Lecture 14: Concept of ground response; local site effects and evaluation methods; ground motion amplifications and estimation; development of response/design spectrum

Topics

- Effects of Earthquake
- Site Effects
- Earthquake damage is influenced by ground motion
- Amplification Definitions
- Basic Physical Concepts
- Topographic effects and A general description and Estimation
- Estimation of site effects including Dimensional effects
- Methods to Estimate Site Effects
- Experimental-Empirical Method
- Standard Spectral Ratio Technique (SSR)
- Generalized Inversion Scheme Technique (GIS)
- Coda wave technique
- Horizontal to Vertical Spectral Ratio Technique (HVSR)
- Comments on SSR and HVSR
- Empirical Methods
- Semi-empirical Methods
- Theoretical (Numerical and Analytical) Methods
- Simple analytical models
- One dimensional response of "soil columns"
- Advanced 2D/3D models and methods
- Development of Response/Design Spectrum

Keywords: *Ground Response, Amplification, Response Spectrum, Design Spectrum*

Topic 1

Effects of Earthquake

- Earthquakes produce various damaging effects to the areas they act upon. This includes damage to buildings and in worst cases the loss of human life. The effect of the rumbling produced by earthquakes usually leads to the destruction of structures such as buildings, bridges, and dams. They can also trigger landslides.

- 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.

Topic 2

Site Effects

- Surface geology and geotechnical characteristics of soil deposits have a paramount importance on seismic ground shaking. The variations of ground shaking in space, amplitude, frequency content and duration are called “site effects”.

- Site effects include primarily the effects of impedance contrast of surface soil deposits to the underlined bedrock, or firm soil considered as rock, which is rather well modelled using 1D ground models (i.e. linear elastic, equivalent linear or non-linear). They also include deep basin effects, and basin edge effects, produced from strong lateral geological discontinuities (i.e. geological anomalies, faults etc).

- These effects which are dominated by the presence of surface waves additionally to body waves can only be studied using 2D and 3D models. Finally, site effects are also dealing with spatial variation of ground shaking characteristics due to surface topography.

- The physics and the importance of site effects is more and more understood and quantified with the increasing number of strong motion measurements in dense accelerometric arrays all over the world. Advanced numerical models using powerful computer facilities have also contributed significantly to the progress during the last two decades.

- Mexico City (1985) and Loma Prieta (1989) earthquakes, recorded in many stations located in different and well constrained ground conditions, relieved for the first time in a very precise experimentally documented way, the importance of the impedance contrast.

- Additional evidence of the significance of the more complex site effects on seismic ground motions have been brought from recent destructive earthquakes (Armenia 1988, Philippines 1990, Northridge 1994, Kobe 1995, Kozani 1995, Aegion 1995, Kocaeli and Duzce, Turkey 1999, Athens 1999, Ji-Ji Taiwan 1999 etc).

- However, there is not yet a wide-spread agreement as regards to what could be the best way to estimate the amplification or de-amplification or the spatial variability caused by site effects.

- There are also different approaches to model and account for site effects in seismic risk studies. A typical example is the very different approach to model site effects, which range from 1D to 3D models, using linear or non-linear material behaviour.

- Probably this may be attributed to the fact that, still, very few site effect studies have been performed both involving a detailed study of subsurface structure and numerous high-quality recordings and/or observations of earthquake ground motion.

- In general, site effects may be defined as the modification of the characteristics (amplitude, frequency content and duration) of the incoming wave field, due to the specific characteristics and geometrical features of the soil deposits and the surface topography.

- The modification is manifested as an amplification or de-amplification of ground motion amplitudes at all frequencies, which is dependent on many parameters such as Dr, PI, Vs, Vp, Go, shear modulus degradation with shear strain increase, soil internal damping, soil non-linearity, etc which are inherent of the dynamic soil behaviour and its physical properties, others are related to the characteristics and the intensity of the incoming wave-field and others are related to purely geometrical features like surface/bedrock topography, lateral geological discontinuities etc.

- In order to understand the physics and the spatial variation of ground motion in each particular case and particularly to be able to quantify the phenomenon, it is necessary to have an accurate description of the above characteristics for the specific site.

- As a result, site and soil characterization is an important and indispensable parameter for site effect analyses.

Topic 3

Earthquake damage is influenced by ground motion

- Earthquake ground motions are influenced by many factors, such as source mechanism, propagation path of waves, local site conditions, and so on. The importance of the maximum amplitude and frequency content has been recognized. Various indices, for example, peak ground acceleration, peak ground velocity are strongly affected by local site conditions, such as complex surface geology and irregular topography.

- On the other hand, experiences from a number of earthquakes have showed that little damage to structures occurred because of the short duration even though the accelerations and spectral amplitudes were large. Many researchers have also noticed the fact that the duration of earthquake ground motions differs from site to site even during the same earthquake. Therefore, an accurate, quantitative prediction of earthquake ground motions cannot be achieved without understanding the duration characteristics.

- Earthquake ground motion is highly uncertain and difficult to be predicted (Geller et al 1997). Earthquake uncertainties include time, location, magnitude, intensity, and duration.

- Three factors of wave vibration are usually employed to characterize strong ground motion: amplitude, frequency and duration.

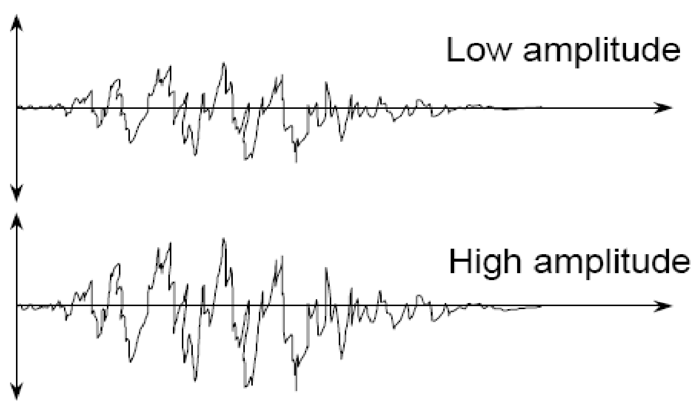

Fig 14.1: Low and High Amplitude of earthquakes waves

- Local geology and topography influence the travel path and amplification characteristics of seismic waves. For example, natural and artificial unconsolidated foundation materials, such as sediments in river deltas and materials used as landfill, amplify ground motions in comparison to motion measured on consolidated sediments or bedrock. Low and high amplitude records are shown in Figure 14.1.

- The thickness of unconsolidated soil also affects the ground shaking. Ground motions may be amplified by sedimentary layers with various thickness and degrees of consolidation.

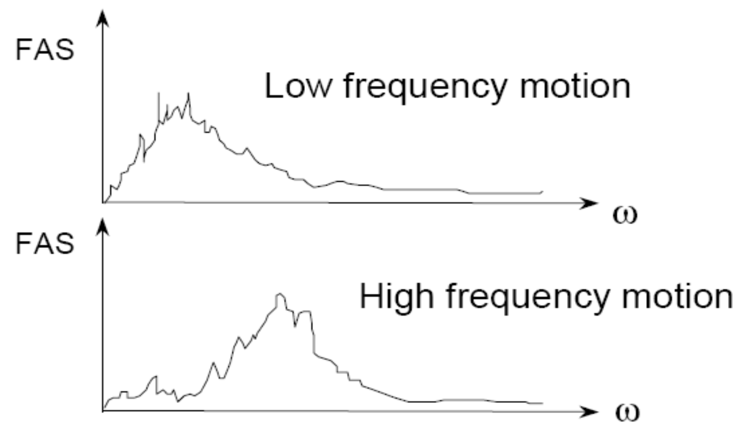

Fig 14.2: Low and High Frequency Motions

- Structures founded on rock will, in general, be subjected to short-period (high frequency) motion, while soft sites result in long period (low frequency) excitation. Typical low and high frequency motions are shown in Figure 14.2. The ratio between the period of the site and that of the building is important in estimating the amplification effects; this is known as site resonance effect. Resonance is a frequency dependent phenomenon.

