PART I: EARTHQUAKE HAZARD AND STRONG MOTION

CHAPTER 3

OBSERVATION, CHARACTERIZATION AND PREDICTION OF STRONG GROUND MOTION

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3.1. Introduction

A seismic risk mitigation strategy has two main technical legs: to construct performing buildings and other structures using an aseismic design and to prepare emergency plans using realistic seismic scenarios. Both technical actions need a precise definition of the seismic action of potentially damaging earthquakes by means of measurable parameters related to shear stresses and strains affecting structures, which are ground motion acceleration and displacement.

An important challenge for seismic risk mitigation is thus to develop methodologies for seismic hazard analysis, and to assess vulnerability of structures and cost functions in terms of ground motion parameters.

In recent decades much progress was made in the study of strong ground motion produced by earthquakes and its application to earthquake engineering. New data and analysis have given us more and more accurate and reliable empirical estimations of strong ground motion for future earthquakes. In parallel, the development of theoretical methods led to the proposition of new explanatory models of the seismic strong ground motions.

In this chapter, after remarking on new advances in instrumentation and its capacity to measure and disseminate strong ground motion data, we describe the main parameters and factors useful in characterizing ground motion. The main components of these more useful predictive methods of ground motion for future earthquakes are analysed. Finally, different formal aspects concerning the definition of seismic actions from the predicted strong ground motion are discussed.

3.2. Strong ground motion measurements

3.2.1. INSTRUMENTATION AND MAJOR NETWORKS

The development of instrumentation with digital recording, in the 1980's, allowed a considerable improvement in the quality of accelerograms and therefore a greater reliability in their interpretation. Let us mention some of the most important improvements:

- Quality of the record, when suppressing the manipulations of the old analogue records (photographic process, digitisation, filtering processes, etc.).
- Activation of the detection system for small ground motions (< 0.01 g), with the consequent availability of a greater number of records.
- Great dynamic range, increasing the resolution for small ground motions.

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- Greater reliability in the lower frequency content of the record when eliminating possible drifts in the record system that, in the old analogue instruments, was necessary to correct by numerical methods.
- Greater reliability in the content of high frequencies provided by the new force-balance sensors.

This situation has been further improved in recent years with the appearance of converters A/D of 24 bits, with which the dynamic range has extended enormously, allowing the recording not only of strong motions, but also of weak motions, until now the dominion of seismographs; thus for example it is possible to record ground motions of 10^{-6} or 10^{-7}g for accelerographs whose maximum scale is 1g. Actually, the resolution in many cases is determined by the background noise of the site.

3.2.1.1. *Major Networks of accelerometers*

In the last few years dense networks of accelerometers have been implemented. This has been possible thanks to advances in telecommunications that allow us to centralize the data in real time.

A clear example can be found in the Kyishin Net (K-net) network in Japan (Kinoshita, 2003) with about 1000 homogenous instruments (see Figure 3.1). It was created after the earthquake of Kobe of 1995, with some basic characteristics:

- Systematic observation of the ground motion.
- Uniform distribution of the stations (with a stations spacing of about 25 km).
- Dissemination of the data via Internet in few days after the event occurrence.
- Information on the soil column at each station's site, obtained by means of down-hole measurement, to provide the users with a useful tool for interpreting soil effects.

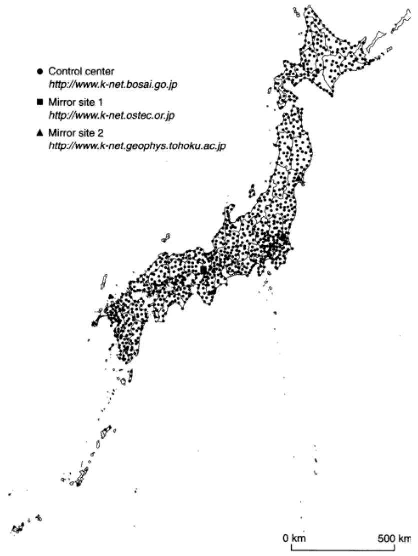

Fig. 3.1. Locations of the K-net network in Japan (Kinoshita, 2003)

Another region dense with instrumentation is Taiwan where several networks of accelerometers have been installed with different purposes: study of rupture process of seismic faults, evaluation of soil-structure interaction, rapid earthquake information, and monitoring buildings and bridges.

In Figure 3.2 we can see the distribution of the 640 free-field accelerometers (as of the end of 2000) belonging to the Central Weather Bureau (CWB), the official centre in charge of monitoring earthquakes in Taiwan (Shing et al., 2003). CWB also has 56 instruments in buildings and bridges. In order to produce an early warning after the occurrence of an earthquake, CWB has 80 instruments that continuously transmit data, via telephone, to the CWB headquarters. For the analysis of rupture process, dense arrays of accelerometers have been implemented. This is the case of SMART-1 that was created in the 1980's with 43 accelerographs installed in three concentric circles of radii 200 m, 1 km and 2 km, respectively, of radio and SMART-2, settled in the 1990's.

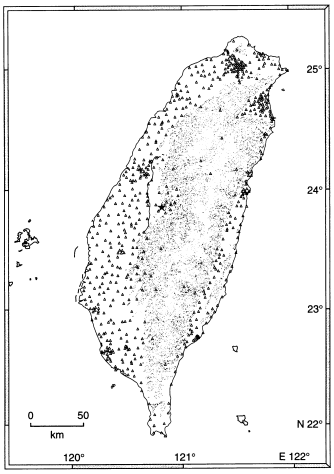

Fig. 3.2. Distribution of the 640 free-field accelerometers of the CWB (Shing et al., 2003)

In U.S.A. the California Strong Motion Instrumentation Program (CSMIP) was established in 1972 by California Legislation to obtain valuable earthquake data for the engineering and scientific communities through a state-wide network of strong motion instruments. The program has installed more than 900 stations, including 650 ground-response stations, 170 buildings, 20 dams and 60 bridges.

In 1997, a joint project, TriNet, between the CSMIP, Caltech and USGS at Pasadena was funded by the Federal Emergency Management Agency through the California Office of Emergency Services. The goals of the project are to record and rapidly communicate ground shaking information in southern California, and to analyse the data for the improvement of seismic codes and standards (Hauksson et al., 2003).

