

CHAPTER 4 LOCAL SITE EFFECTS AND MICROZONATION

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4.1. Introduction

Seismic waves generated at the earthquake source propagate through different geological formations until they reach the surface at a specific site. The travel paths of these seismic waves in the uppermost geological layers strongly affect their characteristics, producing different effects on the earthquake motion at the ground surface. In general, thicker layers of soft, unconsolidated deposits tend to amplify selectively different wave frequencies. These complex physical phenomena are known as *soil effects*. On the other hand, the local topography can also modify the characteristics of the incoming waves, leading to the so called topographic effects. *Soil* and *topographic effects* are considered under the general denomination of *local site effects*. Beyond these effects and under certain circumstances, *induced effects* may occur for large amplitude incoming waves, among which are slope instabilities (landslides) and liquefaction.

Within a more generalized scope, active faulting should also be considered as, in case of fault ruptures. In addition permanent differential displacements and near fault effects are other important issues to be recognized.

In many past and recent earthquakes it has been observed that the local site conditions - soil and topographic effects, as well as induced effects - have a great influence on the damage distribution. It is therefore very important to take into account and predict these possible local site effects when assessing the earthquake hazard at regional and local scale.

Seismic microzonation is the generic name for subdividing a region into individual areas having different potentials for hazardous earthquake effects, defining their specific seismic behaviour for engineering design and land-use planning. Seismic microzoning, including approaches for assessing local ground response, slope instability and liquefaction, has become a useful tool for cost effective earthquake risk mitigation. There is a demand from international, national, regional and municipal administrations for microzoning urban areas generating maps to be taken into account in urban planning, in seismic codes and in civil protection preparedness procedures.

Various approaches are currently applied for microzonation studies. Experimental techniques, together with theoretical approaches involving ground motion modelling under different hypotheses, are used to classify urban areas in various zones of different earthquake response characteristics.

Several review and synthesis papers on the different methods used for geological and geotechnical site characterisation and microzoning have been published (e.g. Bard, 1994; Kudo, 1995; Pitilakis and Anastasiadis, 1998; Bard, 1999; Mulas, 2002; Kawase,

2003; Pitilakis, 2004; among others) and many conferences, symposia and workshops have been organised under this subject. Some special volumes and technical books have been also devoted to this topic (e.g. Priolo et al., 2001; Roca and Oliveira, 2002; Ansal et al., 2004, among others).

Guidelines or recommendations for seismic microzoning have been produced in different countries (e.g. AFPS, 1995; ISSMGE, 1999; DRM, 2004a). The guideline manual from Mayer-Rosa and Jiménez (2000) includes a state-of-the-art and a useful collection of case studies with emphasis in ground amplification while the manual for zonation ISSMGE (1999) points out mainly earthquake induced phenomena such as slope instability and liquefaction. The DRM (2004a, 2004b) study presents a comprehensive treatment of the microzonation based on case studies along with a manual for establishing a microzonation code in Turkey. Microzoning results are being slowly incorporated into recent earthquake construction codes (e.g. Eurocode 8, 2004).

This chapter is an account for readers who are not very familiar with the topic. The purpose of this brief and comprehensive review is to describe and clarify the goals, terminology and concepts involved in seismic microzoning and to present and discuss the main numerical and experimental techniques used in current research and application-related studies, pointing out their limitations, advantages and disadvantages. The societal value of these studies and the need of including them in the framework of seismic regulations are also discussed.

4.2. Importance of local site effects on observed earthquake damage

There can be significant differences in local site conditions due to variations in geological formations, thickness and properties of soil and rock layers, depth of bedrock and water table, surface and underground topography. These variations would have significant effects on the characteristics of earthquake motions on the ground surface. There are large numbers of instrumental field observations obtained during recent earthquakes reflecting the effects of local site conditions.

As reported by many researchers (Borcherdt and Gibbs, 1976; Iglesias, 1988; Gazetas et al., 1990; Seed et al., 1991; Ansal et al., 1993; Lekkas, 1996; Jennings, 1997; Ishihara, 1997; Guéguen et al., 1998; Pergalani et al., 1999; Tertulliani, 2000; Hartzell et al., 2001; Ansal et al., 2001a; Özel et al., 2002) local site conditions could play a dominant role in damage distribution as well as in the recorded strong motion records (Aki, 1993, 1998; Bard, 1994; Reinoso and Ordaz, 1997; Shome et al., 1998).

In addition, one of the controlling factors on building damage, not very related to the local site conditions, is the surface manifestation and type of faulting that took place during the earthquakes. As an example it was possible to observe the diverse effects of fault ruptures during the 1999 Kocaeli, Turkey earthquakes as shown in Figure 4.1. The house located a few meters away from the fault trace with permanent lateral displacements around 4m appears to be intact as shown in Figure 4.1a. However, in the case the fault trace goes through a building, total collapse may take place as shown in Figure 4.1b.

Likewise as shown in Figure 4.1c, even though the lateral displacements were on the order of 4m, the building survived without experiencing total collapse. It is also interesting to see that the building located right next to the normal fault with vertical displacements on the order of 2m (Figure 4.1d) survived the earthquake with minor damages.



Fig. 4.1. Effects of fault rupture on buildings

Figure 4.2 shows different urban areas with different degrees of damage distribution during the 1999 Kocaeli earthquake. Damages to buildings in the near field in Golcük and Adapazarı show varying degrees of damage distribution most likely due to the diverse effects of local site conditions.



Fig. 4.2. Variation of building damage in different zones in the near field during 1999 Kocaeli, Turkey earthquake

Geologic structures such as basins and sediment filled valleys and topographical features may also have very important effects on the variation of the earthquake ground motions. Local site effects on basins and valleys and topographical effects have been

investigated by many researchers (Murphy and Hewlett, 1975; Bard and Bouchon, 1980a, 1980b, 1985; Geli et al., 1988; Faccioli, 1991; Zhao and Valliappan, 1993; Wen et al., 1995; Rassem et al., 1995; Gao, et al., 1996; Chávez-García et al., 1996; Reinoso et al., 1997; Chin-Hsiung et al., 1998; Su et al., 1998; Wald and Graves, 1998; Kawase, 1998; Amirbekian and Bolt, 1998; Athanasopoulus et al., 1999; Paolucci et al., 2000; Sokolov et al., 2001; Chávez-García and Faccioli, 2000).

