other seismological characteristics, such as the different styles of faulting, the radiation pattern, the orientation of the seismic source, etc., should inevitably be taken into account. These issues may be clearly understood resorting to seismological modeling techniques. For example, due to the lack of data, the nature of near-fault ground motions from larger magnitude earthquakes should be examined using seismologically based ground motion simulation methods.

3.2 Attenuation relationships

The other factor which influences a seismic-hazard estimate is represented by the assessment of the attenuation relationships of the ground motion parameters. These relationships can differ in the assumed functional form, the number and definition of independent variables, the data selection criteria, and the statistical treatment of the data. Anyway, in general, attenuation laws assume the same propagation model for all size and type of events, but such a hypothesis is not very realistic. The most frequently used attenuation models of ground motion parameters, like PGA, PGV, etc., have the form:

$$\log y = a + b\,M + c\log r_f + d\,D_f + e\,S \quad (1)$$

where y is the ground motion parameter, a, b, c, d, and e are coefficients empirically determined, r_f is derived from D_f by considering a conventional depth h_0, with $r_f = \sqrt{D_f^2 + h_0^2}$, and S is a binary variable (0, 1) which depends on the soil type. Generally, the coefficients are determined empirically by means of regression analyses and they turn out to be quite sensitive to the data set utilized. Usually regional data sets are statistically not significant, while the national or global data sets, even if statistically significant, can represent very different seismotectonic styles that are therefore not mixable. Quite often the coefficients are obtained in such a way that they turn out to be (almost) independent from magnitude, distance and soil type. A nice example of the strong dependence of attenuation laws on the procedure followed in the data processing is given by Parvez et al. (2001) for the Himalayas.
Moreover, typically the standard deviation associated with the predictions of the attenuation relationships ranges between 50% and 100% of the mean value.

Introducing the relative decay

$$R_y = y_{rf}/y_{source} \quad (2)$$

where the suffix "source" indicates the values at the closest instrument to the source (typically D_{source} may be about 2 km), we obtain

$$\log R_y = c(\log r_f - \log r_{source}) + d(D_f - D_{source}) \quad (3)$$

Thus the relative decay does not depend upon the magnitude (size of the event) and the type of soils (local soil conditions). In general, r_f is different for PGA and PGV because a different conventional depth h_0 is assumed: usually $3 \leq h_0 \leq 10$ km for PGA and PGV. The parameter h_0 has a strong influence on the relative decay, conditioning the reliability of the results.

In the particular case of Sabetta and Pugliese (1987) relations (SP87) c=-1, d=0 thus

$$\log R_y = \log r_{source} - \log r_f \quad (4)$$

and h_0 is 5.8 km for PGA and 3.6 km for PGV.

The attenuation relationships utilized by Ambraseys et al. (1996) for the evaluation of peak ground acceleration (PGA), with h_0 equal to 3.5 km, results (AMB96):

$$\log R_y = 0.922\,(\log r_{source} - \log r_f) \quad (5)$$

Finally, the attenuation law for PGA suggested for the South East Sicily (ASI) by the Authors (Decanini et al., 2001), for h_0=10 km, is:

$$\log R_y = 0.92\,(\log r_{source} - \log r_f) + 0.0005\,(D_{source} - D_f) \quad (6)$$

These results seem to be in contrast with the physical phenomenon, often observed. For example, it has been found that PGV and PGD (and consequently energy) attenuate differently with distance than accelerations, depending on the magnitude range and soil type.

The analysis of selected events and of a set of strong motion records, classified accordingly to magnitude intervals and soil conditions, indicates that the trend of the relative decay of AE_I energy hazard parameter (Decanini and Mollaioli, 1998) is not constant. It depends on magnitude and soil type (see Tables 2 to 6).

If we consider that the energetic parameter AE_I is a good and relatively stable indicator of the global damaging potential of ground motion, it is natural to assume that PGA and PGV cannot follow

	S1			S2		S3
D_f(km)	M (6.5-7.1)	M (5.4-6.2)	M (4.2-5.2)	M (6.5-7.1)	M (5.4-6.2)	M (6.5-7.1)
2.5	1.00	1.00	1.00	1.00	1.00	1.00
8.5	0.34	0.35	0.70	0.49	0.33	0.59
21	0.15	0.18	0.19	0.27	0.12	0.39
30	0.11	0.15	0.07	0.21	0.08	0.32
50	0.07	0.13	0.01	0.13	0.03	0.24

Table 2. Relative attenuation of AE_I as determined from the regression analysis of about 300 recordings worldwide, classified by magnitude (M) and soil type (S1, S2, S3)

	R(PGA)				R(PGV)		$R(AE_I)$	$R(AE_I)^{0.5}$
D_f(km)	Observ.	SP87	AMB96	ASI	Observ.	SP87	Observ.	Observ.
4.5	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
15	0.88	0.46	0.40	0.62	0.54	0.37	0.52	0.72
19	0.54	0.37	0.33	0.53	0.34	0.30	0.29	0.54
24	0.67	0.30	0.26	0.44	0.28	0.24	0.08	0.28
31.5	0.55	0.23	0.21	0.35	0.27	0.18	0.18	0.42

Table 3. Kobe (1995 event), soft soil (S3), relative attenuation, R, of PGA, PGV and AE_I. Comparison between observed and predicted values.

	R(PGA)				R(PGV)		$R(AE_I)$	$R(AE_I)^{0.5}$
D_f(km)	Observ.	SP87	AMB96	ASI	Observ.	SP87	Observ.	Observ.
1.0	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
27.5	0.18	0.21	0.15	0.36	0.18	0.14	0.13	0.36
34	0.35	0.17	0.13	0.30	0.25	0.11	0.12	0.35
106	0.17	0.06	0.05	0.10	0.17	0.04	0.05	0.23

Table 4. Kobe (1995 event), soil S2, relative attenuation, R, of PGA, PGV and AE_I. Comparison between observed and predicted values.

	R(PGA)				R(PGV)		$R(AE_I)$	$R(AE_I)^{0.5}$
D_f(km)	Observ.	SP87	AMB96	ASI	Observ.	SP87	Observ.	Observ.
19.0(*)	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
20.5	0.58	0.93	0.93	0.94	0.45	0.93	0.44	0.66
33	0.46	0.59	0.61	0.64	0.17	0.58	0.34	0.58
36	0.32	0.55	0.56	0.59	0.18	0.53	0.17	0.41

(*)The closest station is as far as 19 km, therefore these data are only indicative (far fault reference)
Table 5. Irpinia (1980 event), soil S2, relative attenuation, R, of PGA, PGV and AE_I. Comparison between observed and predicted values.