In 2001, the California Office of Emergency Services started to improve the California Integrated Seismic Network (CISN), a state-wide system that includes the TriNet system. Five organizations have collaborated to form the CISN in order to further the goals of earthquake monitoring. The founding members of the CISN include: California Geological Survey Caltech Seismological Laboratory, Berkeley Seismological Laboratory, USGS Menlo Park, and the USGS Pasadena. The California Governor's Office of Emergency Services is an ex-officio participant in the CISN.

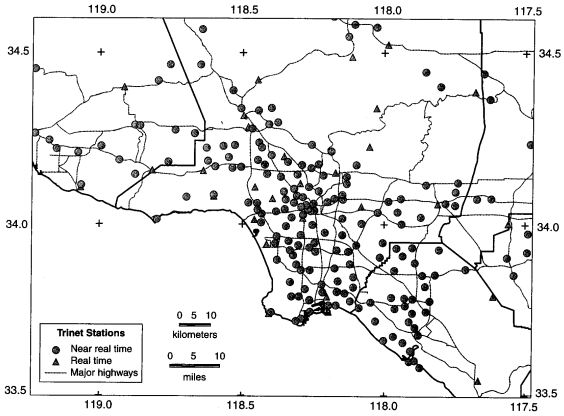

Fig. 3.3. TriNet strong-motion and broadband stations in the greater Los Angeles area. (Hauksson et al., 2003)

3.2.1.2. *Broad Band seismographic stations.*

The improvements of the accelerometers also have been accompanied by the appearance of Broad-Band seismographs (velocity sensors), that allow with a great resolution the record of very low frequencies (<0.05 Hz), completing therefore the records of acceleration for weak motions and long periods, useful for structures sensible to such periods, and for the definition of seismological parameters (Hauskov and Alguacil, 2004).

3.2.2. ANALYSIS OF STRONG MOTION RECORDS

Until the 1980's strong ground motion databases contained accelerograms obtained from analogue records corresponding to earthquakes that occurred in California and some countries of the Mediterranean area.

For many years, these data were the base of the development of empirical methods of determination of the seismic actions that still today are used in the building regulations in many countries.

However, to some extent, all these data suffered from some common problems:

- Due to the high values of activation of the recording system (PGA=0.01g) only records of the strongest ground motions were obtained and, consequently, the resulting datasets are biased because of the lack of records of weak and moderate acceleration ground motions.
- Very often, only one part of the accelerogram was recorded, because the system was activated only by the more energetic part of the signal (S or surface waves).

- The process of digitisation of the signal gave rise to significant distortions of the frequency content. In the low frequencies, due to the problems associated to the base line shift, a high pass filter was necessary, resulting in either excessive cuts of important information, or insufficient cuts, resulting in an over-estimation of the content in low frequencies, which is mainly seen in the displacement time histories obtained by a double integration.
- Due to the fact that the natural frequencies of the accelerometers used to be 25 Hz or even lower, the content in high frequencies was difficult to be reliably estimated because of its dependence on the recovery process and the signal sampling frequency.

From the end of the 1980’s databases have become richer with much data of greater quality, coming from a much larger number of digital instruments of the new networks. Let us mention some examples of earthquakes that produced a huge quantity of records: Loma Prieta (California), 1989, of M=6.9; Landers (Californian), 1992, of M=7.3; Northridge (California), 1994, of M=6.7; Kobe (Japan), 1995, of M=6.9; Chi-chi (Taiwan), 1999 of Mw=7.6; Kocaeli (Turkey), 1999 of Mw=7.4; Bam (Iran), 2003 of Mw=6.8. On the contrary it is important to notice the fact that, even recently, some damaging earthquakes occurred in regions that still have a poor coverage of accelerographs as, for example, Dominican Republic, September 2003, of Mw=6.5 or Al Hoceima (Morroco), February 2004 of Mw=6.5.

The extensive amount of data obtained in all of these events has shown a great variability of the recorded ground motion. These data have contributed, as it will be seen later, to the knowledge of the different factors that take part in the resulting characteristics of earthquake ground motion, mainly:

- The complexity of the time and space distributions of the rupture in the fault plane.
- The irregularities in the rupture that give rise to records of acceleration incoherent in time and with high variability in the values of peak ground acceleration.
- The phenomena of directivity and flying, amplifying the ground motion (lower frequency band) in the direction of the propagation of the rupture.
- The local effects, amplification of the ground motion for different frequencies, depending on the geologic and topographic characteristics of the recording site.

3.2.3. DATA FROM MODERATE EARTHQUAKES

The new instrumentation and the increase of the number of installed instruments allowed to obtain earthquake records of moderate magnitude, between 5.0 and 6.0, with non-negligible damaging capacity; moreover, weak ground motions that until a few years ago were not recorded, because they lay below the resolution of the old accelerometers and over the values of saturation of the seismographs, are now available.

Let us mention, as an example, some of the earthquakes of moderate magnitude recently recorded in the Mediterranean zone, some of them in areas in which accelerograms were not available until now.