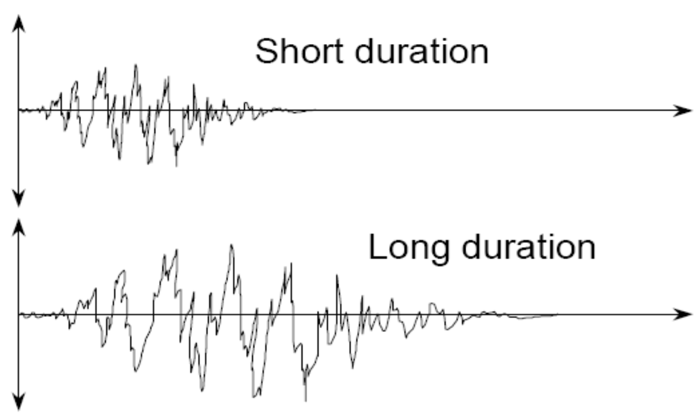

Fig 14.3: Short and Long duration earthquakes

- **Duration** of strong ground motion is an important parameter playing a direct role in the destructiveness of an earthquake, and is a function of fault parameters (i.e., size of the rupturing part of the fault, rupture velocity), path from source to station, local site effects (soft soil, basin effects), and directivity. Typical short and long duration earthquake records are shown in Figure 14.3

- A number of definitions exist in the literature for the duration of the strongest part of shaking [Bommer and Martinez-Pereira, 2000]. Perhaps the most widely used definitions of strong ground motion duration are the (1) bracketed duration and (2) significant duration.

- The bracketed duration is the interval between the two points in time where the acceleration amplitude first and last exceeds a prescribed level such as 0.03 g [Ambraseys and Sarma, 1967] or 0.05 g [Bolt, 1969]. Significant duration is defined as the time required to build up from 5 to 95% of the integral of ($\int a2\ dt$) for the total duration of the record, where a is the acceleration [Trifunac and Brady, 1975]. Arias [1970] showed that this integral is a measure of the energy in the ground motion acceleration.

Topic 4

Amplification Definitions

- The nature of soil response in earthquakes depends on the amplitude and duration of motion. High amplitude motion tends to cause inelasticity in the soil. Long duration shaking increases the susceptibility to liquefaction of saturated and partially saturated soils.

- When the soil responds elastically, the observed motions at the surface are amplified proportional to the input ground motion. On the other hand, for inelastic response, the soil absorbs large amounts of the energy corresponding to large amplitude of ground motions.

- The attenuation relationships of Ambraseys et al. (1996) were used to calculate acceleration spectra for a magnitude 5.5 earthquake at a distance of 10 km on three sites: rock, stiff and soft soil and shown in Figure 14.4.

- It is demonstrated that the amplification characteristics are distinct. Moreover, the acceleration amplification for soft soils extent over a larger period range than the amplifications for the other two soil categories.

- The longer the predominant period of vibration of the site, the greater is the period at which the response spectrum high amplification region occurs. The shape of the spectrum is also different, but not drastically so.

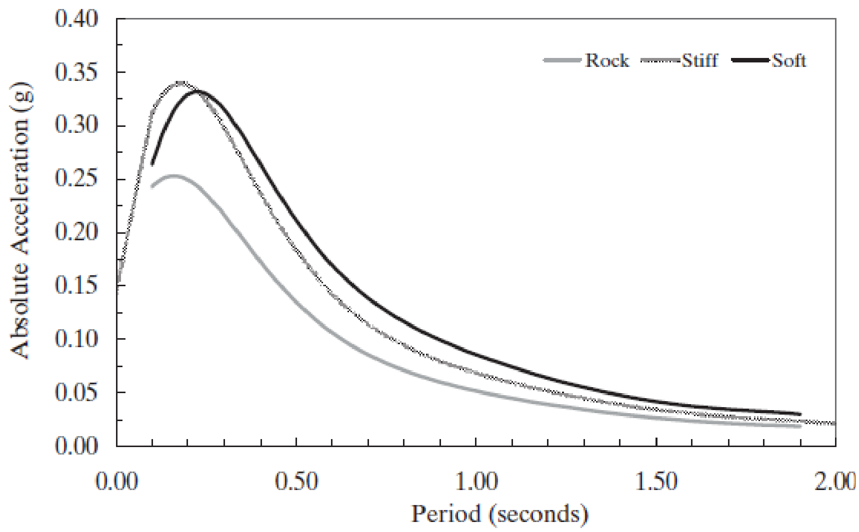

Fig 14.4: Spectra for a magnitude 5.5 earthquake at 10 km for different site conditions (Adapted from Ambraseys et al., 1996)

Topic 5

Basic Physical Concepts

- Earthquake recordings at soil surface include “information” that is related to three stages of the earthquake phenomenon evolution:

    1. The source activation (fault rupture),
    2. The propagation path of seismic energy and
    3. The effect of local geology on the wave-field at the recording site (Figure 14.5).

- The physical amplitude r(t), potentially representing acceleration, velocity or displacement, which is recorded at a site, can be written in the time domain in the form of the convolution of three factors:

$$r(t) = e(t) * p(t) * s(t) \tag{14.1}$$

- Where e(t) is the source signal, p(t) is the function that characterize the propagation from the source to the site and s(t) expresses the effect of local soil conditions on ground motion (which from now on will be denoted as site effects).

$$R(f) = E(f).P(f).S(f) \tag{14.2}$$

- where R(f), E(f), P(f), and S(f) are the Fourier transform of the time depended functions r(t), e(t), p(t), and s(t) respectively. All of the above mentioned factors contribute to overall site response, either independently or in combination with the others. However, only the “site effects” factor is discussed. The other two factors are simply considered in the presentation of different models that are used to estimate ground response.

- The term “site effects” introduces the effect of local geology in the modulation of seismic wavefield at a recording site; where local geology consists of surface sedimentary sites and surface topography. The main parameters that characterize a site are the geometry of the soil stratigraphy (thickness and lateral discontinuities), the shape of the topographic relief and the dynamic, physical and mechanical properties of soil and rock materials.

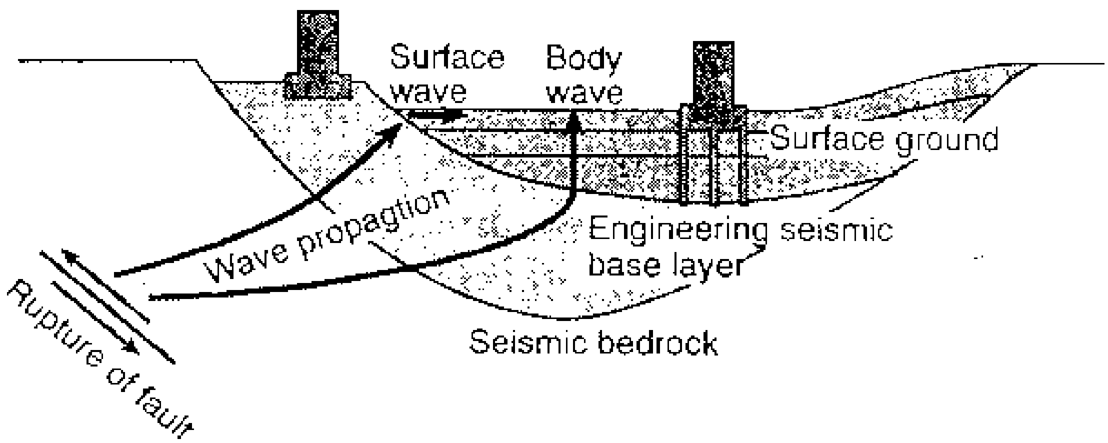

Fig 14.5: Schematic illustration of the wave propagation from fault to ground surface (Yoshida and Iai, 1998; Reproduced with permission from the Swets & Zeitlinger Publ.)

Topic 6

Topographic effects and general description and Estimation

- Surface soil formations are the product of the long-lasting process of erosion, weathering and deposition; they are responsible for significant amplification and spatial variation of surface ground motion. Surface topography, in its simplest form, consists of convex (ridges, mountains, hills …) or concave surfaces (valleys, basins, canyons …) with different behavior during an earthquake.

- In case of convex topographies, significant amplification is observed at the crest compared to that at the foot, while in the concave ones, the amplification varies at the lateral parts than at the base.
- The effect of local geology on ground motion also depends on other parameters such as the intensity, the frequency and the incidence angle of the incoming wavefield (for strong or weak earthquakes) which in combination with the local site conditions might introduce non-linear phenomena.