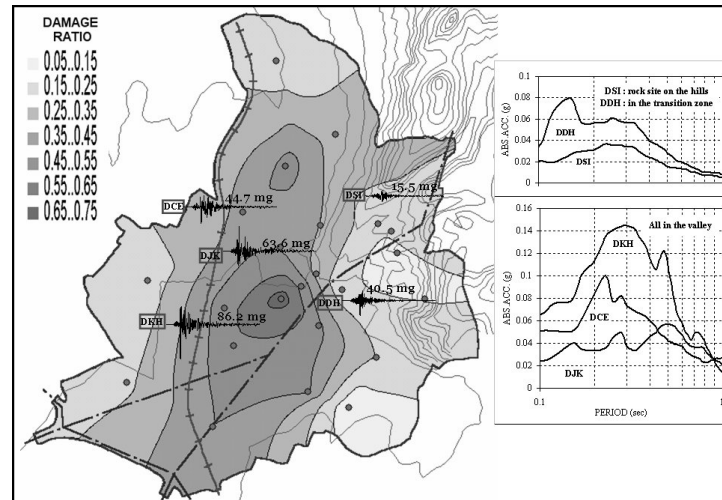


Fig. 4.3. The variation of damage in Dinar after the 1995 earthquake in comparison with the aftershock records from the temporary KOERI network (Durukal et al., 1998)

An example from the recent past, 1995 Dinar (Turkey) Earthquake can be given to demonstrate the importance of local site conditions. The variation of damage distribution in Dinar after the 1995 Earthquake, as shown in Figure 4.3 given by Ansal et al. (2001a), has been determined based on detailed damage survey conducted by the Turkish General Directorate of Disaster Affairs. It appears logical to assume that there would hardly be significant variations in engineering and in the quality of construction in Dinar. Therefore this large variation of the earthquake damage observed may be explained with respect to variations in earthquake characteristics due to different local site conditions. The recorded ground motions during an aftershock ($M_L=4.1$) located on the same fault zone clearly demonstrate the differences in ground motion characteristics. The peak ground and peak spectral accelerations were 0.086g and 0.14g at DKH station located on the alluvium sediments in the valley while it was only 0.015g and 0.04 g at DSI station located on the rock outcrop.

The other important issue concerning local site conditions is related to the landslides induced during and after earthquakes. Especially landslides in residential districts may cause extensive damage and large numbers of casualties. A devastating example of such a landslide that took place during the 1995 Hyogoken-Nanbu earthquake is shown in Figure 4.4.

All of the above mentioned earthquake induced damages and recorded ground motion characteristics clearly indicate the importance of local site conditions during

earthquakes. Thus one logical mitigation measure requires detailed investigation and realistic assessment of the local site conditions.



Fig. 4.4. Large landslide in Kobe, Japan caused by the 1995 Hyogoken-Nanbu earthquake, causing the destruction of a large number of houses located on the slopes

4.3. Zoning, microzoning and resulting maps: a tool for predicting local site effects

The general concept of zoning refers to the process of subdividing a region into sectors with similar behaviour with respect to a given set of parameters. Zoning always relates to a specific application, and, in most cases, is linked to engineering design or land-use planning purposes. Seismic *zonation* and *microzonation* refer to the working scale, regional and local, respectively. They are the basic tools for earthquake damage mitigation on the side of ground motion and ground induced effects, (Mayer-Rosa and Jimenez, 2000; Roca et al., 1999).

Zoning parameters have been treated in chapters 2 and 3 of this book. They are essentially physical variables defining the characteristics of ground shaking such as: macroseismic intensity, peak ground acceleration, velocity and displacement (PGA, PGV and PGD), Fourier and response spectra, duration, etc.

The current output from microzoning studies dealing with soil and topographic amplifications consists of maps defining sectors of different earthquake response, and are referred to a specific parameter or function such as:

- ΔI , increment of macroseismic intensity, I , with respect to the I values of the corresponding national or regional hazard map. An important point is to know if the intensities given in the hazard map correspond to rock site or to the “predominant” - most frequently observed - soil site.

- Δ_{PGA} , increment of the peak ground acceleration at each specific point of the territory with respect to the values for a neighbouring rock site. Similar representations can be done with Δ_{PGV} and Δ_{PGD} .
- T_p , predominant period, defined as the period for which the maximum soil amplifications occur. The fundamental or natural period, T_1 , corresponding to the first mode of vibration of the soil system, is used by several authors as microzoning parameter. However, it should be considered that T_p is a more significant parameter than T_1 as far as their relation to damage in most standard dwelling buildings.
- Transfer function - soil to rock spectral ratio - gives a more complete representation of local effects, as it covers the entire spectral domain.
- A site specific response spectrum is another useful function to characterise ground behaviour for engineering purposes.

In order to obtain these parameters a large amount of territorial information (topographic, geological, geophysical, geotechnical, hydrological, etc.) is needed. In many cases, given the lack of available data, a microzoning project must include surveys for obtaining some of this basic information. In this way, intermediate results and maps issued during the process of a seismic microzoning project can be of a high value themselves for their possible use in other applications. Examples of these intermediate products are maps with geotechnical information, water table, potential active faults, topography and underground local characteristics (i.e. ICC, 2000; SGP, 1988). Given the large amount of data that has to be managed, a Geographical Information System (GIS) is a valuable tool to be used for microzonation and also for risk assessment and for the generation of damage scenarios.

The results of microzoning studies can be integrated in various applications corresponding to different levels: i) National codes which define the minimum requirements for earthquake protection can benefit from zonation maps; ii) Regional and municipal regulations may detail and modify National codes with results from microzoning; and iii) Site-specific studies are needed for the design and construction of important engineering structures, as well as for performing safety analysis of existing important vulnerable structures.

In addition the issue of fault traces, which deserves specific treatment in a microzoning study, are strongly linked with the concept of “active” fault. Whenever the geological study has identified such a feature, a “free-distance” from the fault trace should be kept for special consideration where compulsory measures should be applied, restricting the land-use or requiring more stringent ground motion conditions.

Each one of these levels of application requires a specific mapping scale and the corresponding grade or “grain of information”. Various existing guidelines recommend intervals for these levels (AFPS, 1995, ISSMGE, 1999; Mayer-Rosa and Jiménez, 2000; DRM, 2004a, b). Usual mapping scales range from 1:2,000,000 – 1:250,000 for national or regional hazard assessment to 1:10,000 - 1:5,000 for local effects evaluation at municipality level or to 1:500 for site specific studies.

Sections 4.4 and 4.5 are devoted to the characterisation of soil properties in the linear and nonlinear regime, while Sections 4.6 and 4.7 will present the current numerical and experimental methods to predict earthquake ground response. Finally, in sections 4.8 and 4.9 the topographic, liquefaction and induced effects are presented.

4.4. Geological, Geotechnical and Geophysical approaches for soil characterization

As mentioned before, local soil characterisation plays a decisive role in determining their behaviour under seismic excitation. Detailed geometry of layers and evaluation of linear and nonlinear properties of all types of soils are necessary for an appropriate analysis. These include, in the first place, a description of the geological environment and lithology, then density, the presence of water content, and finally the various moduli of elasticity and damping ratio as a function shear strain. The detail of the analysis depends on the objectives and on the capacity to gather information.

The geological description and interpretation of data contained in detailed geological maps constitutes the first and most basic information necessary to perform a microzoning study. The existence of down-hole data complements the geological information. The more convenient situation as far as gathering the best information on soil strata would be to have the deeper down-hole information for the larger geographical extension. The detail of this information depends on existing available data and on the capabilities to perform survey analysis.

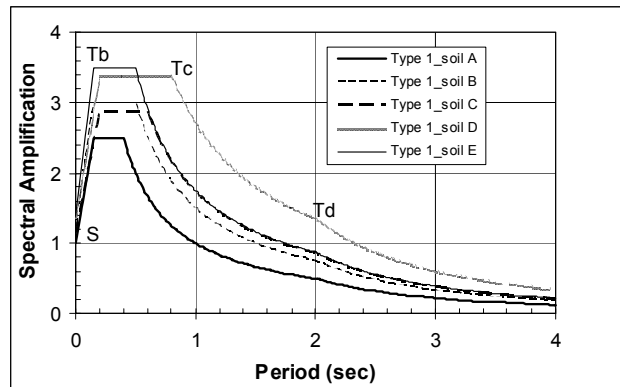
Soil classification used in most modern construction codes is essentially based on this data as the cases of the EC-8, the European Eurocode 8 (2004) and the NEHRP (2000) cases. Table 4.1 presents the soil classes of the recently approved EC-8, according to main mechanical characteristics of the surface layers; the proposed spectra for the different types of soils defined and for earthquakes of magnitude equal to or larger than 5.5 are shown in Figure 4.5.