- The series of Adra (Spain), with two earthquakes of mb=5.0, occurred on 23-12-1993 and the 4-01-1994 in strike-slip faults, with normal component. They produced moderate damages (I=VI-VII) in the epicentral region. Records were obtained, with maximum values of acceleration of 0.025 g and 0.03 g in Adra for the first and the second event, located at 6 km and 30 km, respectively from this town (Martín et al., 1996).
- The earthquake of Eastern French Pyrenees of M_L=5.0, occurred on 18-02-1996 in a strike-slip fault, with some vertical component. It produced weak damages in the region of San Pau de Fenollet (I=VI). A record of peak ground acceleration of 0.04 g was obtained within 8 km of the epicentre and maximum values of 0.004 g and 0.002 g at 70 km of distance (ICC, 1997).
- The earthquake of Konitsa (Greece) of the 5-08-1996, of M=5.6 was recorded at 15 km from the epicentre with a value of maximum acceleration of 0.4 g in the low part of the city of Konitsa (on soft soil), and of 0.17 g in the high part (on rock). These acceleration values agree with the observed larger damages in the low part of the city (Papaioannou et al., 1997).
- The series of earthquakes of Umbria-Marche in Italy, with two earthquakes of magnitudes 5.6 and 5.8, occurring within a 9 hours interval from the 26-09-1997. They caused significant damages (I>VIII) mainly throughout a NW direction, which corresponds to the direction of propagation of the two ruptures (in opposite senses), with mechanisms of normal fault. In the epicentral zone, values of 0.3 g in a lacustrine zone (Colfiorito) and of 0.5 g in the direction of the rupture (in Nocera-Umbra), at about 20 km of the epicentre were recorded (ENEL, 1998).
- The earthquake of Mula (Spain) occurred on 2-02-1999 with a magnitude of 5.0. It caused moderate damages (I=VII) in the epicentral area, near Mula. Records of acceleration in several localities were obtained, with a value of 0.012 g at a distance of 20 km of the epicentre (IGN, 1999b).
- The Nice (France) earthquake of magnitude 4.7 in February 2001, produced accelerograms with maximum values of 0.04 g at about 30 km from the epicentre, which was located offshore. Some records were obtained at up to 300 km of distance (RAP, www-rap.obs.ujf-grenoble.fr).
- The earthquake in central Pyrenees 16-05-2002 with a magnitude of 4.7 produced records of a maximum value of 0.045 g at an epicentral distance around 12 km. Damages corresponding to intensity VII-VIII in the epicentral area were reported (RAP, www-rap.obs.ujf-grenoble.fr).

The analysis of this new set of observations allows us to point out the following:

- For the earthquakes of the Western Mediterranean region, Adra, 1993-1994; Eastern French Pyrenees, 1996; Mula, 1999; Nice, 2001 and Central Pyrenees, 2002 weak acceleration values rather lower than 0.05 g, have been observed. As it can be seen in Figure 3.4, the recorded values are lower than those obtained by average curves of attenuation proposed by Sabetta and Pugliese (1996), Ambraseys et al. (1996) or Sadigh et al. (1997).

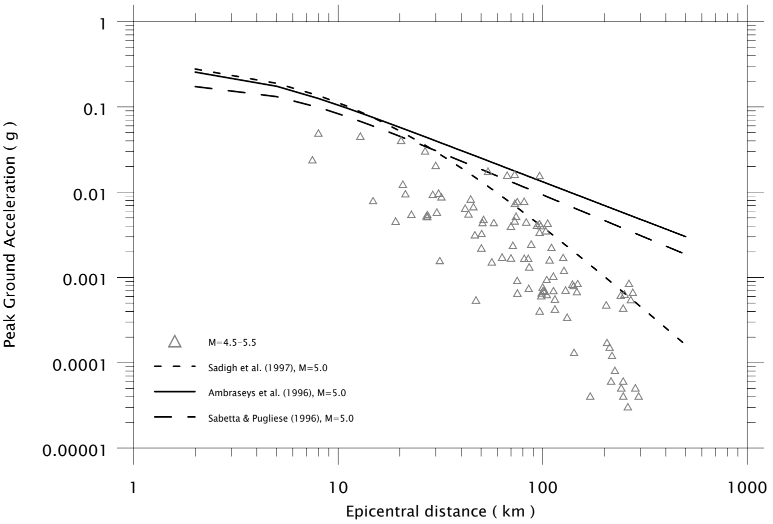

Fig. 3.4. Peak ground acceleration recorded from recent western Mediterranean earthquakes compared to some average curves proposed by different authors (Tapia, personal communication)

- For the earthquakes of the Central and Eastern parts of the Mediterranean region, significant values of acceleration (0.4g) have been observed, as was the case of the city of Konitsa (Greece); these large acceleration values are associated with soil amplification. For the earthquakes of Umbria-Marche, recorded values of 0.3 g and 0.5 g in Nocera-Umbra seem to be related to effects of local amplification and also to the directivity effects.

Therefore, the differences seen between the attenuation behaviour in the two regions for moderate (between 5 and 6) magnitude events are probably related to the particularities of the tectonic characteristics of the two regions. Increasing the recordings in the future and detailed analysis of the data will yield a better interpretation of these observations (Tapia et al., 2005).

Sections 3.3 and 3.4 present a more detailed description concerning the variables that affect the characteristics of the seismic ground motion. An overview of the models currently used for predicting ground motion will also be given.

3.2.4. DISSEMINATION OF STRONG GROUND MOTION DATA

Until the 1980's the necessary data for the study and prediction of seismic actions were only available through a few national and international agencies that some times did not made their data easily available to the public. The more known strong motion databases were those of the National Geophysical Data Center (NOAA, USA) and the European database (ENEA/ENEL, CEA, Imperial College).

In the last few years, the possibility of data storage in supports of great capacity (CD-ROM; DVD-ROM), the advances in communications (Internet) and the protocols of dissemination of the data (FTP, autodrm, etc.) have made possible an easy access of these data.

In USA, the Consortium of Organizations for Strong-Motion Observation Systems (COSMOS) Virtual Data Center www.db.cosmos-eq.org is a portal to other servers where the data is stored and maintained, usually by the owner of the data. Several International contributing members are associated to this virtual data centre. Data can easily be downloaded.

In Japan, different agencies belonging to essential infrastructures, as for example Ports and Airports (PARI, 2003) are providing strong motion data.

In Europe, several networks produced collections of their own records; an example of these facilities is the CD-ROM published by the IGN (IGN, 1999a) with accelerograms recorded in Spain between 1984 and 1997 or the availability of the French Accelerographic Network (RAP, www-rap.obs.ujf-grenoble.fr) data on the Internet. The European Strong-Motion Database www.isesd.cv.ic.ac.uk provides an interactive, fully relational database and databank with more than 3,000 uniformly processed and formatted European strong-motion records and associated earthquake, station and waveform-parameters. The user can search the database and databank interactively and download selected strong-motion records and associated parameters. Information about European organizations involved in strong-motion recordings is also available.

3.3. Explanatory variables of ground motion

The parameters or variables that explain ground motion or seismic action in one site can be grouped in three categories:

- Size and characteristics of the source of the earthquake.
- Position of the site with respect to the source.
- Local characteristics of the site.

For a probabilistic definition of ground motion (SSHAC, 1995) the incorporation of a new variable to a model is justified when an important reduction of the dispersion of the computed ground motion is obtained and when its probabilistic distribution can be proposed. In general a relation between the number and type of used variables and the associated uncertainties exists.