- Generally, it could be stated that there is a large variety of parameters according to which, someone could categorize site effects, a fact that confirm the complexity and the need to understand the physical background of this phenomenon.

- A general description of "site effects" could be defined as follows: "Surface soil formations and surface topography modify the characteristics (amplitude, frequency content and duration) of the incoming wavefield resulting to the amplification or deamplification of ground motion".

- A simple qualitative and quantitative estimation of site effects is often expressed by the amplification factor Amax and resonant – fundamental and higher ones - frequencies fres.

- By combining observations from past earthquakes with computer-based predictions, the SCEC working group quantified how levels of ground shaking are modified by various characteristics of local geology. The two found to be most important are the softness of the ground at a site and the total thickness of sediments below a site.

- Although scientists already knew that ground types of different softness had different levels of shaking relative to each other, the SCEC (Southern California Earthquake Center) study is the first that has assigned numerical values to these effects on such a broad scale.

- Softness of the ground at a site- Seismic waves travel faster through hard rocks than through softer rocks and sediments. As the waves pass from harder to softer rocks and slow down, they must get bigger in amplitude to carry the same amount of energy. Thus, shaking tends to be stronger at sites with softer surface layers, where seismic waves move more slowly.

- Total thickness of sediments below a site- In an earthquake, as the thickness of sediment increases, so too does the amount of shaking. For example, shaking levels double from the edge of the Los Angeles Basin, where the sediments are thin, to the middle of the basin, where sediments reach a thickness of more than 6 kilometers (4 miles). A basin depth calculator can be used to determine this thickness under specific areas.

Topic 7

Estimation of site effects including Dimensional effects

- It has been long recognized that the amplitude of earthquake ground motion is affected by both the properties and configuration of the near surface material through which seismic waves propagate. These properties are impedance -

resistance to particle motion - (Aki and Richards, 1980) and damping (attenuation).

- For horizontally polarized shear waves (SH), impedance can be defined (Equation below) as the product of the density (ρ), the shear wave velocity (Vs) and the cosine of the angle of incidence (Figure below).

$$I = \rho.Vs.\cos\theta, \quad \cos\theta \cong 1 \quad thus \quad I = \rho.Vs \qquad (14.3)$$

- Incidence angle, θ, is usually small near the surface of the earth and its cosine can be assumed to be equal to unity. As a seismic wave passes through a region of decreasing impedance, the resistance to motion decreases and, to preserve energy, the amplitude of the seismic wave increases.

- When there are sharp changes (decrease) in impedance below the earth's surface (such as sediments/rock interfaces), an increase in amplitude of the upwardly seismic wave is observed due to resonance, as some of the seismic waves transmitted into the upper layer get trapped in this layer and begin to reverberate.

- Damping or inelastic attenuation is substantially greater in soft soils than in hard rocks and mitigates the increase in amplitude of seismic motion due to resonance. The fundamental phenomenon responsible for the amplification of motion in soil sediments is the trapping of seismic waves due to the impedance contrast between sediments and the underlying bedrock.

- For the simplest case of a soil layer with density ρ_1 and shear wave velocity Vs_1 overlying a stiffer layer with density ρ_2 and shear wave velocity Vs_2 (Figure 14.6), the impedance contrast is expressed by the formula:

$$C = \frac{\rho_2.Vs_2}{\rho_1.Vs_1} \qquad (14.4)$$

- To understand the basic concept of site effects, the simplification of the physical complex phenomena is instructive. Thus, when the structure is horizontally layered (1- dimensional structures), this trapping affects only body waves traveling up and down in the surface layers (Figure 14.6).

- When the sediments form a 2- or 3- dimensional structure due to soil thickness variations, this trapping also affects surface waves which develop on the sediments/bedrock interfaces and thus reverberate back and forth. In all cases, this effect is maximum when the reverberating waves are in phase with each other. The interference between these trapped waves leads to resonance.

- Resonance therefore, is a frequency-dependent phenomenon related to the geometrical and mechanical (density, P-wave and S-wave velocities, damping) characteristics of the soil structure. While these resonance patterns are very simple in the case of a 1D structure (vertical resonance of body waves), they become more complex in 2D and 3D structures. The fundamental resonant frequency may vary between 0.2 Hz (for very thick deposits or for extremely soft materials) and 10 Hz or more (for very thin layers of deposits or weathered rocks).

- The amplitude of fundamental resonant peaks is mainly related to the impedance contrast between surface soil layers and underlying bedrock, to the material damping of sediments and to a lesser degree with the characteristics of incident wavefield (type of waves, incidence angle, near or far field …). For the simplest case discussed above, the amplification at the fundamental resonant frequency is given by the formula:

$$A_0 = \frac{2}{\frac{1}{C} + 0.5.\pi.\zeta 1} \qquad (14.5)$$

Where C is the impedance contrast and $\zeta 1$ the material damping of the sediments. For the case of very small damping ($\zeta 1 = 0$), the maximum amplification is simply double the impedance contrast. Another interesting observation is that when the wavelength, λ,

$$\lambda = Vs_1.T \qquad (14.6)$$

- λ is much longer than the thickness of the layer (meaning that $\omega H/Vs_1 \cong 0$), the amplitude of surface displacements is doubled. This is called the free surface effect and is caused by upgoing seismic waves being reflected off the free surface of the earth. At the surface, both upgoing and downgoing reflected waves are exactly in phase and the resultant amplitude at that location is doubled.

- Figure 14.6 provides an illustration of the effect of resonance in the frequency domain, particularly a low resistance sedimentary layer overlying hard rock (impedance contrast c=5). Without taking into account the free surface effect (where the amplification would be doubled as mentioned previously), a 100 m thick layer produces peaks of amplification at about 0.5, 1.5, 2.5 Hz and higher. On the other hand, a 50 m thick layer produces peaks at 1.0, 3.0 Hz and higher.

- It can be stated therefore that, the amplification of higher peaks decreases with increasing frequency, due to the consideration of inelastic attenuation or damping, which in this specific case takes a relatively large value. It has been shown, both experimentally and theoretically that this amplitude very often reaches values between 6 and 10, while in the extreme case, exceeds 20 (high impedance contrast and small damping).

- In case of 2D and 3D structures, fundamental frequency depends also on the geometry of the soil structures. The lateral geometry of these structures is affecting the amplification level at resonant frequencies especially when the material damping is small.

- Complex effects that are introduced due to the consideration of the finite lateral extent are due to the locally generated at the discontinuities (edges, faults, etc) and laterally propagated surface waves. The effect of these surface waves is manifested in two ways:

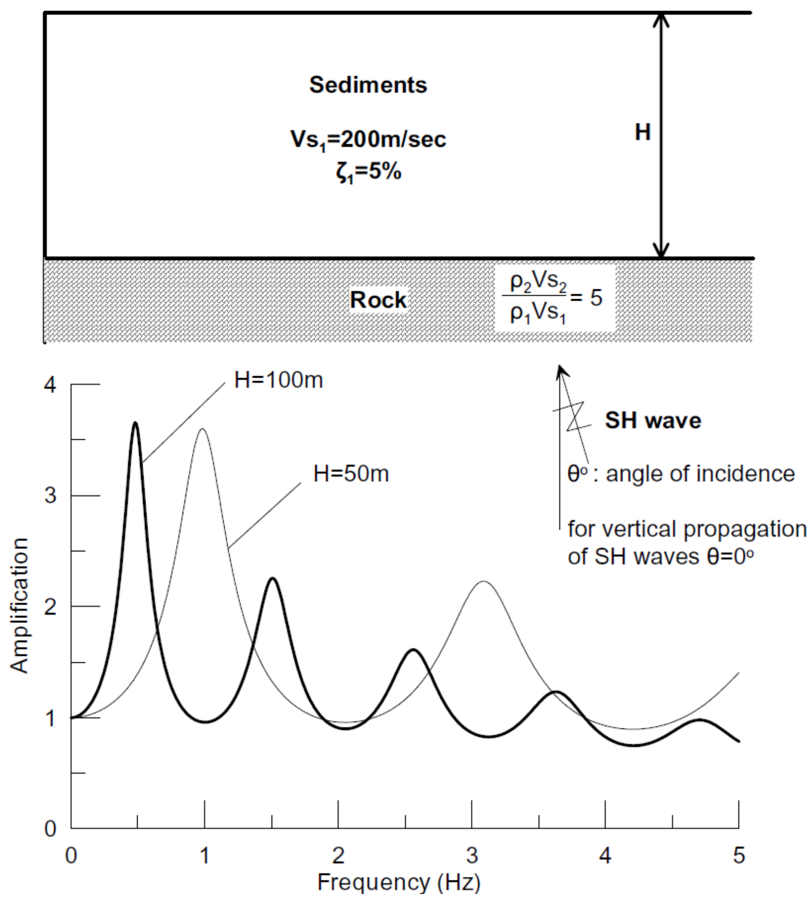

Fig 14.6: Example of a simple model of 1D site amplification

- When the semi-length of the soil structure is much larger than its maximum thickness (shallow basins), the waves have the same frequency characteristics as 1D resonance, thus increasing the 1D amplification level. When the semi-length of the soil structure is comparable to its thickness (deep basins), and the rebervarating back and forth surface waves are in phase, the waves interfere with each other leading to 2D resonance patterns.