The evaluation of local conditions including surface geology to determine the geometry and mechanical characteristics of “layers” can be performed in different ways, essentially using seismological methods, either geophysical and/or geotechnical. The surface geophysical methods include reflection, refraction profiles, spectral analysis of surface waves, electric, electro-magnetic fields and microgravimetry (Montesinos et al., 2003). New digital technology instrumentation and powerful software have enhanced the scope of applications and the accuracy of estimations. Among these techniques we cite the use of dense arrays for better inversion procedures including tomography. The most recent array techniques use the Frequency-Wave number (F-K) algorithm (Kagawa, 1996) applied to surface waves caused by impact sources and ambient noise, and the Spatial Autocorrelation Method (SPAC) for ambient noise (Estrella and González, 2003; Pascalis et al., 2004).

The geotechnical methods include evaluation of wave velocity in particular layers through cross-hole, down-hole techniques, etc., through the execution of borehole logs to perform associated testing.

Table 4.1. Classification of soil types according to main mechanical characteristics of the surface layers according to Eurocode 8

Ground class	Description of stratigraphic profile	Parameters		
		$V_{s,30}$ (m/s)	N_{SPT} (bl/30cm)	c_u (kPa)
A	Rock or other rock-like geological formation, including at most 5 m of weaker material at the surface	> 800	-	-
B	Deposits of very dense sand, gravel, or very stiff clay, at least several tens of m in thickness, characterised by a gradual increase of mechanical properties with depth	360 – 800	> 50	> 250
C	Deep deposits of dense or medium-dense sand, gravel or stiff clay with thickness from several tens to many hundreds of m.	180 – 360	15 - 50	70 – 250
D	Deposits of loose-to-medium cohesionless soil (with or without some soft cohesive layers), or of predominantly soft-to-firm cohesive soil	< 180	< 15	< 70
E	A soil profile consisting of a surface alluvium layer with $V_{s,30}$ values of class C or D and thickness varying between about 5 m and 20 m, underlain by stiffer material with $V_{s,30} > 800$ m/s			
S ₁	Deposits consisting – or containing a layer at least 10 m thick – of soft clays/silts with high plasticity index (PI > 40) and high water content	< 100 (indicative)	-	10 – 20
S ₂	Deposits of liquefiable soils, of sensitive clays, or any other soil profile not included in classes A –E or S ₁			



EC8-00 TYPE 1	S	T _b	T _c	T _d
soil A $V_s > 800$ m/s	1,00	0,15	0,4	2,0
soil B $360 < V_s < 800$ m/s	1,10	0,15	0,5	2,0
soil C $180 < V_s < 360$ m/s	1,35	0,20	0,6	2,0
soil D $V_s < 180$ m/s	1,35	0,20	0,8	2,0
soil E ($h < 20$ m)	1,40	0,15	0,4	2,0

S : spectral value for period zero
 T_B, T_C : period limits (sec) for constant spectral acceleration branch
 T_D : period value defining the beginning of the constant displacement response range of the spectrum.

Fig. 4.5. Eurocode 8 Type 1 elastic response spectra for the 5 subsoil classes, for magnitude equal to or larger than 5.5

Many different methods are available today throughout the specialised literature. Pitilakis and Anastasiadis (1998) present a good summary of those methods, their efficiency, and the degree of uncertainty in property retrieval and on costs of operations.

The average shear wave velocity $V_{s,30}$ in Table 4.1 is computed according to the following expression:

$$V_{s,30} = \frac{30}{\sum_{i=1,N} \frac{h_i}{V_i}} \quad (4.1)$$

where h_i and V_i denote the thickness (in m) and shear-wave velocity (at shear strain level of 10^{-6} or less) of the i -th formation or layer, in a total of N , existing in the top 30 metres. The site will be classified according to the value of $V_{s,30}$ if this is available, otherwise the value of N_{SPT} will be used taking into account the several physical properties that can be obtained from simple *in-situ* tests.

One special important situation departing from the previous soil classification that considers the top 30 m as sufficient to characterize site effects, is the case of thick layers of soft material, in some cases with more than 1 km, corresponding to very old river basins existing for instance in Central Europe. These cases require special treatment because modes with very large periods may be present, modifying considerably the spectral shape in the long period range for large magnitude events.

For microzoning purposes, data from boreholes associated to construction logs have been collected in GIS systems for posterior analysis. This policy is of maximum interest as it can be used for an updating of information at a given area. Contour lines with soil layers shear velocities, thickness, SPT, etc. will help visualising the space variations on soil properties. Results of modelling can easily be also added for comparison.

4.5. Nonlinear effects

Soil behaviour and consequently site effects depend very much on the amount of soil distortion provoked by the wave passage. The behaviour of various types of soils is markedly nonlinear for high amplitude motions and this effect cannot be ignored when dealing with any kind of microzoning. Extrapolation of results obtained from micro-earthquakes and microtremor recordings should be considered carefully in some geological environments where nonlinear effects can appear even at low PGA values (at the rock level). Some simple test of linearity – nonlinearity can be carried out taking as input data the geotechnical dynamical properties of the soils obtained experimentally or deduced from available correlations.

Nonlinearity is well observed in laboratory testing of samples adequately taken from the field, but great uncertainty still exists even though great advances were recently achieved in sampling and testing techniques. Many parameters control the nonlinear behaviour of different soils for increasing amplitude of shear levels. These can be reduced to the changes of modulus of elasticity and damping values (Figure 4.6), which differ from soil to soil and depend on other characteristics such as effective overburden stresses.

Table 4.2 presents a summary of techniques for soil characterisation and numerical modelling corresponding to different levels of soil distortion. In all cases full *in-situ* monitoring for earthquake events is recommended.

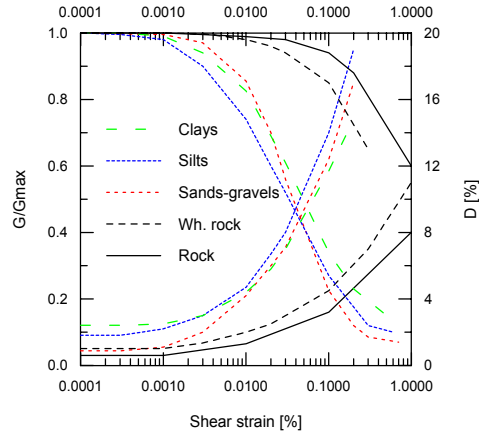


Fig. 4.6 Modulus reduction (G) and damping curves (D) with shear strain amplitude for typical soils (Cid et al., 2001)

Table 4.2. Summary of techniques for soil characterization and the corresponding levels of soil shear strain

Shear strain ($\gamma\%$)	10^{-5}	10^{-4}	10^{-3}	10^{-2}	10^{-1}
Application	Linear	Weak events	Moderate events	Large events	Very large events
Type of test	<i>In-situ</i> prospection	Resonant column	Triaxial	Large Shear testing	
Modelling	Linear elastic	Linear- equivalent	Nonlinear simplified	Nonlinear 1-D; 2-D	Full soil constitutive relationships

Well instrumented sites allow clear identification of nonlinearity when high quality strong motion recordings are obtained, by simply comparing the Fourier spectral ratio of soil to rock site motion for different amplitudes (strong versus weak motion, for instance).