3.3.1. CHARACTERIZATION OF THE SEISMIC SOURCE

The magnitude is the most used variable to measure the size of an earthquake. Multiple scales exist and it is therefore important to maintain coherence with use of the same scale throughout all the study of seismic risk. The magnitude can be defined in different ways:

- The instrumental magnitude is defined on an instrumental record and it is computed from the maximum amplitude and epicentral distance, in a logarithmic scale. M_L, m_b and M_s represent different scales according to the considered distances and waves.
- The Moment magnitude, M_w (Hanks and Kanamori, 1979) is different from the instrumental one as it is related to a physical parameter of the seismic source, the

seismic moment, although actually the seismic moment is not observed directly, but computed from indirect observations (usually seismic records and seldom geodesic or geologic measurements).

- For earthquakes previous to the instrumental period the magnitude can be deduced from the macroseismic observations (intensity), using empirical correlations.

For engineering applications the use of local magnitude, M_L is frequent, according to the original definition of Richter (1935), using records limited in distance to a few hundreds of kilometres. In recent years the Moment magnitude, M_w, has been used for moderate and large earthquakes. It correlates well with $M_{L.}$ for magnitudes between 3 and 6 and it is practically the same magnitude as obtained from surface waves, Ms, for large earthquakes, presenting the advantage of not showing saturation for values higher than 8.0.

As previously mentioned it is important to use the same magnitude scale throughout a study. Therefore, it is recommended to use unified criteria, in particular in the Euro-Mediterranean zone, were many regional and national agencies are involved.

Another characteristic of the source that affects the ground motion is the tectonic regime of the zone where the earthquake occurs (intraplate, zone of subduction, limit of plates, etc.). This characteristic usually is not specified in the available models, so the model must be adapted to the type of study region.

Another characteristic that affects the seismic ground motion is the earthquake focal mechanism (strike-slip, normal or inverse). It is not often used as an explanatory variable. Nevertheless, some relations of attenuation developed recently show that the values of the maximum acceleration (PGA) can be 20-30% greater for inverse faults than for strike-slip faults, for the same magnitude and focal distance (Abrahamson and Somerville, 1996; Boore et al., 1997). These differences can be explained by simple geometric reasons (Cocco, 1998).

The depth of the seismic source is also often not included explicitly as an explanatory variable in current practice, although it can play an important role in the observed ground motion.

3.3.2. LOCATION OF THE SITE WITH RESPECT TO THE EARTHQUAKE

The variable commonly used is distance. There are several ways to define distance:

- For small and moderate size the magnitude earthquake of the rupture is negligible in relation to the distance between the site and the earthquake. In these cases the hypocentral (focal) or the epicentral distance is used. The use of one or another must be consistent with the representation of the earthquake occurrence in source zones of two or three dimensions and the attenuation relationships used in the evaluation of the hazard.
- If the size of the rupture is not negligible in relation to the distance to the site, other definitions like the minimum distance to the rupture or its projection in the surface are used. As in the previous case, consistency with the other steps of the evaluation of the seismic hazard most be maintained.

Another characteristic in addition to the distance is the azimuth of the location with respect to the direction of propagation of the rupture. The physical phenomenon known as directivity causes larger ground motion in the direction of propagation of the rupture. The phenomenon is observed specially for low frequencies (<0.5 Hz) and it is not considered in most of the models of attenuation functions, being implicit in the dispersion of the data and therefore in the nonexplained dispersion. On the contrary, most theoretical models consider directivity. Observations of important space variations of seismic ground motion due to directivity exist, among others, in the earthquakes of Landers (California) of the 28 of June of 1992, Mw 7.3 (Bernard and Herrero, 1994); in the earthquake of Northridge of the 17 of January of 1994, Mw 6.7 (Wald et al., 1996) and in the earthquake of Kobe of the 16 of January of 1995, Mw 6.9; the directivity effects of all these event have been analyzed by Cocco, 1998. See an example in Figure 3.5.

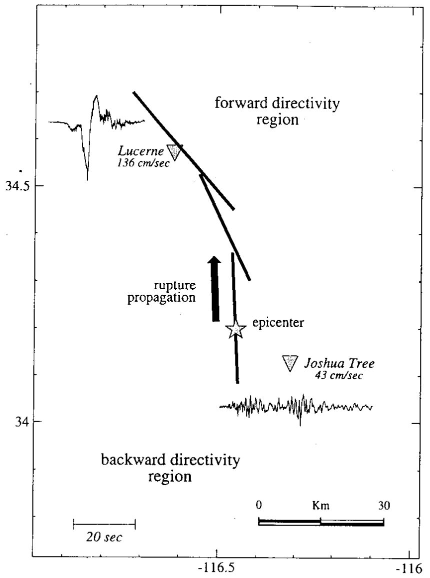

Fig. 3.5. Example of directivity of the rupture during the earthquake of Landers of 1992 (Cocco, 1998)

3.3.3. CHARACTERIZATION OF THE LOCAL EFFECTS

Almost all recent destructive earthquakes have shown the importance of amplification of the seismic ground motion due to local effects in distribution of the damage. Perhaps the most dramatic case happened on the 19 of September of 1985 in Mexico City due to an earthquake with epicentre 300 km away, in the zone of Guerrero in the Pacific coast; the waves of long period were amplified by lacustrine sediments of great thickness on which a great part of the city is founded.

Important amplifications also occurred in the Bay area of San Francisco due to the Loma Prieta earthquake of 1989; or in the most recent cases in the city of Los Angeles with the earthquake of Northridge of 1994 or in the city of Kobe in 1995, in which, aside from having important other effects due to the rupture, as it has been previously seen, large amplifications were observed in the ground motion records leading to great damages.

On the other hand, measurements have been made in different places around the world and in many cases amplification factors are larger than 5 and even 10 in some frequencies. In the Mediterranean area such effects have been observed in cities like ThessaloniKi and Corinth in Greece, Lisbon in Portugal, Nice and Grenoble in France, central Italy, etc. The cause of these amplifications is the presence of soft soils with different thicknesses as well as other aspects of the local topography (see chapter 4).