- The same resonance effects are involved in the seismic wave modulation due to 3D soil structures. The consideration of the second and third lateral dimension in the wave propagation phenomena, in case of 2D and 3D resonance, leads to an increase in ground motion amplification and a shift towards higher values of the peak frequencies.

- An interesting comparison between 1D, 2D and 3D resonance, spectral peaks of amplification is presented in Figure14.7 below. The differences between 1D and 2D resonance are much more pronounced than between 2D and 3D cases. This means that the consideration of the third dimension in the simulation of ground motion leads to quantitative differences relative to 2D analysis (much larger amplification and a small shift in resonant frequencies).

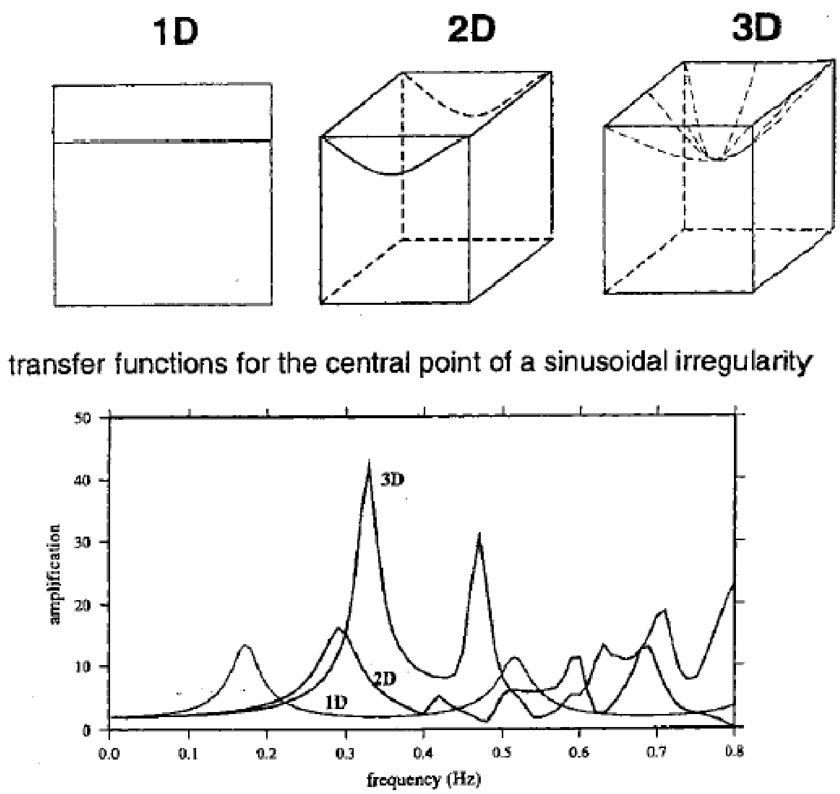

Fig 14.7: Spectral responses computed at the basin center for 1D, 2D and 3D models of semi-shaped basin (Bard and Riepl 1999).

- In the time domain, these resonance patterns affect the peak amplitudes of ground motion (mainly peak ground acceleration, PGA and peak ground velocity, PGV), the waveforms and the motion duration, especially in 2D soil structures.

- Experimental evidence (records) from recent earthquakes (Mexico, Loma Prieta, Northridge etc) showed that PGA were up to 4 times larger at soil than at rock sites. Statistical analyses of records have shown that PGA is most likely to be amplified when the fundamental resonant frequency of a site exceeds 2-3Hz.

- On the other hand, it was also observed that liquefied sandy deposits induce important reduction of peak acceleration (i.e. Kobe case). Therefore, PGA values on sediments cannot be predicted straightforwardly from PGA values on rock and this issue is strongly related to the non-linear phenomena in soil behaviour.

- A general trend however do exists, for moderate accelerations levels (<0.2-0.3g), in the sense that amplification of PGA is expected at soil sites compared to rock sites.

- This behaviour of PGA amplification may be attributed to a) the fact that in soils with low S wave velocity, the accumulated energy results in amplification and therefore, as the ground becomes "softer", amplification becomes larger (elastic range) and b) the fact that under strong dynamic loading the ground becomes "softer", (shear strength decreases) and hence, the peak acceleration becomes smaller and the predominant period of soil profiles is shifted to higher value (non-linear behaviour of soil materials).

- Consequently, amplification occurs under small ground shaking with decreasing absolute value as the ground shaking level is increased. This observation has been already included in UBC97, UBC 2000, NEHRP and EC8- draft code previsions with the introduction of an amplification coefficient depending both on soil classification and input motion amplitude.

- Regarding the duration of ground motion, all recent studies report a significant increase of duration in sediments especially at longer periods when soil stratigraphy is complex. This fact is closely related to the geometry of the structure (2D or 3D) and the existence of strong lateral discontinuities

Topic 8

Methods to Estimate Site Effects

- There are various methods that may be used for site effect evaluation. The choice of the method is usually related to the significance of the engineering project for which it is applied. Generally, the methods are classified in five main categories:

    1. Experimental-empirical techniques that utilise recordings of ground motion or ambient noise to estimate the basic characteristics of the expected ground motion - usually in the frequency domain.

    2. Empirical methods that evaluate parameters of earthquake motions such as acceleration, velocity and response spectra based on site classification, average Swave velocity, topography, earthquake magnitude and existing amplification relationships; usually these methods are incorporated in seismic code provisions.

    3. Semi-empirical methods that compute time histories of earthquake motion by combining recorded earthquake motion of smaller earthquakes as

element motions (i.e. Green's functions); these methods may account for the detailed fault rupture process and the effects of asperities.

4. Theoretical methods where site effects are computed through an analytical and more often numerical 1D, 2D or 3D wave propagation model; different wave types with different incident angles may be used; the main advantage of these methods is the possibility to use complex constitutive relationships for describing soil behaviour under dynamic loading conditions and the ability to model accurately site stratigraphy inclusive of basin topography.

5. Hybrid methods that compute time histories of earthquake motions by coupling a longer period component determined by a theoretical seismic fault model with a computational seismic wave propagation model having a shorter period component determined by a semi-empirical method. The use of each method depends on many parameters and, in any case, requires an increased level of expertise.

Topic 9

Experimental-Empirical Method

- The majority of the experimental techniques that have been developed during the last decades analyze site effects in the frequency domain because this is a relatively easier way to handle earthquake recordings.

- It is reminded that earthquake recordings may be represented in the frequency domain as the product of Fourier spectra of the source effect, the path effect and the site effects. In order to estimate the influence of local geology (site effects), the removal of the influence of the first two terms (source and path effects) is necessary.

- For this purpose, several methods have been proposed which are classified in two major categories based on the criterion of the use of a "reference site"; the reference site can be generally defined as this particular control location that is free of all kinds of site effects and it is usually the nearby rock site. The most commonly applied experimental techniques are briefly presented below.

Topic 10

Standard Spectral Ratio Technique (SSR)

- The most popular and widely used technique to characterize site amplification has been the Standard Spectral Ratio, SSR, (Borcherdt, 1970), which is defined as the ratio of the Fourier amplitude spectra of a soil-site record to that of a nearby rock-site record from the same earthquake and component of motion (Figure 14.8).