Figueras et al. (1992), analysing records from the SMART-1 accelerometric array in Taiwan, showed a very different behaviour for small and large acceleration events. In the left part of Figure 4.7 the undamped response spectra obtained on rock (thick line) and on different soil sites (thin lines) for a weak motion (top) corresponding to an earthquake of magnitude 5.3 at 30 km distance to recording sites, and for a stronger motion (bottom) corresponding to an earthquake of magnitude 6.2 at 6 km distance.

The response spectra on soils are amplified, in all the frequency range, in the case of the lower input motion while for the stronger event a reduction in the amplitude of the high frequencies is observed (nonlinear behaviour). In the lower frequencies, the amplification observed on soil is much larger for the stronger motion. The same phenomena can be seen in the time histories (right): For the smaller event, peak accelerations (PGA) of 44.09, 47.16 and 48.69 cm/s^2 are observed at sites on rock, on

medium deep soil and deeper soil, respectively. This corresponds to peak ground displacements (PGD) of 0.91, 1.39 and 1.57 mm, respectively. For stronger ground motion (bottom) the acceleration obtained on rock is 181.50 cm/s^2 and on two soil sites it is reduced to 148.64 and 108.06. The PGD on rock is 5.5 mm and on soil sites 27.77 and 40.81 mm (this means that amplification of the PGD reaches a factor of 7) as displacements are related with the low frequency band of the spectra.

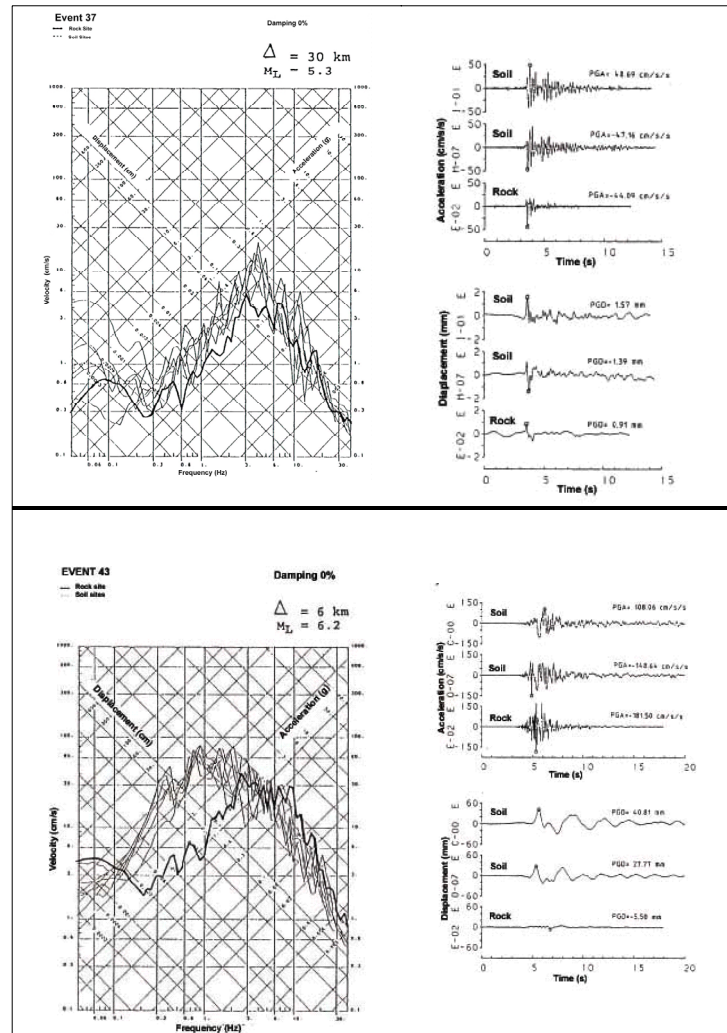


Fig. 4.7. Fourier spectra, accelerograms and displacement time histories obtained on rock and soil sites at the SMART-1 array, showing a very different behaviour depending on the input acceleration. Top: magnitude 5.3 event at 30 km distance. Bottom: magnitude 6.2 event at 6 km distance (Figueras et al., 1992)

4.6. Numerical methods for estimating local effects

The geological environment around a site is in general very complex both in geometry and in material characteristics. Current situations include basins with three-dimensional geometry filled with soft, unconsolidated materials with diverse properties, anisotropy and inhomogeneities (Figure 4.8).

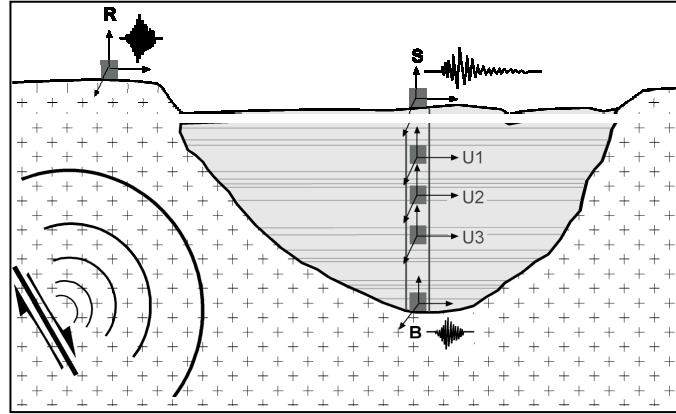


Fig. 4.8. Sketch of a sedimentary basin with instruments on rock outcrop, basement, boreholes and surface soils

Understanding of the entire process of wave propagation through this real medium is not an easy task, not only due to the complexity of the geological model, but also due to the complex nature of the multiple waves propagating inside the structure that will result in the ground shaking at each point on the surface. In addition to that, in case of large amplitude motions, as mentioned before, nonlinear behaviour of soils has to be considered. In order to analyse these phenomena and approach the prediction of the characteristics of ground motion at the surface, simplifications both in the wave field description as well as in the geological structure have to be made.

Numerical modelling with linear and nonlinear soil properties require quite sophisticated methods in 1-D, 2-D or in 3-D. While linear modelling might be easier to handle, but must include all kind of possible propagating waves, for the nonlinear analysis even the 1-D model requires a good characterisation of the mechanical properties of the soil layers.

4.6.1. LINEAR METHODS

4.6.1.1. 1D Models

The simplest approach to the problem is to consider a single horizontal layer with infinite length and uniform characteristics, overlaying a rigid semi-infinite body. This layer, exhibiting average characteristics of the soil in the basin, has a shear velocity V_1 , density ρ_1 , and thickness H (m). An estimation of the fundamental frequency of the basin is given by $f_0 = V_s/(4H)$. The amplitude of surface motion for the case of vertical incident SH waves can be computed with the impedance contrast between the two media, $C = (\rho_2 V_2)/(\rho_1 V_1)$ ($i=1$: soil medium; $i=2$: lower medium).

A less simple model consists of a series of horizontal infinite parallel layers over a bottom half space. The existence of various types of waves propagating inside the basin, even for the simplified horizontal layered case (inclined SH+SV; surface Rayleigh and Love waves; etc.) causes myriad solutions that can be observed at the surface. Also the problem of reflection/refraction (Thomson, 1950 and Haskell, 1953) at each boundary requires a great deal of expertise in order to adapt the models to more realistic situations where energy is absorbed.