	R(PGA)				R(PGV)		$R(AE_I)$	$R(AE_I)^{0.5}$
D_f(km)	Observ.	SP87	AMB96	ASI	Observ.	SP87	Observ.	Observ.
0.2(*)	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
3.2	1.51	0.88	0.76	0.95	0.48	0.75	0.34	0.58
4.8	0.58	0.77	0.62	0.90	0.68	0.60	0.32	0.57
7.3	0.41	0.62	0.46	0.82	0.39	0.44	0.19	0.43
9.0	0.58	0.54	0.39	0.75	0.44	0.37	0.22	0.47
10.2	0.56	0.50	0.36	0.71	0.22	0.33	0.10	0.32

(*)The closest station is at 0.2 km from the surface projection of the source, therefore this is a good example of near fault reference.

Table 6. Imperial Valley (1979 event), soil S2, relative attenuation, R, of PGA, PGV and AE_I. Comparison between observed and predicted values.

the same law of relative attenuation. This is a clear example of the difficulty, which is intrinsic when using attenuation laws. The introduction of the parameter $(AE_I)^{0.5}$ allows a better comparison of the relative decay of destructive potential of earthquake ground motion than peak ground values (PGA and PGV). For the events herein illustrated, and considering the relative decay of PGA, the average values of the ratio Observed/Predicted are: 1.4 for SP87, 1.7 for AMB96, and about 1 for ASI. The ratio corresponding to PGV is about 1.3 for the SP87 relationship.

By considering the specific cases illustrated in Tables 3 to 6, it can be seen that the predictions of the relative attenuation of PGA and PGV are generally in disagreement with the observed values and between themselves. This aspect evidences the great uncertainties deriving from the existing attenuation functional forms relative to the adopted hazard parameter.

4. Deterministic seismic zoning, hazard assessment and damaging seismic energy

While waiting for the accumulation of new strong motion data, a very useful approach to perform immediate microzonation is the development and use of modeling tools. These tools are based, on one hand, on the theoretical knowledge of the physics of the seismic source and of wave propagation and, on the other hand, exploit the rich database, already available, that can be used for the definition of the source and structural properties. Actually, the realistic modeling of ground motion requires the simultaneous knowledge of the geotechnical, lithological, geophysical parameters and topography of the medium, on one side, and tectonic, historical, palaeoseismological, seismotectonic models, on the other, for the best possible definition of the probable seismic source. The initial stage for the realistic ground motion modeling is thus devoted to the collection of all available data concerning the shallow geology, and the construction of a three-dimensional structural model to be used in the numerical simulation of ground motion.

With these input data, we model the ground motion using two approaches based on the modal-summation technique (Panza, 1985; Panza and Suhadolc, 1987; Florsch et al., 1991; Panza et al., 2001). The hybrid technique (e.g. Fäh et al., 1993), which combines the modal-summation and the finite-difference scheme, and the mode-coupling analytical technique for laterally heterogeneous models (e.g. Vaccari et al., 1989; Romanelli et al., 1996; 1997; Panza et al., 2001).

To minimize the number of free parameters we account for source finiteness by properly weighting the double-couple point source spectrum using the scaling laws of Gusev (1983), as reported in Aki (1987). Even if this is a rough approximation of the physical source process, when a large earthquake is considered in the calculation of synthetic seismograms at distances of the same order of the fault dimensions, the adoption of a spectral scaling law ensures to obtain reliable spectral scenarios. The adoption of a spectral scaling law corresponds to averaging on the directivity function and on the regional variations due to different tectonic regimes. This limitation is therefore much less severe if spectral or PGA amplification is the main topic of interest instead of actual time-histories, and small- to medium-magnitude events are considered.

However, also kinematics models for a spatially extended source (e.g. Panza and Suhadolc, 1987) can be tackled by our approach. In such a case the generation of seismic waves due to an extended source is obtained by approximating the source with a rectangular plane surface corresponding to the fault plane on which the main rupture process is assumed to occur. Effects of directivity and of the energy release on the fault can be easily modelled, simulating the wide-band radiation process from a finite earthquake source/fault. The source is represented as a grid of point subsources, and their seismic moment rate time functions are generated considering each of them as realizations (sample functions) of a non-stationary random process. Specifying in a realistic way the source length and width, as well as the rupture velocity, one can obtain realistic far-field source time functions. Furthermore, assuming a realistic kinematic description of the rupture process, the stochastic structure of the accelerograms can be reproduced, including the general envelope shape and peak factors.

The methods have been applied, for the purpose of seismic microzoning, to several urban areas like Augusta (e.g. Panza et al., 2000b), Beijing (Sun et al., 1998), Benevento (e.g. Marrara and Suhadolc, 1998a), Bucharest (e.g. Moldoveanu et al., 2000), Catania (e.g. Romanelli and Vaccari, 1999), Mexico City (e.g. Fäh et al., 1994), Naples (e.g. Nunziata et al., 2000a,b), Rome (e.g. Fäh et al., 1993) and Thessaloniki (e.g. Marrara and Suhadolc, 1998b) in the framework of the UNESCO/IUGS/IGCP project "Realistic Modelling of Seismic Input for Megacities and Large Urban Areas" (Panza et al., 1999a). For urban areas where the realistic numerical modeling has been compared with recorded data (like Beijng, Benevento, Bucharest, Mexico City, Naples, Thessaloniki), the results of such comparison is fully satisfactory for engineering purposes and no data fitting is required. For events with magnitude in the range 6.5-7.1 and distances in the range 10-30 km, these pilot studies show that, distances from the causative fault, D_f, being equal, the elastic energy spectra computed from synthetic signals are comparable with those computed from real records (e.g. see Fig. 3)

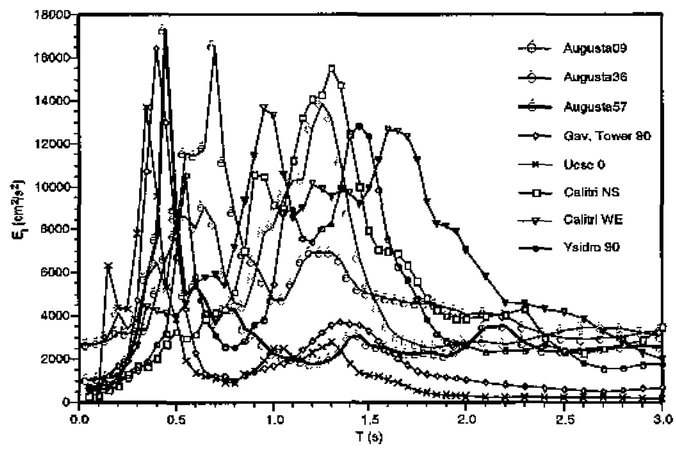

Fig. 3. Elastic energy E_I (cm^2/s^2) spectra. Comparison between Augusta synthetic signals and strong motion records of Irpinia 1980 (Calitri station) and Loma Prieta 1989 (Gav. Tower, Ucsc and Ysidro stations) earthquakes (from Decanini et al., 2001).