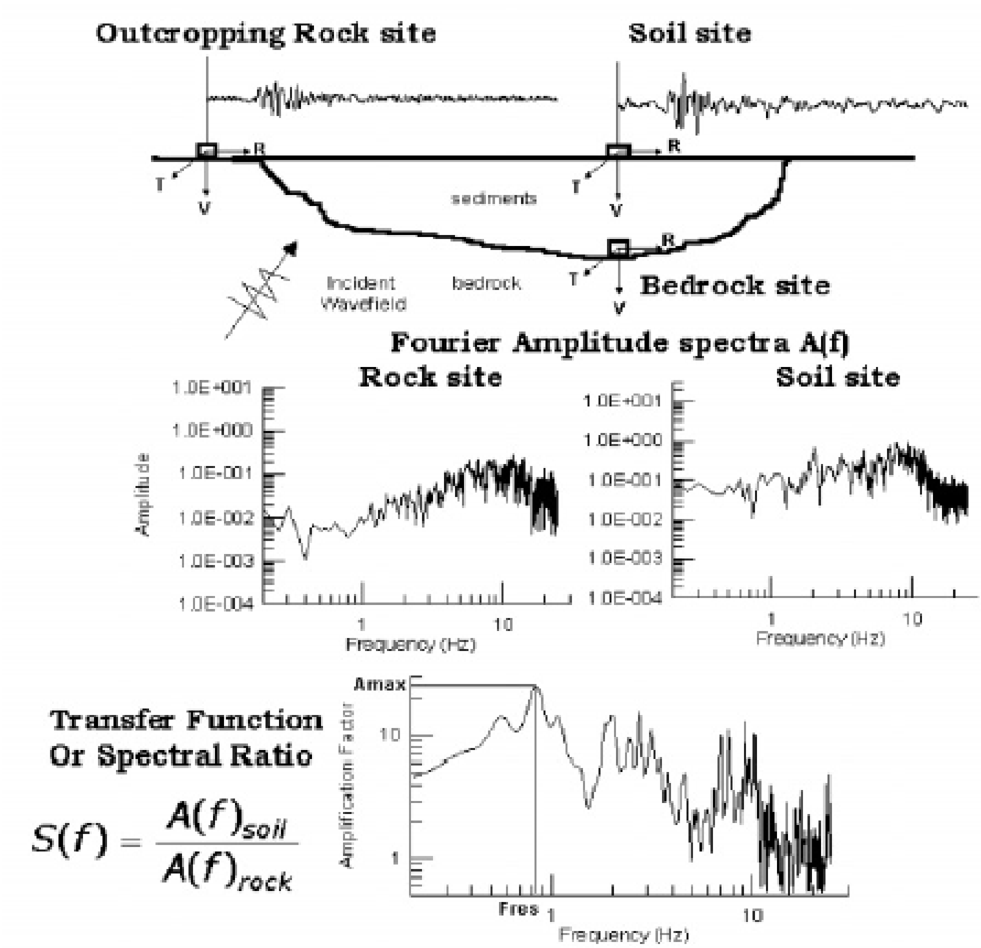

Fig 14.8: General description of the Standard Spectral Ratio Technique (SSR)

- Source information is the same for this pair of records and when the two sites are closely located, the path effect is also considered the same. Hence, the ratio of the Fourier amplitude spectra expresses only the effect of the local soil conditions at the specific site.

- Theoretically speaking though, this technique is applicable only to cases that the data are derived from dense local arrays with at least one station on outcropping conditions defined as reference station.

- A usual option for the selection of the reference station is a site of outcropping rock, while less frequently, a bedrock site having a downhole accelerometer installed in a borehole is the used for this purpose.

- The basic conditions for the application of this particular technique in the case of a surface reference station are:

  1. The existence of simultaneous recordings at a soil site and at the reference site,
  2. The reference site has to be free of any kind of site effects (sediments and topography) and
  3. The distance between the soil site and the reference one ought to be small (i.e. smaller than the epicentral distance), in order to consider that the effect of the propagating path of the seismic energy is the same for the two sites.

- However, the condition that an outcrop rock reference site should be free of any kind of site effects often it is not valid.

- For this reason, a careful examination of the reference site is obligatory in order to correctly estimate amplification in sedimentary sites (Stiedl et al., 1996).

Topic 11

Generalized Inversion Scheme Technique (GIS)

- Andrews (1986) recast the method of spectral ratios into a generalized inverse problem by decomposing the body-wave spectra uk(f) into source, site, and propagation components as

$$u_k(f) = \frac{1}{r_k}\dot{m}_j(f)s_i(f) \qquad (14.7)$$

- Here $m_j(f)$ is the moment rate spectrum for the jth earthquake, $s_i(f)$ is the site response spectrum for the ith site, and r k is the appropriate geometrical spreading factor. The simplicity of Andrews' decomposition is obtained through his neglect of the body-wave radiation patterns: the source mechanisms for the earthquakes are not incorporated into the spectra model.

- Both Andrews (1986) and Bonamassa and Mueller (1988), who also use this formulation, demonstrate that this decomposition only separates the source and site spectra up to an unresolved degree of freedom, that is, up to an undetermined function of frequency that can be multiplied onto each source spectrum and divided from each site spectrum.

- At first glance, then, Andrews' decomposition does not appear to be a significant improvement over the method of spectral ratios, as the desired source or site response spectra are still undetermined.

- We note, however, that there is only a single degree of freedom missing for each connected or linked set of recordings. Here the term linked describes a data set in which each station can be linked to every other station through a mutually recorded event, or through a set of other stations and mutually recorded events.

- If a method can be devised to restrict or resolve the missing degree of freedom, then all the source and site spectra can be determined simultaneously. Clearly, the accuracy of the derived spectra depends on how well the method exploits the spectral information contained in the body waves.

- Boatwright et al. (1991) suggested a generalized inversion scheme where shear-wave spectra are represented with a parameterized source- and path-effect model and a frequency-dependent site response term for each station.

Topic 12

Coda wave technique

- The coda portion of a local earthquake record can be defined as that energy arriving after the passage of all direct body and surface waves. The word "coda" actually comes from Latin, meaning tail or end.

- One reason that coda waves can be so useful to seismologists is that, for a given region, their spectral characteristics (shape) are nearly independent of source and receiver location and source orientation. This property is expressed by writing the power spectrum of coda waves as a function of frequency (ω), and lapse time or time measured from the source origin time (t):

$$P(\omega,t) = |S(\omega)|^2 \; C(\omega,t) \tag{14.8}$$

- Here, S (ω) depends on the earthquake source and recording site conditions, while C(ω, t) only depends on frequency and lapse time, and is independent of sourcereceiver location. Evidence supporting the stability of the coda shape is given by Aki (1956), Aki (1969), Rautian and Khalturin (1978), and Tsujiura (1978).

- In the 1969 paper, Aki shows that a simple model of coda waves as a superposition of secondary waves backscattered from randomly distributed heterogeneities can account for the observed coda decay C(ω, t).

- Seismologists have taken advantage of this simple property in using coda to isolate source (Chouet et al., 1978), path (Rautian and Khalturin, 1978; Aki, 1980; Herrmann, 1980; Roecker et al., 1982), and site {Aki, 1969; Tsujiura, 1978) effects on seismic waves generated by local earthquakes. Results from these studies lead one to believe that the backscattered waves comprising the coda are predominantly shear waves.

- In particular, the Q of shear waves was found to agree with the Q or coda waves calculated using a simple single backscattering model (Aki and Chouet, 1975; Sato, 1977) over the 1- to 24-Hz band for a number of regions. Furthermore, the site effect of coda waves with respect to a reference station was shown to agree with that of shear waves for horizontal components.

- This result has recently been reinforced by seismologists interested in strong motion problems (King and Tucker, 1984; R. Benites, personal communication). As expected from the backscattering model, the coda wave site effect measurements always display less scatter than those of shear waves.

Topic 13

Horizontal to Vertical Spectral Ratio Technique (HVSR)

- All techniques mentioned above are using a reference site but in practice, appropriate reference sites are not always available. For this reason different methods that are not depending on reference sites have been developed. One of them is the Horizontal to Vertical Spectral Ratio.

- This extremely simple technique consists of using the spectral ratio of the horizontal to the vertical component of ground motion and estimates the Fourier amplitudes in different frequencies accordingly. The basic assumption of the method is that the vertical component of the ground motion in cases where the soil stratigraphy is flat and horizontal is supposed free of any kind of influence related to the soil conditions at the recording site.