This problem has been addressed by many researchers, considering not only the linear behaviour of the material, but also introducing the concept of nonlinearity. A later numerical approximation by Kennet and Kerry (1979) is known as the reflectivity method or the matrix propagation method. The structure is considered as a pile of homogeneous horizontal layers over the bedrock (half space). Each layer is characterised by its reflection and transmission coefficients. Figure 4.9 presents the transfer functions obtained with application of the Kennet method to different 1D structures.

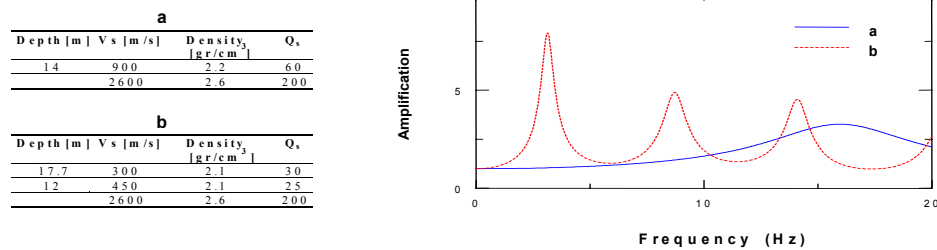


Fig. 4.9. 1D structural models and corresponding transfer functions computed with 1D lineal method. a) one sedimentary layer over a bottom halfspace; b) two sedimentary layers above a halfspace (Figueras, 1994)

4.6.1.2. 2D-3D Models

A step forward to solve the non-horizontal geometry of the layers is first to develop a 2-D model of the basin using more elaborate mechanical algorithms, such as Finite-Element (Paolucci, 1999; Gomes et al., 1999), Finite-Difference (Kamiyama et al., 1999; Moczo, 1989), discrete element methods (Sincranian and Oliveira, 2002) and Discrete wave-number methods (Bouchon, 1985). While 1-D methods give in general a good account for the soil response in many situations, these 2-D methods are needed to analyze edge-effects in some geometric layouts, in particular, for steep or abrupt lateral contrasts as those present in some alluvial valleys. One of the most used methods for 2-D computations is the Discrete wave-number, algorithm by Aki and Larner (1970), developing an idea of Lord Rayleigh (1896), considering the diffraction of plane waves at irregular discontinuities. This method has been further improved by Bard and Bouchon (1980a, b), Bard and Gariel (1986) and Sánchez-Sesma et al. (1989), among others. An example taken from the Volvi Valley (Greece) is shown in Figure 4.10, where the response in the time domain can be seen for a Ricker 1Hz wave propagation in the basin using the 1-D linear Kennett method and 2D finite-differences method. In the 2D modelling case the effects can be seen for wave conversions, wave diffractions and the creation of surface waves.

Complex models: Even though the theoretical basis is quite similar, different approaches have been developed, with increased degree of detail: 2-D, 3-D with various mechanical behaviour (visco-elastic, nonlinear), etc. Essentially four methods have been developed: i) analytic, which have closed form solutions for simple geometries; ii) ray method good for high frequency; iii) modal superposition of the Earth, adapted to the low frequency spectra; iv) boundary-integral methods (Sánchez-Sesma and Campillo, 1991); v) finite element or finite differences methods including linear and nonlinear properties (Moczo et al., 2000). All these methods need a great deal of calibration, but they are very useful for studying sensitivity of parameter values, etc.

Hybrid methods (Panza, 1993; Fäh, 1994) use the mode superposition of the Earth composed by concentric sphere layers to propagate the seismic motion from the source to a neighbourhood boundary around the site, and then use finite elements to propagate this motion from the boundary to the site considering the local soil 2-D characteristics. This method, initially developed for a lateral homogeneous Earth, has been extended to situations allowing for some lateral heterogeneity. It has the great advantage of simulating the entire wave field (P, S, surface, converted P-S waves, etc., if a large number of modal functions are taken into account), and consequently, simulating in a more realistic way the motion entering the region of more soft layers around the site. If used together with nonlinear soil characteristics, this method can be of great importance in merging the better description of wave field from source to near site, with the geotechnical approaches dealing with nonlinear effects of surface layers.

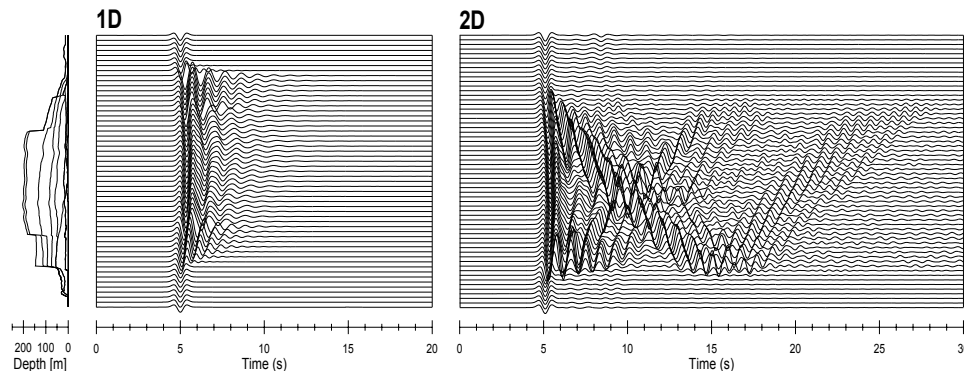


Fig. 4.10. Comparison between lineal 1D (Kennett) and 2D (finite-difference) numerical simulation of the propagation of a Ricker 1Hz wavelet along a sedimentary basin (EuroseisRisk project)

4.6.1.3. Empirical Green's Function method

The empirical Green's Function method is based in the principle that one can obtain the dynamic response of a given space (Earth) at a certain site for a unit impulse applied at another location, if there is a small event located at that location, for which the wave propagation was recorded at the site. From this point onwards the principle of superposition holds and can be generated for a wide range of situations. Convolution of the source function with the Green's function can produce a wave passage at that particular site. Of course there are many limitations of this method, even though it can

well represent the “path and the site effect” under certain circumstances: it should cover a wide range of spectral contents and cannot be extrapolated for energies high above the ones recorded.

There are other semi-empirical approaches such as Tsurugi et al. (2000) consisting of trying to remove source and path effect from moderate magnitude earthquake records.

4.6.2. NON-LINEAR METHODS

The geotechnical community has a long history of developing nonlinear methods. There are very simple methods, in geometry of soil strata, in the nonlinear approximation and in the type of propagating wave, which are commonly used in current applications, as well as quite sophisticated methods dealing with complex geometries, complex nonlinear representations and various types of waves. For a thorough review of the different concepts related to nonlinear soil mechanics see Prevost (1993).

The simplest case to analyse is a soil column under a quasi-linear behaviour, subjected to a vertical incidence of a shear wave. Even for this situation there are few models to compute the response of a soil column. For this case, knowledge of the variation of modulus of elasticity and of damping with shear strain is required for each layer composing the soil column. The simplest method (Seed and Idriss, 1969) considers that the soil behaves linearly but the modulus of elasticity and the damping change as a function of the level of distortion introduced by the amplitude of input. The SHAKE algorithm is essentially based on these ideas (Schnabel et al., 1972).

Another way to consider the nonlinear soil behaviour is the so-called method of characteristics (CHARSOIL) developed by Streeter et al. (1974) which is a 1-D finite differences method that propagates shear waves in different soil stratification and evaluates the soil response considering elastic, visco-elastic and non-linear behaviour; in this case the Ramberg-Osgood curve is used. Figueras (1994) introduced the water table parameter in the Charsoil algorithm in order to evaluate pore water pressure in modelling of the strong ground motion recorded on the SMART-1 accelerometer array in Taiwan.