Thus, where recordings are absent or very limited, the synthetic time series can be reasonably used to estimate the expected ground motion, including ground velocity and displacement time series, before the next strong earthquake will occur. These time series can be readily used for the estimation of the damaging potential in energetic terms (Fig. 3).

4.1 Umbria-Marche (Central Italy) sequence

The Umbria-Marche earthquake sequence started on September 26, 1997 and took place in a complex deforming zone, along a normal fault system in the Central Apennines. The seismic sequence left significant ground effects, which were mainly concentrated in the Colfiorito intermountain basin.

The crustal events generated extensive ground motion and caused great damage in several urban areas. The extent of macroseismic data and the abundance of recorded ground motions permits a good knowledge of the source and structural parameters to better understand the nature of the ground shaking and the resulting damage patterns.

Predicting the intensity of shaking due to an earthquake before it occurs can prevent damage. Doing this rapidly after an earthquake can be useful for emergency rescue.

These objectives all belong to the overall objective of understanding and predicting the ground motion, therefore reducing the seismic risk.

Before the seismic sequence, started on September 1997, probabilistic (Fig 4) and deterministic maps were available for the Italian territory. The probabilistic map (Fig 4) indicates, for the Umbria-Marche region, peak ground accelerations (PGA) not exceeding 0.4g, for 475 years return period, and 0.24g, for 100 years return period (Corsanego et al. 1997). A first-order deterministic seismic zoning of Italy (Fig. 5), obtained by the application of the method developed by Costa et al. (1993) and its extensions (Panza et al., 1996) lead to theoretical peak values (Panza et al., 1996; 1997; 1999b) well in agreement with the representative EPA (effective peak acceleration) values observed ~ 0.3g. The EPA is defined as the average spectral acceleration in the period interval from 0.1 s to 0.5 s divided by 2.5, therefore it is equivalent to the DGA calculated by Panza et al. (1996) using design response spectra.

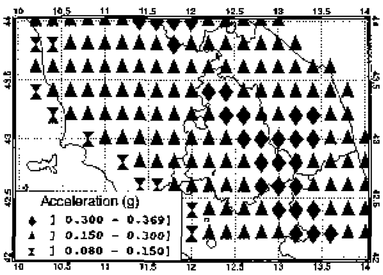

Fig. 4. Probabilistic estimation of maximum acceleration for 475 years return period (from Corsanego et al., 1997).

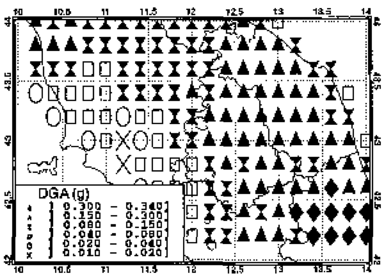

Fig. 5. Deterministic design ground acceleration focussed on the Umbria-Marche region (modified from Panza et al., 1996).

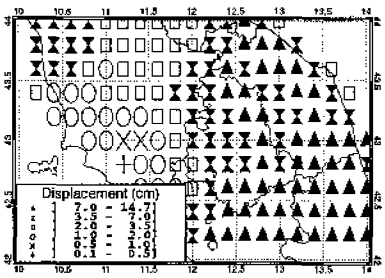

Fig. 6. Computed peak ground displacements, consistent with the acceleration values given in Fig. 5.

The information about ground displacement can be of great importance, but such information is difficult to be extracted from analog recordings, thus the available experimental database is very scarce. The realistic ground motion modelling we have developed represents an efficient way to minimize the problem arising from the lack of statistically significant observations about ground displacement. In fact, the good agreement obtained between modelled and observed acceleration and velocities makes it reasonable to use the modelled displacements (Fig. 6), as boundary conditions in the design.

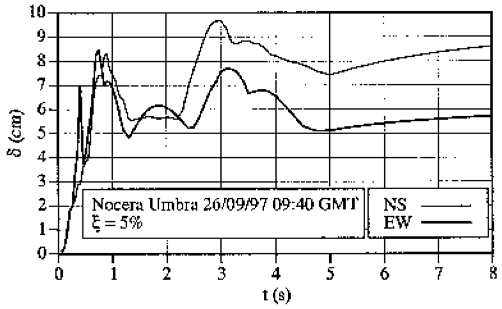

Fig.7. Displacement spectra of Nocera Umbra strong motion records (rock site). 5% damping. Event of September26, 1997, 09:40 GMT, $M_L = 5.8$, $M_W = 6.0$.

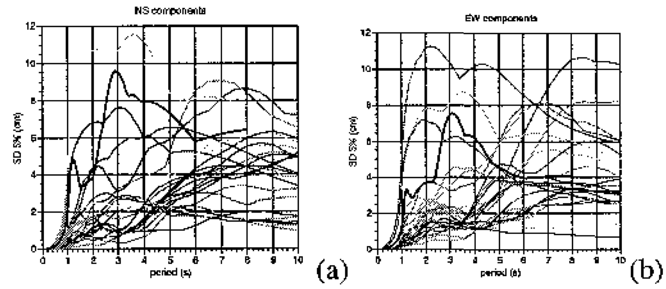

Fig. 8. a) Displacement response spectra (5% damping) computed at the grid point close to Nocera Umbra for 23 sources located in the surroundings at distances between 13 and 90 km. Thick black line corresponds to the spectrum of the signal, NS component of motion, recorded at Nocera Umbra (R1168), filtered at 1 Hz. b) Same as a) but for the EW component of motion.

The displacement response spectra (5% damping) of the observed signals are shown in Fig. 7 for the NS and EW components of motion recorded at Nocera Umbra during the main shock of the sequence. The same kind of response spectra, but obtained with the observed signals filtered with the cut-off frequency used in our modeling (1 Hz), are compared (Fig. 8) with the displacement response spectra obtained from all the synthetic signals computed in the grid point (43.2°N, 12.8°E), i.e. the grid point closer to Nocera Umbra. The predictive capabilities of our modeling, made in 1996, are quite evident and indicate that future events may generate even larger seismic input.