- Figure 14.9 shows the general layout of the method which was first applied to the S wave portion of the earthquake recordings obtained at three sites in Mexico City by Lermo and Chavez-Garcia (1993).

- Generally, the Fourier spectra ratio exhibit similarities between SSR and HVSR technique, with a better fit in frequencies rather than amplitudes of the resonant peaks.

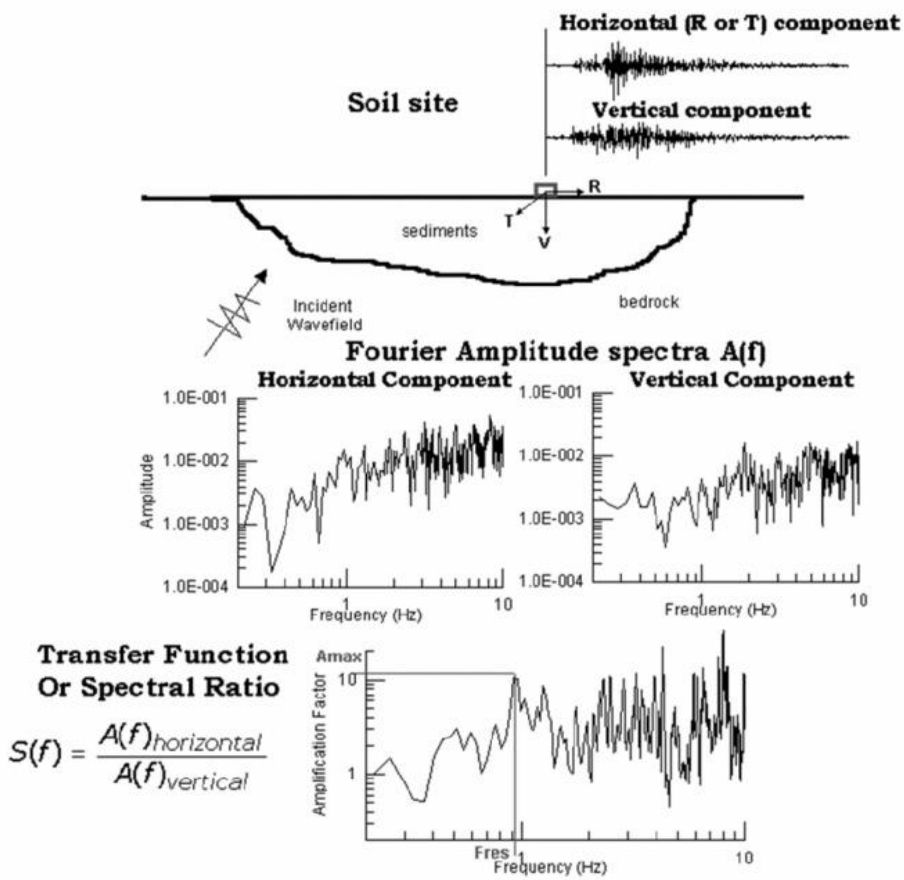

Fig 14.9: Description of the Horizontal to Vertical Spectral Ratio Technique (HVSR)

Topic 14

Comments on SSR and HVSR

- SSR and HVSR are the most commonly used experimental techniques for the estimation of site amplification due to local soil conditions; there are plenty of literature references on comparative results on their applicability and reliability.

- Herein, some of these works are briefly summarized and their main conclusions are highlighted. Detailed comparisons between SSR technique and other reference station techniques (Field et al., 1992; Stiedl, 1993; Field and Jacob, 1995) led to few basic qualitative conclusions such as:

  1. The estimation of site effects with the use of SSR technique is relatively stable even if records are quite noisy,
  2. The process should be based on a significant number of earthquake recordings (the use of a limited number of records should be avoided) and

3. The amplification level determined with SSR technique is quite similar with that determined from other techniques and especially with the GIS.

- Other comparisons between results of SSR and HVSR techniques led to controversial conclusions. As it is already stated above, Lermo and Chavez-Garcia (1993) applied HVSR to the S wave portion of the earthquake recordings and found similarities between standard spectral ratios and these HVSR with a good fit in both frequencies and amplitudes of the resonant peaks.

- Some other researchers used HVSR technique on data sets from weak and strong motion records and concluded that the shape of the spectral ratios presents very good statistical stability with minor dependency on source and path effects and that it is quite well correlated with surface geology, while their amplification level seems to depend on the type of incident wave, a fact that does not affect the fundamental resonant frequency.

- Field and Jacob (1995) after systematic comparisons with other techniques concluded that the shape of the transfer function is satisfactorily reproduced by HVSR technique, although there is an underestimation of the amplification factor compared to SSR.

- On the same issue Raptakis et al. (1998, 2000), using a large and high quality date set from EUROSEISTEST experimental site, proved that the significant differences between SSR and HVSR amplitudes at the fundamental frequency are attributed to the considerable amplification of the vertical component due to diffracted Rayleigh waves at the lateral discontinuities of the basin (Figure 14.10).

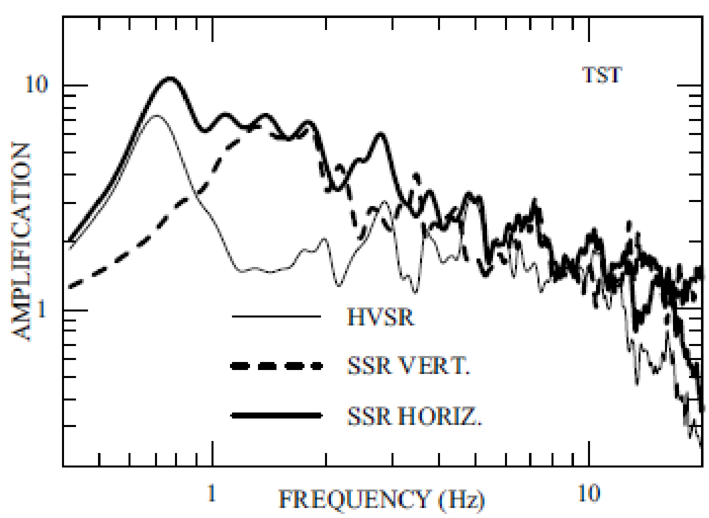

Fig 14.10: Mean spectral ratios of HVSR technique compared to SSR horizontal and vertical components (after Raptakis et al., 1998; Reproduced with permission from D.Raptakis and the Earthquake Engineering Research Institute)

- In conclusion, both SSR and HVSR techniques are reliable in estimating the fundamental frequency of the soil profile. However the amplification amplitude is comparable only when the soil layering is horizontal and there aren't lateral geometrical variations.

- In those cases, due the presence of in-ward propagating surface waves, it is expected that part of them will affect the vertical component and hence the amplitude of the HVSR method.

- For this reason, in cases where the stratigraphy is not flat and horizontal, which is pertinent in many real site conditions, the use of HVSR technique should be applied with caution at least for the derivation of the amplification factor at the fundamental frequency.

Topic 15

Empirical Methods

- Empirical methods are practically used either for preliminary analyses or in the frame of seismic code prescriptions with well specified amplification factors defined according to the soil classification and the earthquake intensity.

- Simple relationships giving the amplification factors for the peak acceleration or/and velocity with the average shear wave velocity of the soil profile are proposed in the literature (Joyner and Fumal 1984, Midorikwa 1987, Borcherdt et al., 1991).

- All these relationships should be used only for preliminary studies and with extreme caution. In this paragraph a senior problem is discussed concerning the site characterization using exclusively the average S-wave velocity over the 30m from the surface, which was first introduced by Borcherdt (1994) and then adopted in most modern codes.

- The major question is how accurate is the use of Vs_{30} for soil and site characterization. Certainly, the main advantage is the simplicity in evaluating the site conditions by conventional geotechnical surveys which rarely exceed 30-40m.

- On the other hand, the question remains whether the simple knowledge of the s-wave velocity over the limited depth of 30m is an accurate parameter to estimate site amplification characteristics. It is interesting to notice two examples from recent down-hole recordings that prove the opposite (Figure 14.11).