The local effects are better treated in studies at local level, for which it is important to have data relative to the dynamic properties of soils. Nevertheless, some variables that control the amplification and that have been used in predictive models of attenuation of the ground motion can be described. A synthesis of those studies can be found in Joyner and Boore (1988). Most studies only consider if the site is located on rock or in soft soil. Some studies have taken into account the thickness of sediments in a simplified way, considering only two categories: lower or higher than 30m (Sabetta and Pugliese, 1996), Figure 3.6, or the shear wave velocities in the first 30m (Boore et al., 1993, 1994).

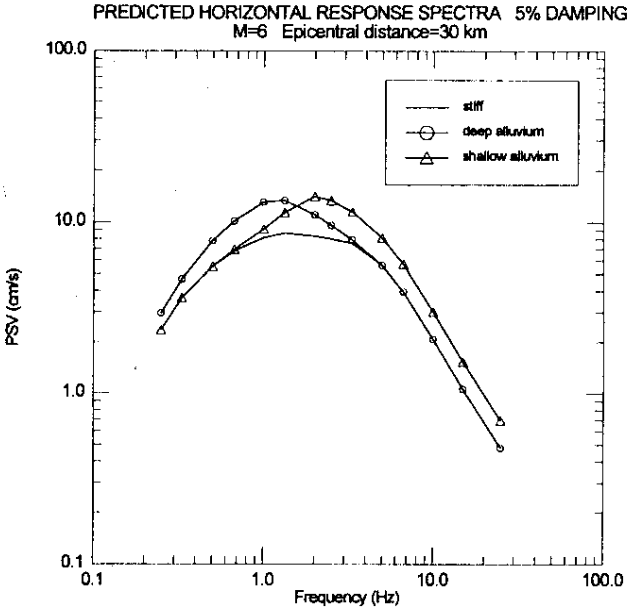

Fig. 3.6. Dependency of the horizontal synthetic spectra on site geology (Sabetta and Pugliese, 1996)

An important aspect is selection of the reference site or the type of hard rock contained in it. It is necessary to know the shear wave velocity of the site material. In most cases hard rock is considered to be those consistent materials with velocity higher than 750 m/s. In the case of larger velocities, for example 2800 m/s, which corresponds to rocks of the Palaeozoic age that have remained unaltered, effects of amplification can be observed in consistent or rocky ground sites (v=750 m/s). In any case it is important to choose the type of site of reference that is consistent with the used model of attenuation.

3.4. Predictive methods of ground motion

A brief description of some common components that appear in the predictive models (not only based on data) follows. The sequential consideration of the different components presented below gives rise to a so-called prediction model. We will understand by *method* a way or general procedure to make the prediction, whereas we will use the term *model* for a particular application of a method that allows calculation of the seismic ground motion.

3.4.1. EMPIRICAL METHODS

Empirical methods can be divided into methods using instrumental data and methods based on macroseismic data:

3.4.1.1. *Methods that use instrumental recordings*

For some specific studies it can be enough to have records of earthquakes of similar size, same type of fault and equal distance to the site.

For studies that require a definition of ground motion for different values of magnitude and distances it is usual to establish a regression analysis to fit a functional form to a set of available spectra. The details about those methods can be found in Joyner and Boore (1988), Boore et al. (1993, 1994), Sabetta and Pugliese (1996), among others. Differences in the results are mainly due to the data used, to the election of the explanatory variables and to the selected functional forms (Figure 3.7).

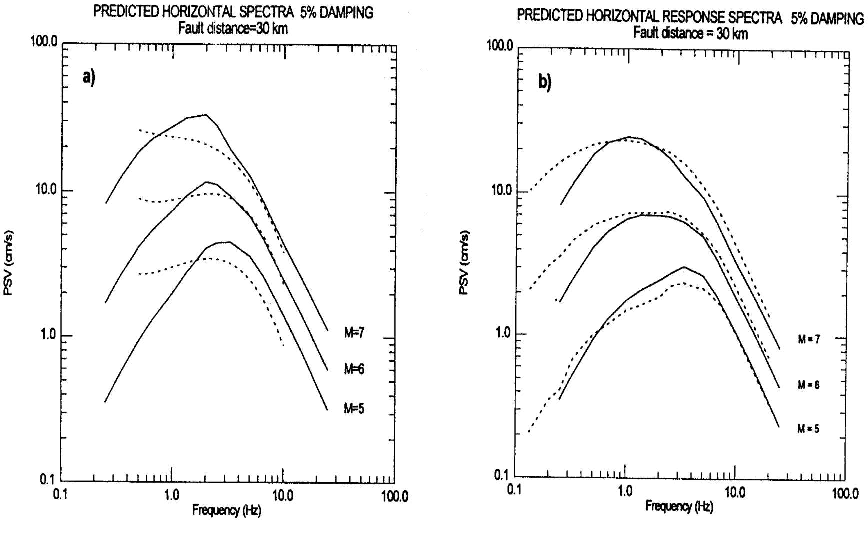

Fig. 3.7. a) Comparison of mean horizontal spectra from recent attenuation relationships: Boore et al. (1993, 1994) for a soft soil site, with Sabetta and Pugliese (1996) for a shallow alluvium site; b) Comparison of mean horizontal spectra from recent attenuation relationships: Sadigh (1993) for a rock site with Sabetta and Pugliese (1996) for a stiff site. (From Sabetta and Pugliese, 1996).

Most of these methods consider the type of soil of the recording site and the regressions are made classifying the type of soil in a simple way. In general, those methods are limited by the lack of data in some ranges of distance and magnitude, in particular for short distances and large magnitudes and also for distances larger than 100 km, (weak motions, until recently located below the threshold of the accelerograph). The introduction of new data and theoretical concepts has to help to eliminate possible bias in the deduced values.

3.4.1.2. *Methods that use macroseismic data*

In regions of moderate seismicity with a long series of macroseismic information available, macroseismic intensity is a useful variable to determine the laws of occurrence of earthquakes. In these cases, the ground motion at one site can be approached by the intensity deduced by attenuation laws adjusted from site intensity data observed during regional past earthquakes. Then, the seismic risk analysis can be carried out completely with the variable intensity, from the definition of the earthquake occurrence, through the expression of hazard maps, to the use of damage probability matrices defined for the different intensity degrees to obtain the estimation of losses.