4.2 Bovec event of Easter 1998

For Bovec, Slovenia, event (12 April 1998) the only available strong motion records belong to the Rete Accelerometrica of Friuli Venezia Giulia (RAF) (minimum epicentral distance >30 km), therefore the only relevant comparison is with the epicentral macroseismic intensity, which has been observed equal to IX (MCS).

From the deterministic maps shown in Fig. 9 and considering the conversion tables between peak values of ground motion and macroseismic intensity (MCS), proposed by Panza et al. (1999), the epicentral macroseismic values observed, IX (MSC), are in perfect agreement with the values predicted by our modelling.

5. Conclusions

Case studies of seismic hazard assessment techniques indicate the limits of the currently used methodologies, deeply rooted in engineering practice, based prevalently on a probabilistic approach,

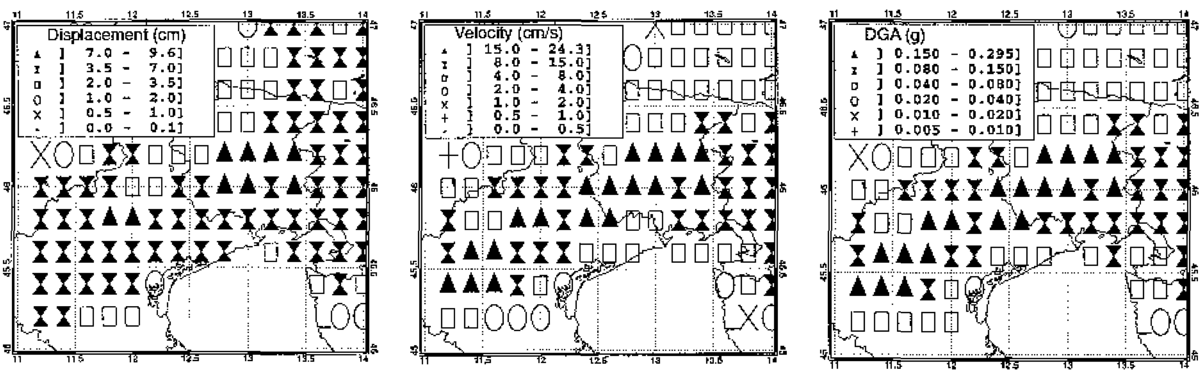

Fig. 9. Deterministic peak ground displacement, velocity and EPA=DGA, computed by Panza et al. (1996; 1997; 1999b).

and show that the related analyses are not sufficiently reliable to characterize seismic hazard. The probabilistic analysis of the seismic hazard is basically conditioned by the definition of the seismogenic zones. Within each of them the seismogenic process is assumed to be rather uniform, however the uncritical assumption of homogeneity can introduce severe errors in the estimate of the seismic hazard in a given site. Further shortcomings are connected with the choice of the other components needed for the calculation of the rate of probability of exceeding various levels of ground motion, over a specified period of time, i.e. the parameters characteristic of the damage potential of earthquake ground motion, and the attenuation relationships for the estimation of the ground motion at a site for a given earthquake.

The quantification of the critical ground motion expected at a particular site, requires the identification of the parameters that characterize the severity and the damage potential. Such critical ground motion can be identified in terms of energy and displacement demands which should be evaluated by considering the seismological, geological, and topographic factors that affect them.

In view of the limited seismological data, it seems more appropriate to resort to a scenario-based deterministic approach, as it allows us the realistic definition of hazard in scenario-like format to be accompanied by the determination of advanced hazard indicators as, for instance, damaging potential in terms of energy. Such a determination, due to the limitation of the number of strong motion records, requires to resort to broad band synthetic seismograms, that allow us to perform realistic waveform modelling for different seismotectonic environments, taking into account source properties (e.g. dimensions, directivity, duration, etc.), lateral heterogeneities, and path effects.

Each synthetic strong ground motion history, characterized as a function of its damage potential, constitutes a useful addition to the records database which increases our choices in selecting acceleration histories for various analyses. The growing database for near-field and soft soil strong motion signals (recorded and modelled), which can be considered as limit conditions, gives the opportunity to enhance the state of knowledge in damage potential evaluation.

The results we have reported are the outcome of a rather unusual but very fruitful close collaboration between seismologists and seismic engineers, that we consider a prerequisite for the achievement of a significant step forward in the future.

Appendix: Parameters used to describe the severity of an earthquake

A fundamental need for the definition of the seismic hazard of a given site or, in general, a region, is to select a parameter descriptive of the earthquake severity. A large number of parameters has been proposed for measuring the capacity of earthquakes to damage structures. However, recently observed damage distribution and strong motion acceleration records indicate the need for a more comprehensive definition of the existing parameters and for the introduction of new ones to account for the complex characteristics of earthquake induced strong ground motions in the engineering analysis and design. The adoption of inadequate parameters can lead to the definition of unrealistic design earthquakes and consequently to the unreliable evaluation of the seismic risk for the existing built environment, or to the insufficient protection of new one.

The parameters fundamentally involved in the evaluation of the level of severity associated with strong motion are, for engineering purposes, the frequency content, the amplitude and the effective duration. Because of the complexity of the earthquake ground motions, generally more than one parameter is required to describe the most important ground motion characteristics.

In general, these parameters can be obtained either directly or with some simple calculation from the digitized and corrected records, from the parametric integration of the equation of motion of elastic and inelastic single-degree-of-freedom (SDOF) systems, and considering the energy balance equation for elastic and inelastic systems. Application of the Duhamel (convolution) integral to a linear elastic SDOF system gives the expressions for the displacement response time history u(t) and allows to define a pseudo-velocity, $v(t)= \omega\, u(t)$, and a pseudo-acceleration, $a(t)= \omega^2\, u(t)$ (Clough & Penzien 1993, Chopra, 1995). They get their names from the fact that they have units of velocity and acceleration, respectively, but they are not equal to instantaneous velocity, and acceleration, respectively, of the system, since earthquake time histories are far from being purely harmonic motions. In terms of peak values, one can define the displacement, pseudo-velocity and pseudo-acceleration response spectra:

$$S_d(x,\omega)=|\,u\,|_{max}; \qquad S_d(x,\omega)=\frac{1}{\omega}S_{pv}(x,\omega); \qquad S_{pa}(x,\omega)=\omega S_{pv}(x,\omega)$$

where ω is the natural frequency (spectral variable) of the SDOF, u is the displacement, $S_d(\xi,\omega)$ is the spectral displacement $S_{pv}(\xi,\omega)$ is the pseudo-spectral velocity, and $S_{pa}(\xi,\omega)$ is the pseudo-spectral acceleration. Accordingly with the following equation, the pseudo-velocity $S_{pv}(\xi,\omega)$ can be related to the maximum energy stored in the SDOF during the earthquake ground motions:

$$E=\frac{kS_d^2(x,\omega)}{2}=\frac{k\,S_{pv}^2(x,\omega)/\omega^2}{2}=\frac{mS_{pv}^2(x,\omega)}{2}$$

where k and m are the stiffness and the mass of the SDOF systems. Note that a SDOF system of zero natural period (infinite natural frequency) would be rigid, and its spectral acceleration would be equal to the peak ground acceleration.