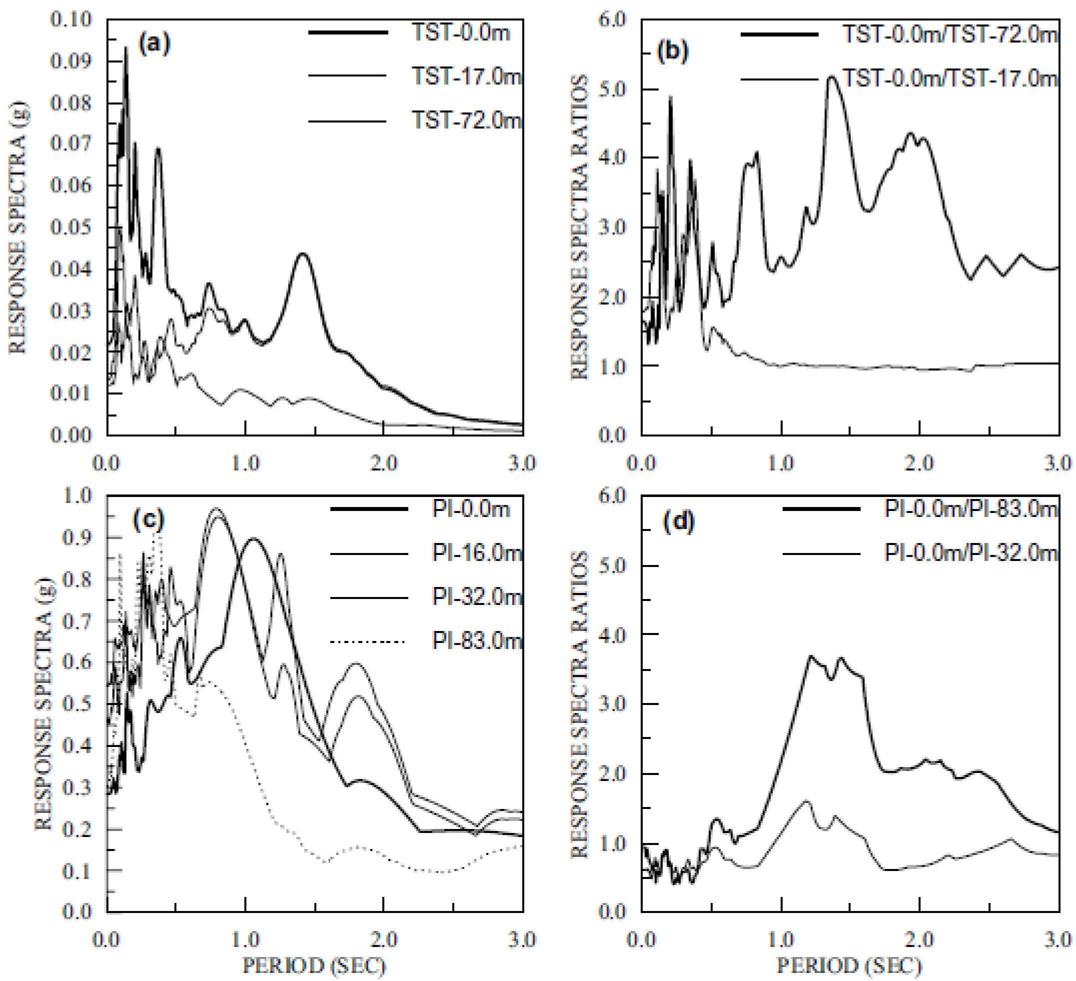

Fig 14.11: Response spectra (left) and response spectra ratios (right) at the Euroseistest (up) and Port Island (down) vertical arrays. (Pitilakis et al.,1999; Reproduced with permission from the Swets & Zeitlinger Publ.)

- In both sites the spectral ratios between the surface and down-hole records at various depths are considerably different at long periods (T>1sec). Large amplifications of the deep incident wave field are practically absent when we are computing the transfer ratio for shallower depths.

- Long period waves, mainly surface waves, generated at the lateral discontinuities disappear when only the uppermost layers are taken into account together with a 1D SH wave pattern (the case of Euroseistest valley). In the Port Island array in the U.S., due to liquefaction and strong inelastic behaviour of surface soils, the ground motion is de-amplified and the most severe response is observed at the fundamental period of the deposit (T=1sec).

- The recorded response spectral ratio between surface and -32m presents practically no amplification for T>0.5sec, while the amplification between surface and -83m is quite important.

- In conclusion the use of Vs^{30}, as a basis for soil and site characterization is misleading in many cases. It should be used only when the actual site conditions are appropriate to that i.e. relatively shallow "seismic bedrock" or very firm soil conditions, flat stratigraphy.

- In conclusion, empirical methods are mainly used for a quick simplified evaluation of the basic parameters of ground amplification: fundamental frequency of the soil profile and amplification ratio. They are useful
    1. For microzonation studies and
    2. With their special form of spectral amplification factors for different soil categories in seismic code prescriptions for the design of structures.

- In all cases they should be applied and used very carefully because their statistical background and the a-priori limited information required regarding site characterization may lead to serious errors.

Topic 16

Semi-empirical Methods

- The semi-empirical methods compute time histories of earthquake motions caused by large scenario earthquake by combining recorded earthquake motions by smaller seismic events.

- The Green's function technique is based on the idea that the total motion at a particular site is equal to the sum of the motions produced by a series of independent ruptures of many small parts on a causative fault.

- The method requires an approximate definition or estimation of certain parameters such as the geometry of the source, the slip functions describing the slip displacement vector with time for each elementary source, the velocity structure of the crustal materials between the source and the site and the Green's functions that describe the motion at the site due to an instantaneous unit slip at each elementary source.

- Normally the Green's function at each site, account implicitly the particular site specific ground behaviour in the linear elastic range. The empirical Green's functions technique (EGF) (Hartzell 1978) bypasses these complicate computations by using the weak motions of small earthquakes as empirical Green's functions to simulate strong motion.

- Figure 14.12 illustrates the principles of the method. The method is essentially a deterministic one as it computes time histories for a defined earthquake scenario and other parametres. However it is possible to use statistical Green's functions which are computed as the statistical average of the recorded earthquake motions for different small seismic events.

- The EGF technique is particularly useful for generating near-field motions and when it is important to account the detailed fault rupture process and the effects of asperities. It is less accurate when strong non-linear behaviour is expected for local soils.

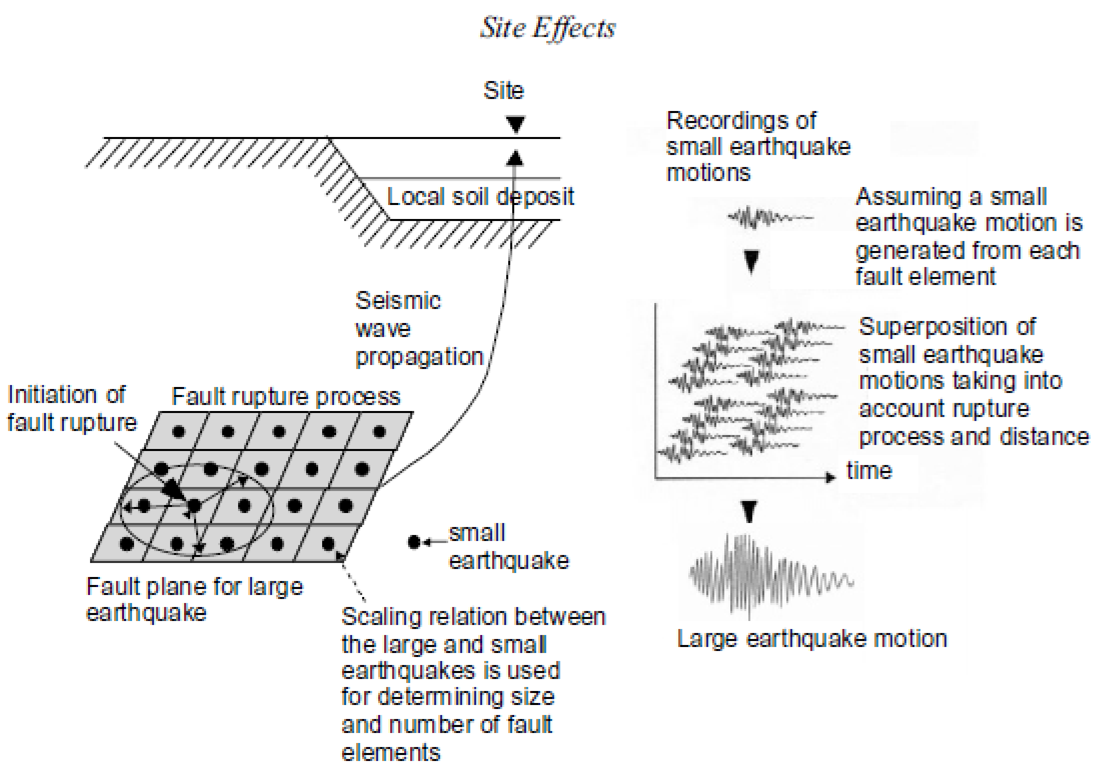

Fig 14.12: Procedure for generating earthquake strong ground motions with the empirical Green's function technique (reproduced from ISO/WD 23469-draft).