The most recent algorithms include 3-D nonlinear analyses based on the most complete constitutive laws of all materials present in the basin or other topographic situations under analysis. The influence of the boundaries where ground motion is applied still constitutes a great complexity, partially solved within these problems through the consideration of absorbing boundaries or coupling to boundary methods. ® ABACUS is one among the few commercial software packages available for these analyses, already used in conjunction with the study of volcanic hills (Sincraian and Oliveira, 2002). Another method was developed at École de Ponts et Chaussées, Paris (Aubry et al., 1986; Aubry and Modaressi, 1996).

The nonlinear analysis of soil deposits is of major importance in the evaluation of liquefaction potential, compaction, lateral spreading and landslides, and indispensable for the estimation of their effects.

4.7. Experimental methods for estimating local site effects

4.7.1. OBSERVATIONS FROM EARTHQUAKES

The most direct way to investigate seismic local effects is to analyse the response of the different soil conditions which are present in the study area to real, strong, moderate and small, seismic events. The following methods are currently being used:

4.7.1.1. *Macroseismic observations*

This is a direct method of observation of effects after an earthquake. Observed damage mainly on buildings but also in other systems (structures and lifelines) can be mapped according to pre-established scales for damage classification. One of the last attempts to improve the estimation of intensity was the new European Macroseismic Scale, EMS-98 (Grünthal, 1998). Damage observations are extremely useful information that serves critically to calibrate any microzonation method.

Guidoboni et al. (2003) show the interest of this type of analysis studying the damage distribution in the city of Palermo, Italy, for three past earthquakes that occurred in 1726, 1823 and 1940. Dividing up the study area using a grid of 100 m×100 m elements they showed a systematic amplification of effects in some of the grid elements which they interpreted in terms of near-surface geology. Instrumental records obtained from a M5.6 earthquake that occurred off the Palermo coast in 2002 validated the macroseismic results.

4.7.1.2. *Strong ground motion recording*

When dense networks of strong motion recorders are installed in a specific area, the direct use of the records after a moderate or strong earthquake gives the most reliable evaluation of site effects. These records include most of the information of the site, including nonlinear effects. However, complete sets of records from dense networks are unfortunately scarce and only in a very few cases was it possible to draw zoning maps from them. This is the case of the work carried out by Iglesias (1991) comparing maximum horizontal acceleration patterns observed in Mexico City for recent earthquakes with the observed damage in former events. Even though the comparison was quite satisfactory there were still some discrepancies observed at several sites, probably due to the complex nature of wave propagation in the Mexico City valley related to source location.

Duration of ground motion clearly increases in central valleys in comparison with rock sites, as the example of Volvi, Greece (Beauval et al., 2004) and of São Sebastião, Azores (Montesinos et al., 2003).

4.7.1.3. *Experiments based on weak earthquake ground motion recording*

Fortunately, in a given place, moderate-to-strong earthquakes do not occur very often and, consequently, strong motion records can not be obtained in a short time period. Records from small events are used instead to characterize local effects. The most direct technique to investigate the effect of soft sediments consists of computing the spectral ratio between two seismic records from a given earthquake, one obtained at the surface and the other at a certain depth in a borehole (Sensors S and B in Figure 4.8); this is the so called SBSR, *Surface - to - Borehole Spectral Ratio*.

Strong motion networks in different countries have operative sets of accelerometers installed in boreholes at different depths. Records of an earthquake obtained in the Ashigara Valley (Japan) in rock site and different soil (surface and borehole) sites are shown in Figure 4.11, as an example of the clear amplification of the ground motion, and the increase on the record duration, from depth to the surface.

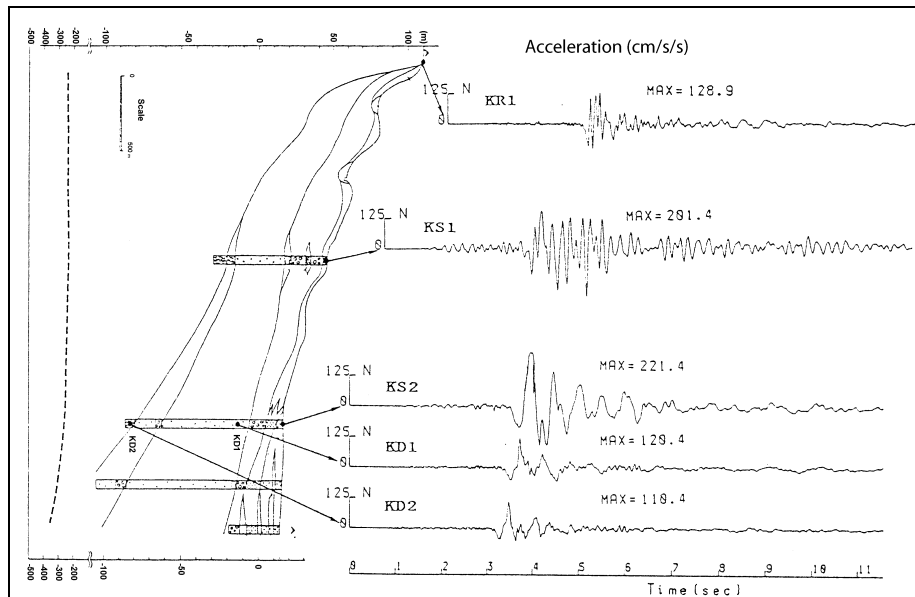


Fig. 4.11. Records of a $M=5.1$ event in the Ashigara Valley (Japan). Recorded on rock site (KR1) and different soil sites, KD1 and KD2 are boreholes at 30 and 80m depth (Kudo, 1991)

However, considering the high cost of these experiments, this method can be applied only at very specific sites and can not be used massively as a microzonation technique.

In the *Standard Spectral Ratio (SSR)* method, introduced by Borchardt (1970), instead of using the borehole sensor needed when applying SBSR, the Fourier spectrum of a given earthquake recorded at the site to be investigated (site S in Figure 4.8) is divided by that of a nearby reference site on bedrock (site R). Provided that the two sites have similar source and path effects and that the reference site has negligible site response, the obtained soil-to-rock spectral ratio gives a reliable estimation of earthquake soil response. Steidl et al. (1996) pointed out that the choice of the reference site might be critical, since rock sites might have their own site response and then a deconvolution would be needed to obtain an estimate to the bedrock record.

Alternate non-reference techniques have been developed. One of these methods, the so-called *Horizontal- to - vertical spectral ratio (HVSr)*, is based on the computation of the spectral ratio between the horizontal and vertical (H/V) spectra of the S-wave window at each site. This method was introduced by Lermo and Chávez-García (1993) to characterize site response. The basic assumption is that only the horizontal

components are influenced by the local structure. Lermo and Chávez-García (1993) found, for three different sites in Mexico, that both frequencies and amplitudes of resonant peaks were similar in the SSR and the HVSR. Theodulidis and Bard (1995) concluded that the HVSR shape appears to be well correlated with surface geology but the absolute level of amplification does not coincide with the absolute level of measured HVSR, which seems to be dependent on the incident wave type. Theodulidis et al. (1995) have applied H/V spectral ratio method to strong motion records from Greece and Taiwan obtaining reasonable results.