PGA, PGV, PGD, EPA and EPV

The most commonly used measure of amplitude of a particular ground motion is the peak ground acceleration, PGA, which corresponds to the largest value of acceleration obtained from the recorded accelerogram. As the inertia forces depend directly on acceleration, PGA is one of the parameters widely used to describe the intensity and damage potential of an earthquake at a given site. However, PGA is a poor indicator of damage, since it has been observed that time histories with the same PGA could be very different in frequency content, strong motion duration, and energy level, thus causing varying amounts of damage. In fact, PGA may be associated with high frequency pulses which do not produce significant damage to the buildings as most of the impulse is absorbed by the inertia of the structure with little deformation. On the other hand, a more moderate acceleration may be associated with a long-duration pulse of low-frequency (acceleration pulse) which gives rise to a significant deformation of the structure.

For example, after the 1971 Ancona earthquake (M_L = 4.7) a large PGA value (716 cm/s^2) was recorded at the Rocca station, located at a distance of about 7 km from the surface projection of the fault rupture. This high PGA value is associated to a short duration pulse of high frequency, as indicated in Fig. A1 where the acceleration time histories is shown, and generated a limited damage. A peak ground acceleration quite close (827 cm/s^2) to the above mentioned one, was recorded at the Sylmar station (Fig. A2), sited at about 2 km from the surface projection of the fault rupture, after the destructive 1994 Northridge earthquake (M_w=6.7). In this case, the peak ground acceleration is associated to a long duration pulse of low frequency. The moderate difference between these two PGA values seems to disagree with the large difference between the magnitude of the two seismic events. In other words, analyses of strong motion data have clearly shown that even small earthquakes can produce high accelerations and that these accelerations are not necessarily damaging.

The peak ground velocity PGV (shown in Fig. A3) is another useful parameter for the characterization of ground motion amplitude. Since the velocity is less sensitive to the higher-frequency components of the ground motion, the PGV, more likely than the PGA, should characterize the damaging potential of ground motion.

Peak ground displacement PGD is generally associated with the lower-frequency components of an earthquake ground motion. It is, however, difficult to determine accurately PGD, due to signal processing errors in the filtering and integration of accelerograms and due to long-period noise. The situation will certainly improve with the dissemination of good quality digital instruments.

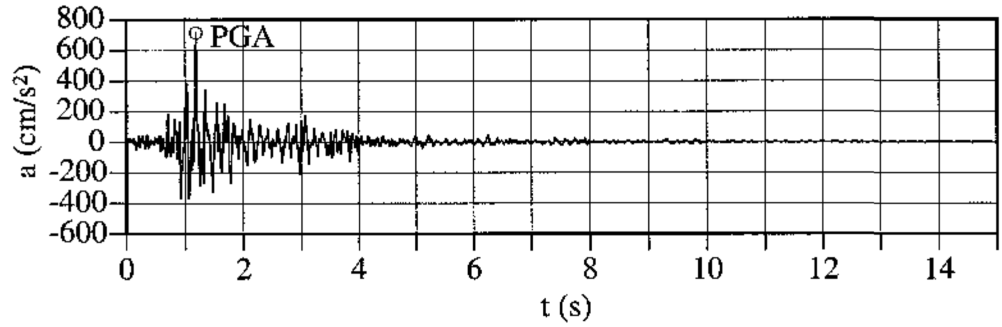

Fig. A1. 1971 Ancona earthquake (M_L=4.7); acceleration time history: Rocca NS record.

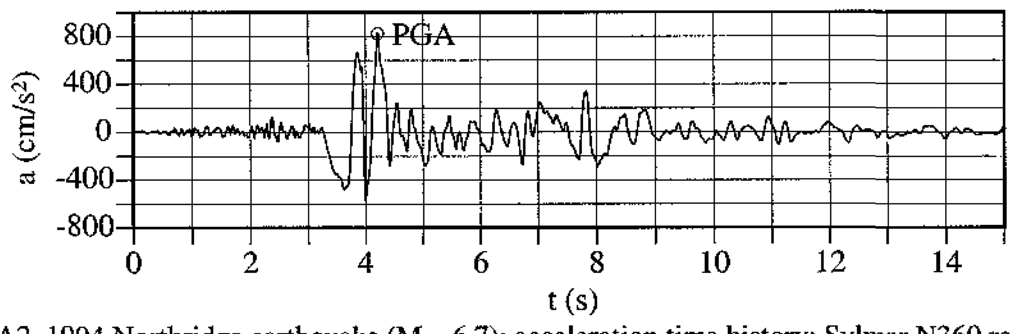

Fig. A2. 1994 Northridge earthquake (M_w=6.7); acceleration time history: Sylmar N360 record.

From the point of view of damage potential, the area under the largest acceleration pulse, which represents the incremental velocity (IV), makes many earthquake strong motion records particularly damaging. As indicated in Fig.A3, the maximum incremental velocity represents the distance between two consecutive peaks. The larger the change in velocity, the larger the acceleration pulse. In the case of the Takatori record obtained after the 1995 Kobe earthquake (Fig.A3), the PGV is equal to 127 cm/s, while the IV is equal to 227 cm/s).