3.4.2. COMPONENTS OF NONEMPIRICAL METHODS

In some cases, the use of empirical methods is not appropriate, usually because of lack of data in the region of study and the poor reliability in the use data from other regions. Alternatively the ground motion can be defined from hybrid methods that combine the functional forms deduced from fault mechanism and wave propagation theory, with parameters determined by regional data or analogy with other regions or experiences.

3.4.2.1. *General aspects*

Prediction in retrospective sense. Risk studies try to define the statistical distribution of future seismic action as a function of magnitude and distance. The objective of many seismological studies is the "retrospective prediction" of the distribution of ground motion for a given earthquake, for which instrumental records are available. The intention is to know the details of the seismic source, is to say its geometry and the time and space evolution of the rupture. The methods used to generate synthetic records can be predictive for future earthquakes. However, many simulations would be needed in order to archive the required statistical significance. As more data and more sophisticated computing resources are available, the more reliable will be the results.

Complexity of the ground motion. It seems clear from the observation of accelerograms that seismic ground motions present a great complexity, especially in the high frequencies. The simple model formed by a fault with uniform sliding in a homogenous medium does not give rise to a complexity in the motion (these models are useful only for study of the long period components). A good model must reproduce complexity and randomness in the motion. Figure 3.8 shows an example of this complexity.

Some methods try to model the Earth complexity, whereas others classified as phenomenological look for functional forms derived from physical models, with parameters that can be considered by adjustment to the data. A fundamental idea in those methods is that the dynamic processes are too complex to be modelled in a deterministic way especially for a future earthquake.

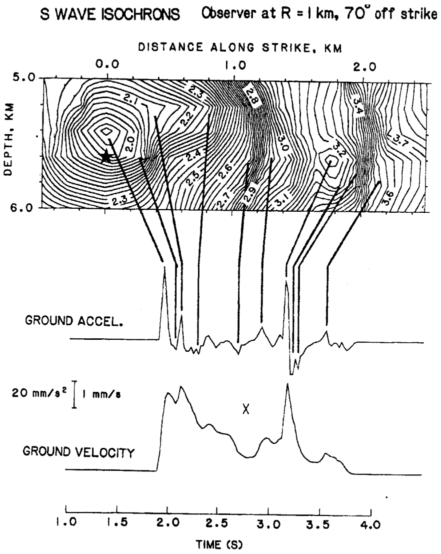

Fig. 3.8. Example of an acceleration record simulated for a time distribution of the rupture shown in the upper part for an observer located at 1 km of distance and an azimuth of 70º. The distribution of isochrones is shown together with the amplitude of the ground motion (Cocco, 1998)

3.4.2.2. *Parts of the problem.*

The current methods divide the problem in three parts: seismic source, path and local effects.

Seismic Source. The seismic source is described by the time and space distribution of the rupture (or slip) in the fault plane. This information is never available for future earthquakes and therefore methods to obtain the radiation of the source are needed. Some methods use a point source to represent the rupture of the fault, valid for ranks of distance larger than the size of the fault, whereas others consider the rupture as a sum of sub-events on a finite fault.

- Point Source. The called "stochastic" models are member of the group of models that consider a point source. In these methods the radiation is described in terms of spectra, whose amplitude is given by relatively simple functions, of smoothed shape and whose phase is almost-random, so that the ground motion duration is related to the size of the source and to the distance between source and site. In most methods, the spectral amplitude follows seismological models with a physical basis. So it is the case of the well-known model of Brune (1970, 1971) also known as the ω^2-model, characterized by a corner frequency f_c, and later modified with another cut-off frequency f_{max} (see an example in Figure 3.9 from Catalan et al. (1999).

The most well known stochastic model in literature is that proposed by Boore (1983). However, the possible spatial variation of the movement along the fault is not taken into account, when considering it a point source. Later developments have allowed us to explain these variations considering a time-window, whose form contains the information of the rupture process (Cocco, 1998).

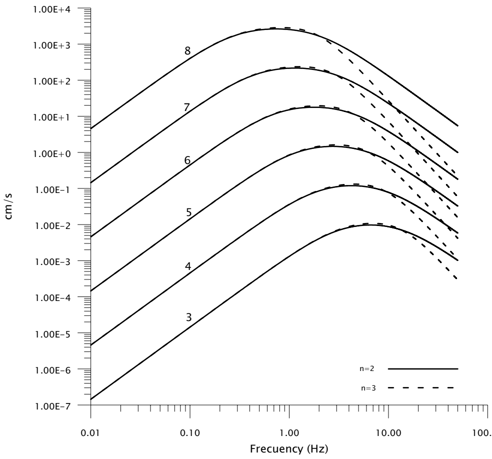

Fig. 3.9. Acceleration Spectra corresponding to a modified Brune Model for different magnitudes considering an epicentral distance of 60 km. Attenuation of amplitudes for high frequencies with n=2 and n=3, for some dependency of frequency (Catalan et al., 1999)

- Extensive Source. The seismic ground motion produced by an extensive source can be calculated combining the motions produced by sub-events distributed on the fault plane. The sub-events can be defined in several ways:
  - Using actual records of small earthquakes, so that they contain the same information about the path and site as the record of the great earthquake (e.g. Irikura, 1983).
  - By generation of a random distribution of slips with certain properties (e.g. Bernard and Herrero, 1994).
  - Using a fractal distribution of the size and a random position of sub-events (e.g. Zeng et al., 1994).

Path. The energy emitted by the source is modified throughout the path followed by the waves until they reach the site. This modification can be modelled by two types of approaches:

- Green Function. Some methods use empirical Green functions from records of small earthquakes that have followed the same path, as it has been mentioned also for treating the extensive source (e.g. Irikura, 1983). Others calculate the Green functions for stratified media (Bouchon and Aki, 1977) from the complete modelling of the wave field. The main problem in computation is the difficulty in knowing enough details about the internal Earth structure, and from the details one has to generate the high frequencies contents (short wavelengths).
- Simplified methods. Quite often the path effect is parameterised in the frequency domain by the product of two factors: the geometrical spreading and the anelastic attenuation. The first of them is modelled for a homogenous medium by a diminution of the wave amplitude proportional to r^{-1} (spherical wavefronts) or r^{-2}

for distances superior to 100 km (cylindrical wavefronts). The second one has less importance for the frequencies of interest at the regional distances.