A number of other techniques have been proposed, among them those based on the inversion of *coda wave* and analysis of the coda decay (Phillips and Aki, 1986). One of the main drawbacks of these techniques is that in populated areas the ambient noise induced coda records are very difficult to obtain. Consequently, these methods have not been widely used for microzoning purposes.

4.7.2. MICROTREMOR MEASUREMENTS

One of the main practical problems associated to the methods that are based on weak or strong earthquake ground motion recording is that several earthquakes have to be recorded simultaneously on rock and on soils sites, imposing long periods of observation, even more when the seismic activity is moderate. Recording seismic events under different soil conditions for microzoning purposes is a slow and costly task. Microtremor measurements, instead, are easy and affordable to be carried out.

The first to use *microtremors* as a good source for the study of local effects was Kanai (1957) considering that the context of microtremors was white noise. The origin of this noise, also known as *ambient noise* or *cultural noise*, is still under debate, but a large portion might be due to surface waves and essentially of Rayleigh nature. While for frequencies below 0.5 Hz *microseism* is caused by oceanic waves or other perturbations of meteorological origin at large distances, for shorter periods (frequencies larger than 1 Hz) microtremors are essentially due to human activities such as traffic. The nature of surface waves, as an important part of microtremors, constitutes the basis of the experimental methods to determine the natural periods and amplifications of the soil strata.

The following techniques based on microtremor recordings are currently being used:

An analogous technique to that of the SSR described above uses spectral ratios between microtremor recordings at different soil sites and at the reference rock site (*sediment-to-bedrock noise ratio, NSR*). The main problem of this technique is the possible different origin of the noise recorded at the site under investigation and at the reference site. The identification of a common wave train for the stations involved is very difficult. Kagami et al. (1986), Field et al. (1990) and Seo et al. (1991) among others applied this method to different areas with successful results within given frequency bands. However, Gutierrez and Singh (1992) and Lermo and Chavez-Garcia (1994) among others report dissimilarities between spectral amplitudes of strong motion and microtremor records.

A technique using horizontal-to-vertical spectral ratios of microtremors (instead of earthquakes as in the HVSR technique) was first applied by Nogoshi and Igarashi (1970, 1971) and later popularised by Nakamura (1989b). This technique, usually called

the Nakamura's horizontal- to -vertical noise ratio (*HVNR*) or, simply, the *H/V* or *QTS*, *Quasi-Transfer Spectra*, is very frequently used for microzonation studies. Even though it is not completely supported by a sound theoretical basis, it has been shown as useful in some places.

Problems, possibilities and limitations of this method have been discussed by many authors (Lermo and Chávez García, 1994; Lachet and Bard, 1994; Mucciarelli, 1998; among others). It should be considered that Nakamura's method gives a good account of the fundamental frequency at the site but do not give confident values of the corresponding amplification factor (Nakamura, 2000). In some soil conditions the largest amplifications occur not at the fundamental frequency but at higher modes. In simple situations, such as the case of a relatively homogeneous layer of soft, low velocity, soil lying over the rock basement (high impedance contrast), Nakamura's method is very efficient for determining the fundamental frequency which, in this case coincides with the predominant frequency (frequency for which the maximum amplification occurs). But when one tries to determine the fundamental frequency of more complex multilayer systems Nakamura's method gives low values as it provides an estimation of the fundamental frequency (produced by the deeper structure), which is not the frequency for which the maximum soil amplification takes place. This problem has been encountered in several cases, e.g. comparing modelling results with microtremor measurements in the city of Barcelona (Cid et al., 2001) as illustrated in Figure 4.12. While in zone III and I Nakamura measurements do not differ much from the predominant frequencies obtained from modelling, in zone II Nakamura's measurements account for the "fundamental frequency", first peak on the transfer function obtained numerically, which is a lower frequency than that where the maximum amplifications occur. The consideration of predominant frequency as one important parameter for microzonation should be taken with caution, as discussed in Chapter 8, because performance of buildings will depend not only on source / path of seismic waves, but also on the inelastic response of soil and structure.

The composition of noise wavefield is still a very controversial topic. The project SESAME (Bard, 2004) (<http://SESAME-FP5.obs.ujf-grenoble.fr>) offers several advancements in this field by comparing analytical developments with in-situ measurements. It contains a great proportion of surface waves in relation to body waves but the proportion of Rayleigh to Love waves is very questionable. Following Bard (2004), "the origin of *H/V* peak is multiple: Rayleigh wave ellipticity, Airy phase of fundamental Love wave mode, and partly fundamental resonance of S body waves", also a checklist of the main problems that may or may not influence the final results of *H/V* method is provided.

It can be concluded that the use of simple experimental methods without comparison with modelling results are not reliable unless they are based on strong motion records produced by several earthquakes. Both numerical and experimental methods should be complementarily applied in microzoning projects.

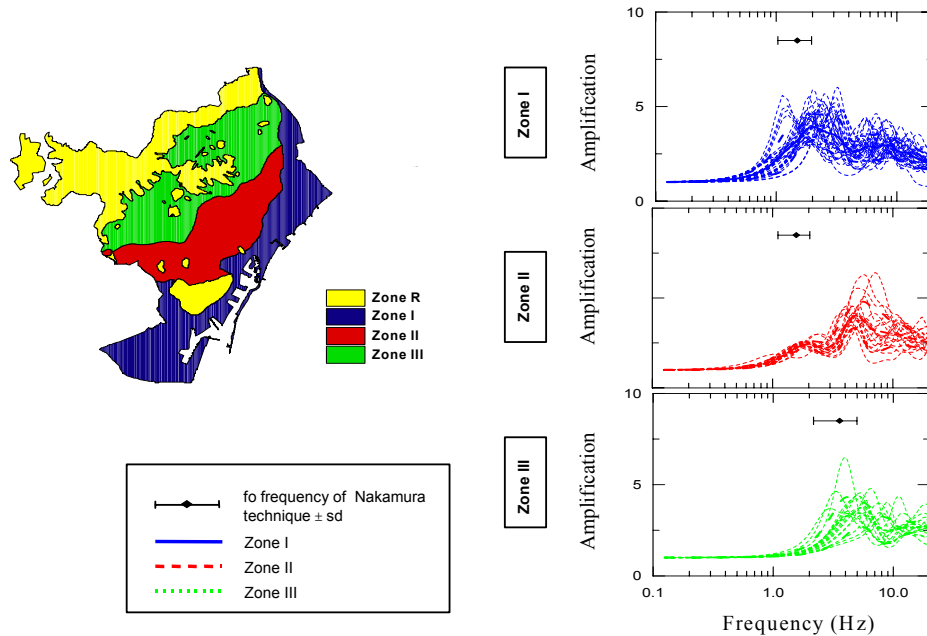


Fig. 4.12. Three plots with the transfer functions obtained at different points in three zones of Barcelona are shown together with the mean frequency (with standard deviation brackets) measured in each zone

4.8. Topographic effects

The influence of topography on the seismic signal is well known. It has been observed in past earthquakes such as the 1971 San Fernando, 1985 Central Chilean, 1989 Loma Prieta, 1994 Northridge and 1999 Athens events, among others, that concentrated patterns of damage and unusually high amplitude recorded ground motion near the crests of ridges are present (Celebi, 1987; Spudich et al., 1996; Bouckovalas and Koutretzis, 2001). Buildings located at hill tops suffer much more intensive damage than those located at the base.