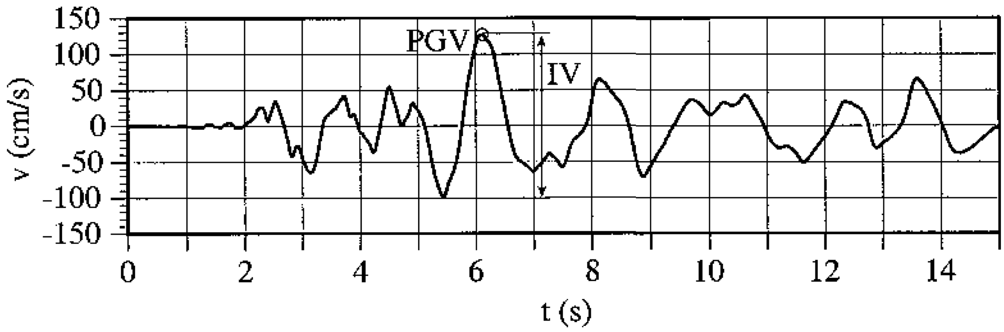

Fig. A3 – Velocity time history. Takatori 000 record. 1995 Kobe earthquake (M_w=6.9)

Realizing the limitation of using peak instrumental values, since damage cannot be related only to the peak values, but may require the occurrence of several repeated cycles, Applied Technology Council (1978) ATC introduced the concept of effective peak acceleration, EPA. The effective peak acceleration EPA is defined as the average spectral acceleration over the period range 0.1 to 0.5 s divided by 2.5 (the standard amplification factor for a 5% damping spectrum), as follows:

$$EPA = \frac{\overline{S}_{pa}}{2.5}$$

where $\overline{S}_{pa}$ is the mean pseudo-acceleration value. The empirical constant 2.5 is essentially an amplification factor of the response spectrum obtained from real peak value records. Thus EPA is correlated with the real peak value, but not equal to nor even proportional to it. If the ground motion consists of high frequency components, EPA obviously will be smaller than the real peak value. It represents the acceleration which is most closely related to the structural response and to the damage potential of an earthquake. The EPA values for the two records of Ancona and Sylmar stations are 205 cm/s^2 and 774 cm/s^2 respectively, and describe in a more appropriate way, than PGA values, the damage caused by the two earthquakes.

The effective peak velocity EPV is defined as the average spectral velocity at a period of 1 s divided by 2.5. The process of averaging the spectral accelerations and velocities over a range of periods minimizes the influence on the EPA and EPV of local spikes in the response spectrum. EPA and EPV can be thought of as normalizing factors for the development of smooth response spectra. Although effective peak acceleration is a conceptually sound parameter for the damage potential characterization of earthquake ground motion, at present there is no clear and standardized definition of this parameter.

Other ground motion parameters

Several observations derived from analyses of strong motion records of recent earthquakes indicate the considerable influence of the duration on the cumulative damage of the structures. For example, time histories with high amplitudes but short duration can be associated to moderate damages compared to ground motion with lowest amplitude but with longest duration. Moreover, it is

well known that the major drawback in the use of elastic response spectra, S_{pa}, is the neglecting of the duration. Different approaches have been followed for the problem of evaluating the duration of strong motion in an accelerogram. The bracketed duration (Bolt, 1973) is defined as the time between the first and the last exceedances of a threshold acceleration (usually 0.05g). Among the different duration definitions that can be found in the literature, one commonly used is that proposed by Trifunac and Brady (1975), $t_D = t_{0.95} - t_{0.05}$, where $t_{0.05}$ and $t_{0.95}$ are the time at which respectively the 5% and 95%, of the time integral of the history of squared accelerations are reached, which corresponds to the time interval between the points at which 5% and 95% of the total energy has been recorded.
The Arias Intensity (Arias, 1969), I_A, is defined as:

$$I_A = \frac{p}{2g}\int_0^{t_t} a_g^2(t)dt,$$

where t_t and a_g are the total duration and ground acceleration of a ground motion record, respectively. The Arias intensity has units of velocity. I_A represents the sum of the total energies, per unit mass, stored, at the end of the earthquake ground motion, in a population of undamped linear oscillators. Arias Intensity, which is a measure of the global energy transmitted to an elastic system, tends to overestimate the intensity of an earthquake with long duration, high acceleration and broad band frequency content. Since it is obtained by integration over the entire duration rather than over the duration of strong motion, its value is independent of the method used to define the duration of strong motion.

Housner (1952) defined a measure expressing the relative severity of earthquakes in terms of the area under the pseudo-velocity spectrum between 0.1 and 2.5 seconds. Housner's spectral intensity I_H is defined as:

$$I_H = \int_{0.1}^{2.5} S_{pv}(T,\xi)dT = \frac{1}{2\pi}\int_{0.1}^{2.5} S_{pa}(T,\xi)TdT,$$

where S_{pv} is the pseudo-velocity at the undamped natural period T and damping ratio ξ, and S_{pa} is the pseudo-acceleration at the undamped natural period T and damping ratio ξ. Thus, Housner's spectral intensity is the first moment of the area of S_{pa} $(0.1<T<2.5)$ about the S_{pa} axis, implying that the Housner spectral intensity is larger for ground motions with a significant amount of low frequency content. The I_H parameter captures important aspects of the amplitude and frequency content in a single parameter, however, it does not provide information on the strong motion duration which is important for a structural system experiencing inelastic behaviour and yielding reversals. Housner (1956) also gave a definition of the maximum input energy of an elastic SDOF system on the basis of the pseudo-velocity spectrum S_{pv}. In fact, the pseudo-velocity spectrum S_{pv} reflects the energy demand of an elastic SDOF system as follows:

$$E_v = \frac{1}{2}m(S_{pv})^2$$

This parameter can be utilized for the estimation of earthquake damage potential from an energy perspective. The pseudo-velocity spectrum constitutes approximately the lower bound of the hysteretic energy spectrum adjusted in terms of equivalent velocity (Decanini & Mollaioli 1998, Uang & Bertero, 1988).

Araya & Saragoni (1984) proposed the destructiveness potential factor, P_D, that considers both the Arias Intensity and the rate of zero crossings, v_0 and agrees with the observed damage better than other parameters. The destructiveness potential factor, which simultaneously considers the effect of the ground motion amplitude, strong motion duration, and frequency content on the relative destructiveness of different ground motion records, is defined as:

$$P_D = \frac{\pi}{2g}\frac{\int_0^{t_0} a_g^2(t)dt}{\nu_0^2} = \frac{I_A}{\nu_0^2} \qquad \nu_0 = \frac{N_0}{t_0}$$

where t is the time, a_g is the ground acceleration, $\nu_0 = N_0/t_0$ is the number of zero crossings of the acceleration time history per unit of time (Fig. A4), N_0 is the number of the crossings with the time axis, t_0 is the total duration of the examined record (sometimes it could be a particular time-window), and I_A is the Arias intensity.