Local Effects. As seen in Section 3.3.3 the consideration of the possible amplification of ground motion due to specific local conditions, say, effects of soft soils and steep topography, is absolutely necessary. In general the effects are considered through the estimation of the transfer function, that is, the spectral relation between a record in a given site and a record placed in a reference location, usually hard rock. Also the increase of the duration of the ground motion can be of importance. Observations of these effects in recent earthquakes and a more complete overview of the methods are developed in Chapter 4.

3.5. Definition of Seismic Action

The seismic action on a structure is defined by the time-history series corresponding to the acceleration or accelerogram or its spectral representation, in the frequency domain. For non-linear dynamic analysis, an accelerogram representative of the action to be considered is needed.

In many cases the structural analysis needs only the maximum value of the acceleration (peak ground acceleration or PGA) and a few ordinates of the linear response spectrum for some frequencies of interest, in most cases between 0.2 and 20 Hz.

One of the ways to obtain a representation of the seismic action is to analyse the hazard in terms of Peak Ground Acceleration (PGA) and to use a spectral form obtained independently to convert PGA in a response spectrum. One example of this procedure is the development of a smoothed acceleration response spectrum from Eurocode 8 (EC8, 2003), described in section 3.5.2.

Recently, the use of variable spectrum forms to define seismic zonation has been extended since the first proposal in the USA (Frankel et al., 1996).

Seismic action can be defined in several forms depending on the method used to evaluate the seismic damage of a structure or to design a future one. In the methods based on forces acting on the structure, the seismic action is defined in terms of the acceleration spectra, but recent methods based on displacements and the performance of the structure rely on demand spectra to represent the seismic action.

3.5.1. PEAK GROUND ACCELERATION (PGA) AND RESPONSE SPECTRUM

The Peak Ground Acceleration or PGA is defined as the absolute maximum value of the representative temporary series of the ground acceleration. It is useful to define lateral forces and shear stresses in procedures that use equivalent static forces like the specified ones in the Seismic Codes. When being controlled by the spectral value corresponding to the greater frequency, its value is very sensible to the processes that can alter the spectral content at high frequencies, such as the site conditions or the instrumental transfer function. Moreover, PGA is not easily related with a given frequency range of interest, depending on the distance to the source of the earthquake. The frequencies that control the value of PGA are often not in the rank of interest of the structural answer. For example, the maximum values of the acceleration can exceed 5 g in the case of the record of explosions at short distances, but for frequencies near 400 Hz. For the above reasons the PGA is not recommended for the definition of the seismic action of design, being more representative of the complete response spectrum.

The response spectrum describes the answer of a damped linear oscillator to a seismic excitation. The more used measurement is the PSA (T) or spectral maximum acceleration defined by:

$$\mathrm{PSA}\ (T)=(2\pi/T)^2\, S_d\,(T), \qquad (3.1)$$

where S_d (T) is the maximum displacement of the mass of a damped linear oscillator with an undamped natural period T, relative to the point of anchorage to the ground. In most applications a damping of 5% is used. The response spectrum is useful to calculate directly the answer for most structures, since these can be modelled by the linear oscillator.

Despite its extended use, the response spectrum shows some disadvantages:

- A non-linear analysis needs a more complex representation.
- In spite of calculating a PSA for any frequency, a not-null value does not imply that the ground motion contains energy to this frequency. Thus, for example, if the excitation of the oscillator is made to frequencies lower than 5 Hz, the answer to higher frequencies will simply reproduce the ground acceleration.
- The Response Spectrum does not have the same properties as the Fourier Spectrum, when a value of not-null damping is used. In this case the spectral relations can give rise to erroneous interpretations.
- The spectrum is computed generally for a horizontal seismic action without taking care of the direction.
- Importance of the spectrum corresponding to the vertical component of the motion is usually not given and it is a current practice to deduce it from the horizontal spectrum applying a factor of 2/3. If vertical actions are considered important for a given structure or building, the vertical response spectrum must be computed independently.

3.5.2. SMOOTHED ACCELERATION RESPONSE SPECTRUM FROM EUROCODE 8

For the horizontal components of the seismic action, the Eurocode 8 (EC8, 2003) defines the elastic response spectrum, *Sa* (*T*), using the following expressions:

$$0 \le T \le T_B \qquad S_a(T) = \mathrm{pga}\left[1 + \frac{T}{T_B}(B_C - 1)\right] \qquad (3.2)$$

$$T_B \le T \le T_C \qquad S_a(T) = \mathrm{pga}B_C \qquad (3.3)$$

$$T_C \le T \le T_D \qquad S_a(T) = \mathrm{pga}\left(\frac{T_C}{T}\right)B_C \qquad (3.4)$$

$$T_D \le T \le 4\,\mathrm{sec} \qquad S_a(T) = \mathrm{pga}\left(\frac{T_C T_D}{T^2}\right)B_C \qquad (3.5)$$

where:

$S_a(T)$ = ordinate of the elastic response spectrum,
T = vibration period of a linear single degree of freedom system,
pga = peak ground acceleration (PGA),
B_C = factor defined as $S_{a\,max}$/ pga,
T_B, T_C = limits of the constant spectral acceleration branch,
T_D = beginning of the constant displacement response range.

A diagram for the Eurocode 8 (EC8, 2003) elastic response spectrum, Se (T), is shown in Figure 3.10.

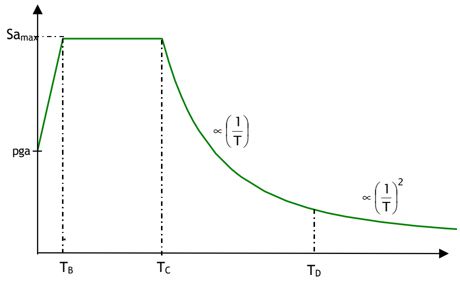

Fig. 3.10. Diagram for the Eurocode 8 (EC8, 2003) acceleration response spectrum formulation

Eurocode 8 offers the possibility of two types of response spectra that depends on the maximum surface wave magnitude of the earthquakes that are expected to affect the selected site. If it is higher than 5.5, spectrum type 1 is used, but when it is lower than 5.5, the type 2 spectrum should be used (see Figure 3.11).