Research on topographic effects has generally focussed on numerical studies of two-dimensional ridges or canyons (Geli et al., 1988; Zhang et al., 1998; Bouckovalas and Papadimitriou, 2004) and on empirical studies based on instrumental deployments that are in general limited to low amplitude recordings of aftershocks (Celebi, 1987; Pedersen et al., 1994). The main results from topographic effects studies pointed out by Brune (1984), Sanchez-Sesma (1983, 1985) are: i) amplification of SH waves near the crests of canyons; ii) the presence of a shear fundamental resonance in a 3-5 Hz frequency band; iii) dependence on the radiation wave field, angle of incidence and canyon dimensions.

Chávez-García et al. (1996; 1997) present a new comparison between numerical and empirical approaches; they use on one hand a generalised inversion technique and on the other the experimental HVSR (Horizontal-to-Vertical Spectral Ratio) technique explained in the previous section. They conclude by recommending the use of the HVSR, Nakamura, technique, which is in principle oriented to the study of the influence of soil conditions on ground motion, as a good approach to analyse also topographic effects. An overview of the subject of topographic effects can be found in Bard (1998) and Alvarez Rubio (1999). The Guidelines AFPS (1995) from the French Association for Earthquake Engineering give a simple way to calculate the topographic amplification coefficient and have been extensively used elsewhere. At present many countries and regions of the world have available high precision digital terrain models (DTM) which are very useful to predict the effect of topography on earthquake ground motions. However, one of the main problems in the identification of such effects is still the difficulty to distinguish between the topographic or geological origin of the observed ground amplifications. The various available techniques have to be applied simultaneously in order to reach satisfactory results.

4.9. Liquefaction and induced effects

Liquefaction is defined as the transformation of a granular material from a solid to a liquefied state as a consequence of increased pore water pressure and reduced effective stress (Martin et al., 1975; Marcuson 1978, Castro and Poulos, 1977). Increased pore water pressure is induced by the tendency of granular materials to compact when subjected to cyclic shear deformations. The change of state occurs most readily in loose to moderately dense granular soils, such as silty sands and sands and gravels capped by or containing seams of impermeable sediment. As liquefaction occurs, soil stratum softens, allowing large cyclic deformations to occur. In loose materials softening is also accompanied by a loss of shear strength that may lead to a large shear deformations or even flow failure under moderate to high shear stresses, such as beneath a foundation or a sloping ground. In moderately dense to dense materials, liquefaction leads to transient softening and increased cyclic shear strains, but a tendency to dilate during shear inhibits major strength loss and large ground deformations. A condition of cyclic mobility or cyclic liquefaction may develop following liquefaction of moderately dense materials. Beneath gently sloping to flat ground, liquefaction may lead to ground oscillation or lateral spread as a consequence of either flow deformation or cyclic mobility. Loose soils also compact during liquefaction and reconsolidation, leading to ground settlement. Sand boils may also erupt as excess pore water pressure dissipates. (Youd et al., 2001)

Figure 4.13 is a clear example of the liquefaction phenomenon as observed by the tilted buildings and excessive settlements in Adapazarı during the 1999 Kocaeli earthquake.

Foundation material did not support the shearing stresses developed during the passage of seismic waves causing the partial sinking of the building which led to overturning in some buildings with very shallow foundation depths and excessive settlements in others. These phenomenon observed throughout parts of Adapazarı did not occur in buildings supported by piles or in buildings with basements.

One possible approach is microzonation mapping in terms of the liquefaction susceptibility that may be based on the method developed by Youd et al. (2001). In this approach safety factors need to be calculated along the whole depth of the borehole for all liquefiable soil layers, based on the available SPT-N blow counts using the surface peak ground accelerations calculated from site response analysis.



Fig. 4.13. Evidence of liquefaction related damages during the 1999 Kocaeli earthquake

In order to evaluate the severity of induced liquefaction on the ground surface the method developed by Iwasaki et al. (1978) could be used. Iwasaki et al. (1978) quantified the severity of possible liquefaction at any site by introducing a factor called the liquefaction potential index, P_L , defined as

$$P_L = \int F(z)w(z)dz \quad (4.2)$$

where z is the depth below the ground water surface, measured in meters; $F(z)$ is a function of the liquefaction resistance factor, F_L , where $F(z)=1-F_L$ but if $F_L>1.0$, $F(z)=0$; and $w(z)=10-0.5z$.

For the purpose of demonstrating the proposed approach, the liquefaction susceptibility microzonation map was produced for the Gölcük region in western Turkey. Based on the results reported by Iwasaki et al. (1978), three zones (A, B, and C) were identified with respect to liquefaction potential index. Zone A is where the liquefaction potential index is $P_L>15$, zone B is the intermediate zone where the liquefaction potential index is $5>P_L>15$, and zone C is the safest zone where the liquefaction potential index is $P_L<5$. The microzonation map for liquefaction susceptibility determined by this approach is shown for the Gölcük region with respect to surface geology in Figure 4.14 (Ansal et al., 2004).

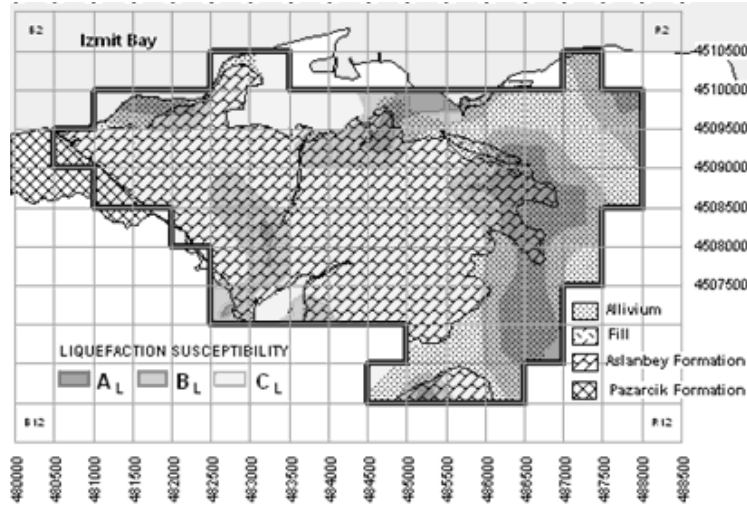


Fig. 4.14. Comparison of liquefaction susceptibility map with geological formations (Ansal et al., 2004)

4.10. Final Considerations

Seismic microzoning is clearly a powerful tool towards reducing earthquake risk in urban areas.

- Different experimental and modelling techniques are currently used for microzoning. However, it is still necessary to assess the limits of validity of those methods through comparison of results obtained in different areas using various techniques and also to calibrate them with real strong earthquake data. Comparison of experimental methods dealing with low amplitude in-situ measurements (such as wave velocity) and laboratory testing (resonant column, etc.) is of great importance.
- For this purpose it is recommended that the information from the various studies which are being carried out throughout the world should be collected and analysed under homogeneous criteria.
- More research in these fields is necessary in order to reduce the uncertainties that are present in the current studies and to satisfy the needs of society for having better established seismic codes.

Once microzoning analysis is well established its results should be incorporated in seismic regulations, both at the land-use and structural engineering levels (at the local level such as EC-8), especially in zones with dense population as in urban areas.

There still are microzonation methods of very different scope: some require simple techniques with one or two-parameters, others are very sophisticated with various parameters and detailed in-situ and laboratory measurements. Studies comparing these two different approaches in the light of cost-benefit analyses should be encouraged.