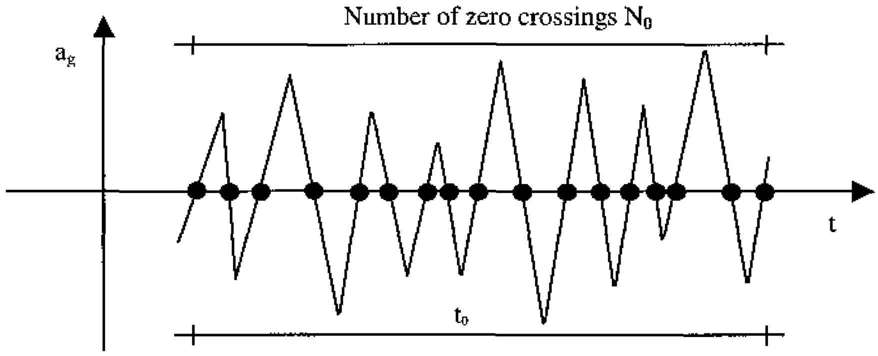

Fig. A4. Evaluation of the parameter ν_0.

The amplitudes of ground motion acceleration and strong motion duration are incorporated in the Arias intensity, while ν_0 [sec-1] results an average index of the frequency content of the time history. Araya and Saragoni (1984) and Saragoni et al. (1989) have shown that the horizontal earthquake destructiveness potential factor PDH (sum of the PD values corresponding to the two horizontal components, PDH=PDx+PDy) correlates well with the Modified Mercalli macroseismic Intensity I_{MM} values. However, it is possible that two different time histories have similar destructiveness potential factors but very different values of the zero crossings rate and Arias intensity. A time history with a small zero-crossing rate would cause less damage to short period structures than a time history with a larger zero-crossing rate close to the fundamental period of the structures, although both time histories have the same destructiveness potential factor.

In designing structures to perform satisfactorily under earthquake excitations the concept of response spectrum was introduced as a practical mean of characterizing ground motions and their effects on structures. The response spectrum, a concept that has been recognized for many years in the literature (e.g., Newmark & Hall, 1982), describes the maximum response of a SDOF system to a particular input motion as a function of its natural frequency (or period) and damping ratio. The response may be expressed in terms of acceleration, velocity, or displacement. The importance of the response spectra in earthquake engineering has led to the development of methods for predicting them directly as a function of soil conditions, magnitude and source-to-site conditions. Response spectra are often used to represent seismic loading in terms of design spectra, which are the result of the smoothing, averaging or enveloping of the response spectra of multiple motions.

Although the response spectrum provides the basis for the specification of design ground motions in all current design guidelines and code provisions, there is a growing recognition that the response spectrum alone does not provide an adequate characterization of the earthquake ground motion. In order to give a major conceptual improvement, methods using ground motion spectra based on EPA and EPV have been suggested.

Energy based parameters

Linear elastic response spectra or linear elastic design response spectra recommended by seismic codes have been proved to be inadequate by recent seismic events, as they are not directly related to structural damage. Extremely important factors such as the duration of the strong ground motion and the sequence of acceleration pulses are not taken into account adequately. Therefore response parameters based on the inelastic behaviour of a structure should be considered with the ground motion characteristics.

In current seismic regulations, the displacement ductility ratio μ is generally used to reduce the elastic design forces to a level which implicitly considers the possibility that a certain degree of inelastic deformations could occur. To this purpose, employing numerical methods, constant ductility response spectra were derived through non-linear dynamic analyses of viscously damped SDOF systems by defining the following two parameters:

$$C_y = \frac{R_y}{mg}$$

$$\eta = \frac{R_y}{m\ddot{u}_{g(max)}} = \frac{C_y}{\ddot{u}_{g(max)}/g}$$

where R_y is the yielding resistance, m is the mass of the system, and $\ddot{u}_{g(max)}$ is the maximum ground acceleration. The parameter C_y represents the structure's yielding seismic resistance coefficient and η expresses a system's yield strength relative to the maximum inertia force of an infinitely rigid system and reveals the strength of the system as a fraction of its weight relative to the peak ground acceleration expressed as a fraction of gravity. Traditionally, displacement ductility was used as the main parameter to measure the degree of damage sustained by a structure.

One significant disadvantage of seismic resistance (C_y) spectra is that the effect of strong motion duration is not considered. An example of constant ductility C_y spectra, corresponding to the 1986 San Salvador earthquake (CIG record) and 1985 Chile earthquake (Llolleo record) is reported in Fig. A5 a,b, respectively. By comparing these spectra it seems that the damage potential of these ground motions is quite similar, even though the CIG and Llolleo are records of two earthquakes with very different magnitude, 5.4 and 7.8, respectively.

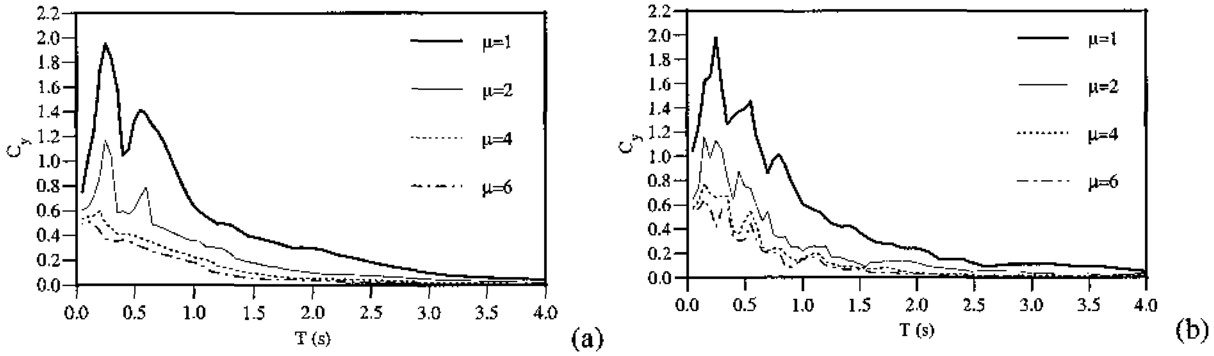

Fig. A5. Comparison between constant ductility C_y spectra. (a) 1986 San Salvador earthquake (CIG record); 1985 Chile earthquake (Llolleo record)

In other words, the elastic and inelastic (in terms of displacement ductility) response spectra are not sufficient for the estimation of the damage potential of the earthquake ground motion because they do not give a precise description of the quantity of the energy that will be dissipated through hysteretic behaviour; in the inelastic case they give only the value of the maximum ductility requirement. To overcome this problem other ductility definitions, e.g. hysteretic or cyclic ductility, were introduced.