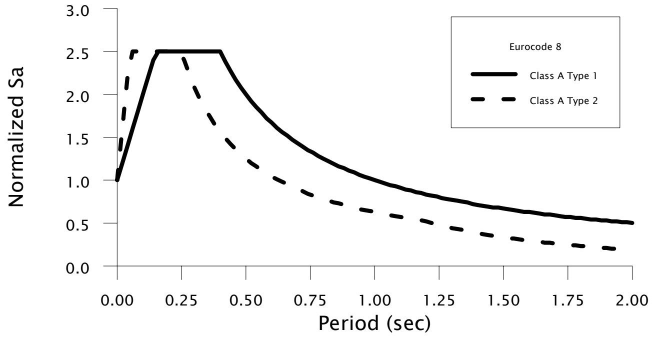

Fig. 3.11. Response spectra of Eurocode 8 for two types of magnitudes in case of soil class A

3.5.3. IMPLICATIONS IN THE USE OF FIXED SPECTRAL FORMS ANCHORED TO THE PEAK GROUND ACCELERATION

It has been a common practice to use a fixed spectral form scaled ("anchored") to a given PGA. According to what has been discussed in the previous sections, the use of

PGA to scale spectral forms and the use of the above described practices present some important problems.

Some of the consequences of the different methods and values of variables on the spectra are summarized as follows:

- Peak ground acceleration is a very sensitive parameter to the recording conditions (geology and instrument), it is not associated to a frequency in particular and its value is difficult to predict due to the random character of the complexity of the rupture that generates the incoming waves.
- The great earthquakes produce a greater proportion of low-frequencies, in relation to smaller earthquakes and, for this reason, the PSA(fr)/PGA relation will grow with the magnitude of the event.

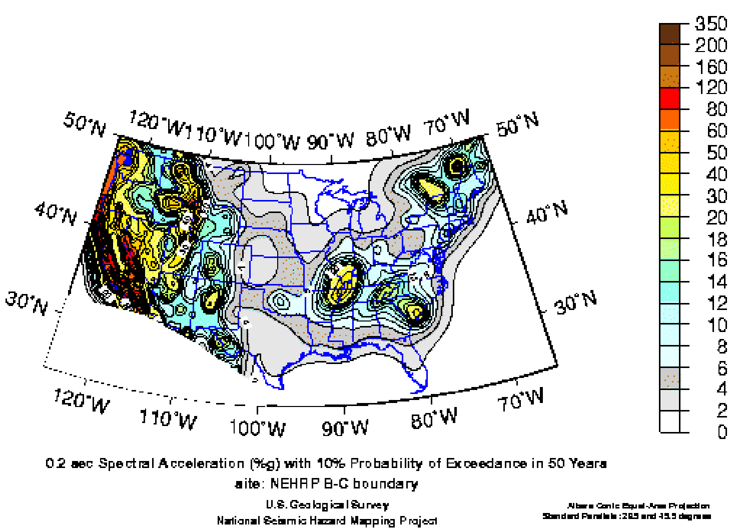

Fig. 3.12. Spectral accelerations for 5 Hz in %g with a 10% probability of being surpassed in 50 years in the U.S.A (Frankel et al., 1996)

Recently, there have been proposals, in particular in the U.S.A., to use variable spectrum forms to define the seismic zonation (Frankel et al., 1996). In Figure 3.12 there is an example of a map with the results of a Probabilistic Seismic Hazard Assessment for one spectral value.

3.5.4. DEMAND SPECTRUM OR ACCELERATION-DISPLACEMENT RESPONSE SPECTRUM (ADRS)

The demand spectrum is the 5% damped acceleration response spectrum expressed in an acceleration-displacement (AD) diagram. In the AD diagram, ordinates are expressed in terms of spectral acceleration, S_a, while abscissas are expressed as spectral displacement, S_d. The demand spectrum represents the spectral acceleration and spectral displacement that the seismic event demands on the structure. It is also often called acceleration-displacement response spectra or ADRS. The conversion from the 5%

damped acceleration response spectrum (S_a, T) to a demand spectrum (S_a, S_d) only requires a definition of the spectral displacements using the following transformation:

$$S_d = S_a \left[\frac{T^2}{4\pi^2} \right] \quad (3.6)$$

A smoothed demand spectrum or ADRS diagram is shown in Figure 3.13. Each point in the demand spectrum represents the spectral acceleration, S_a, and the spectral displacement, S_d, corresponding to a vibration period, T. As can be seen the structural period in the acceleration displacement response spectra diagram can be represented by a line passing through the origin (Mahaney et al., 1993). The slope of this line is inversely proportional to the structural period, that is, as the structural period increases, the slope of the line decreases.

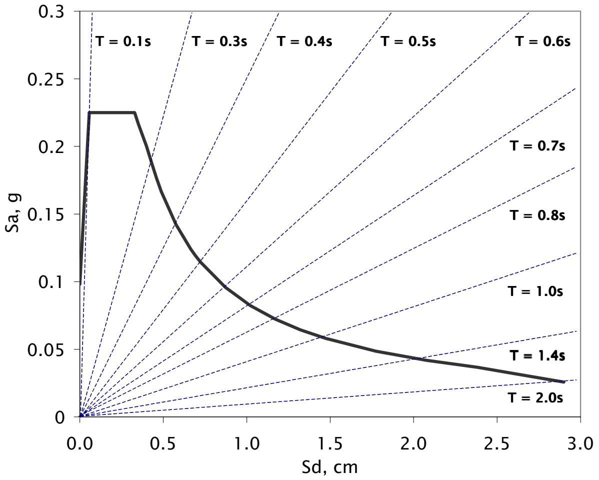

Fig. 3.13. Smoothed form of the demand spectrum or ADRS diagram

Having analytical formulation for smoothed demand spectra can be very useful when they are used for the performance evaluation of large building stocks by allowing programming of the methods to be performed automatically. The acceleration response spectrum obtained can be smoothed using code- like formulations. The analytical formulations for smoothed acceleration response spectra can be then used to obtain the analytically expressed smoothed demand spectra.

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