However, in this context, the introduction of appropriate parameters defined in terms of energy can lead to more reliable estimates, since, more than others, the concept of energy provides tools which allow to account rationally for the mechanisms of generation, transmission and destructiveness of seismic actions. Moreover, energy-based parameters could provide more insight into the ultimate cyclic seismic performance than traditional design methods do, and could be considered as effective tools for a comprehensive interpretation of the behaviour observed during recent destructive events. In fact, energy-based parameters, allowing us to characterize properly the different types of time histories (impulsive, periodic with long durations pulses, etc.) which may correspond to an earthquake, could provide more insight into the seismic performance.

Among all the different parameters proposed for defining the damage potential, perhaps the most promising is the Earthquake Input Energy (E_I) and associate parameters (the damping energy E_ξ and the plastic hysteretic energy E_H) introduced by Uang & Bertero (1990). This parameter considers the inelastic behavior of a structural system and depends on the dynamic features of both the strong motion and the structure. The formulation of the energy parameters derives from the following balance energy equation (Uang & Bertero, 1990), $E_I = E_k + E_\xi + E_s + E_H$, where ($E_I$) is the input energy, ($E_k$) is the kinetic energy, (E_ξ) is the damping energy, (E_s) is the elastic strain energy, and (E_H) is the hysteretic energy.

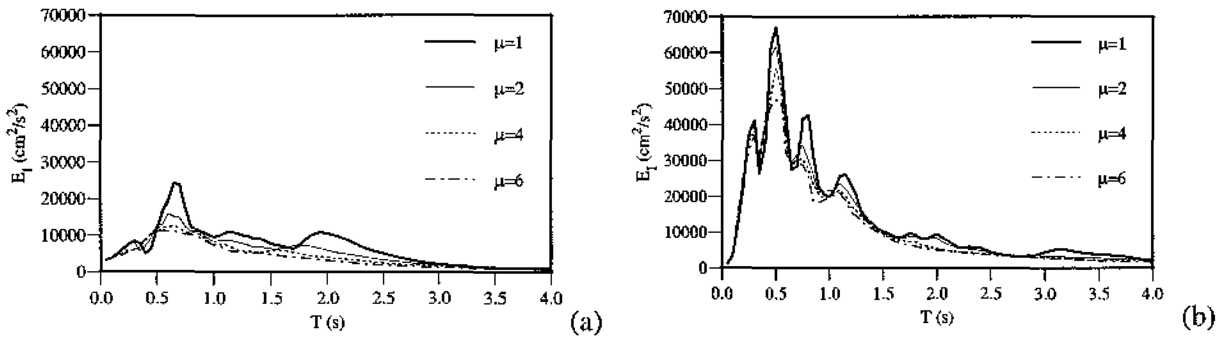

Fig. A6 – Comparison between constant ductility input energy E_I spectra. (a) 1986 San Salvador earthquake (CIG record); 1985 Chile earthquake (Llolleo record)

The absolute input energy, according to the definition of Uang & Bertero (1990), which seems suitable for the estimation of the energy terms in the range of periods of interest for the majority of structures, has the advantage to point to the physical input energy. In fact, E_I represents the work done by the total base shear at the foundation displacement. The input energy can be expressed by:

$$\frac{E_I}{m} = \int \ddot{u}_t du_g = \int \ddot{u}_t \dot{u}_g dt$$

where m is the mass, $u_t = u + u_g$ is the absolute displacement of the mass, and u_g is the earthquake ground displacement. Usually the input energy per unit mass, i.e. E_I/m, is simply denoted as E_I.

Re-examining the comparison of the damage potential of the CIG and Llolleo records in terms of input energy (Fig. A6), a completely different picture is obtained. In fact, the E_I of the Llolleo record is considerably higher than that of the CIG record, both in the elastic and inelastic cases.

A similar picture is obtained using another energy-based parameter, recently introduced (Decanini et al., 1994, Decanini & Mollaioli 1998) and denoted as *seismic hazard energy factor*, AE_I, which represents the area enclosed by the elastic input energy spectrum according to different intervals of periods:

$$AE_I = \int_{T_1}^{T_2} E_I(\xi = 5\%, T)\,dT$$

In their procedure for the evaluation of the design earthquake Decanini and Mollaioli (1998) consider the interval of periods between T_1=0.05 and T_2=4.0 seconds.

The advantage of using AE_I derives from the fact that, unlike the peak energy spectral value, which generally corresponds to a narrow band of frequencies, it takes into account the global energy structural response amount, and therefore it is the most stable parameter in energetic analysis. AE_I can be seen as the energy version of the Housner Intensity I_H, with the difference that the pseudo-velocity spectrum constitutes the lower bound of the input energy spectrum (Uang & Bertero, 1988), as illustrated in Fig. A7.

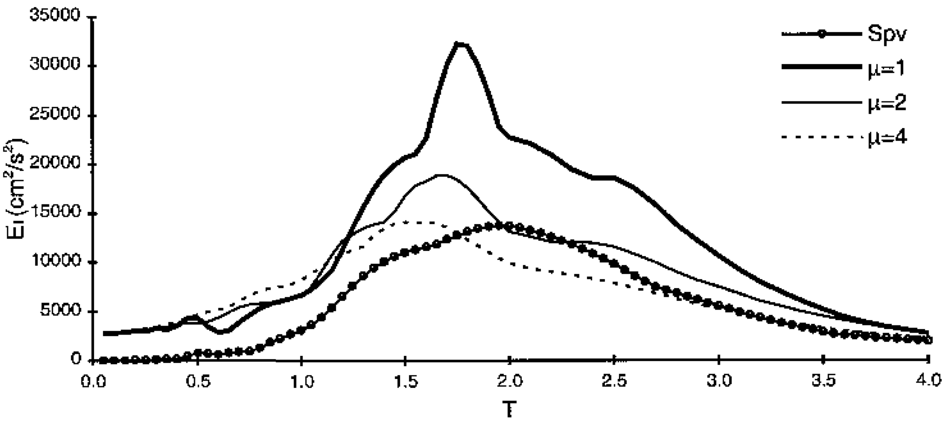

Fig. A7 – Comparison between input energy E_I and pseudo-velocity S_{pv} spectra. 1977 Bucarest earthquake

In conclusion, for a reliable estimation of the destructiveness potential of earthquake ground motions it seems appropriate to perform a comparison of their input and hysteretic energy spectra and associated seismic hazard energy factors, also taking into account the influence of the factors that may be considered external to the structural systems (magnitude, local soil conditions, source-to-site distance, etc.).

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