Topic 17

Theoretical (Numerical and Analytical) Methods

- When the geological structure of an area and the geotechnical characteristics of the site are known, site effects can be estimated through theoretical analysis. The prerequisite of sufficient geotechnical knowledge of the soil structure including surface and deep topography is therefore obvious.

- Such an approach requires an in-depth understanding of the constitutive models describing the soil behaviour under dynamic solicitations and methods used to solve the wave propagation problem in 1, 2 or 3 dimensions.

- There are many models and methods which make the simple reference a rather difficult task and anyway beyond the task of the present chapter and book. Thus, in the present section the basis of the most conventionally used methods to account for site effects in ground response studies for microzonation purposes will be discussed.

Topic 18

Simple analytical models

- As already mentioned, site amplification in soil sediments is related to resonance effects which are presented in the frequency domain in the form of spectral peaks in the Fourier transfer functions.

- A simple analytical approach which does not require any numerical computations, aims to estimate the fundamental period of the soil, τ_0, and the corresponding amplification factor A_0. A simple simultaneous estimation of these two parameters is possible only for sites that can be approximated as one layer over bedrock structure.

- This is a relatively easy way since only soil density, S-wave velocity, thickness, and damping of sediments as well as S-wave velocity of bedrock are required. For multi layered sites, only the fundamental period could be satisfactorily estimated; Dobry et al. (1976) summarized the most significant methods.

- On the contrary there is no approximate and reliable formulae for the estimation of fundamental amplification factor A_0 in horizontally multi layered sites. Such formulae would imply many parameters, including damping, S-wave velocities and thickness of each layer.

- However, an upper bound of A_0 may be estimated using the impedance contrast between the lower stiffness surface layers and most rigid deep formations, together with the material damping of the surface soil deposits. The approximation is very crude and may lead to large overestimations and potential errors.

Topic 19

One dimensional response of "soil columns"

- A number of analytical methods exist that allow numerical computations of the seismic response of a given site. The most widely used computations are based on the multiple reflection theory of S-waves in horizontally layered deposits (1D analysis of soil columns). According to this theory, "soil columns" are excited by incoming vertically incident plane S-waves that correspond to a surface bedrock motion representative of what is expected to occur in the area for a specific earthquake scenario.

- The parameters required for the analysis are the shear wave velocity, density, the material damping factor and the thickness of each layer. The above parameters may be obtained through in-situ geophysical and geotechnical surveys and appropriated dynamic laboratory tests.

- Alternatively, but with less accuracy, approximate correlations may be applied using conventional geotechnical parameters such as SPT, CPT, PI, Dr among others. These analyses may be performed considering either linear or non-linear behaviour for the soil.

- In the latter case, the non-linearity is usually approximated with an equivalent linear method that uses an iterative procedure to adapt soil parameters (i.e. stiffness and damping) to the strain level that each particular soil layer experiences during a specific earthquake motion.

- Specific curves expressing the degradation of shear modulus G and the respective increase of material damping, with the increasing shear strain level have been proposed by numerous researchers according. Figure 14.13 presents a typical set of $G/G_0 - \gamma - D\%$ curves.

- They have been estimated from resonant column tests on undisturbed specimens and they describe the dynamic behaviour of soil in the Euroseistest experimental site.

- Average curves have been also proposed for different soil materials (clay with varying PI, sands, soil mixtures, etc). They must be used with caution because the actual behaviour for a given soil at a specific site may strongly vary from these average curves.

- This was the case in Mexico City where the lacustrine clayey deposits of extremely high plasticity index were found, through appropriate dynamic test (RC, CTX), to behave almost linearly despite the large strains experienced during the strong 1985 event and contrary to the previous belief that they should exhibit highly nonlinear behaviour because of their very low rigidity.

- The last twenty years many interesting numerical codes have been developed with advanced non-linear and elastoplastic constitutive models that may also account forliquefaction phenomena. They certainly require additional parameters describing soil behaviour under complicated loading and drainage conditions which are not easily acquired even with sophisticated laboratory tests.

- Moreover the validation of these models with experimental results, mainly from actual seismic recording, is still a major unsolved problem. This fact combined with the need of complicate soil parameters is affecting seriously their wide use in practice.

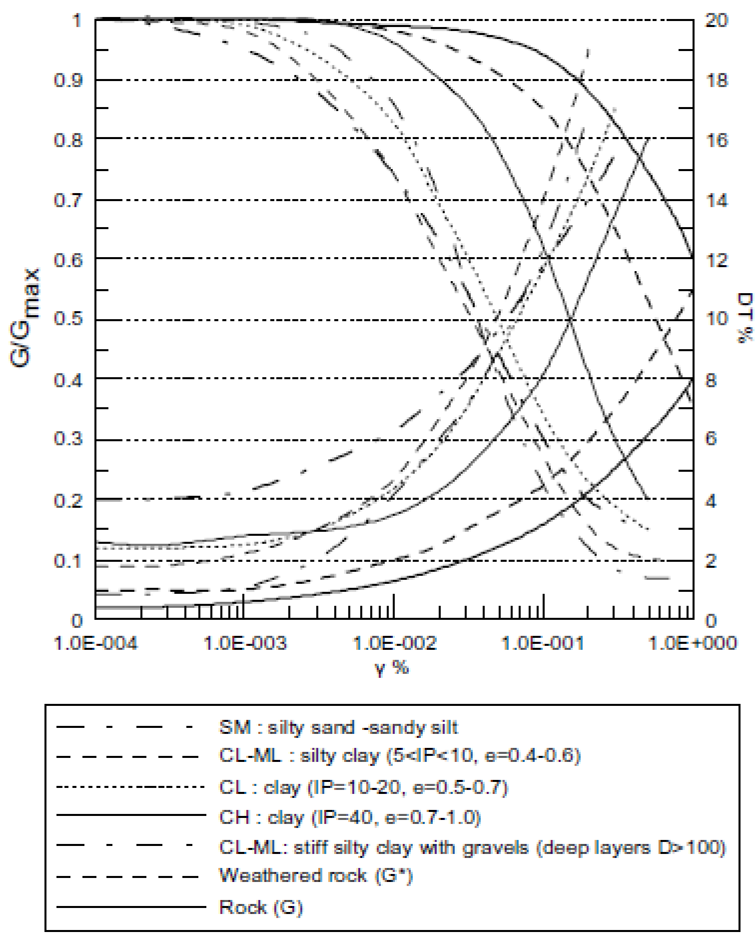

Fig 14.13: Shear modulus and material damping dependency on shear strain for the soil formations at EUROSEISTEST site (after Pitilakis et al., 1999; Courtesy of the Journal of Earthquake Engineering)

Topic 20

Advanced 2D/3D models and methods

- All numerical and analytical methods have the same theoretical basis (i.e. wave motion equations). However, many different models have been proposed to investigate several aspects of site effects which involve complex phenomena.

- For example, one has to consider for the various types of incident wave-field (near or far field, body and/or surface waves), the geometry of the structure (1D, 2D and 3D), the behaviour and the dynamic properties of soil materials (visco-elasticity, nonlinear behaviour, saturated media, etc). Typically, these advanced methods may be classified into four groups:

    1. Analytical methods which may be used for a limited number of simple geometries.

    2. Ray methods which are difficult to use when the wavelengths are comparable to the size of heterogeneities (usually the most interesting case).

    3. Boundary based techniques which are the most efficient when the site under consideration consists of a limited number of homogeneous geological units.

    4. Domain based models (finite difference and finite element methods) which allow accounting for very complex soil structures and constitutive models for the dynamic behaviour of soils but they are expensive from a computational point of view.

- The development of these methods contributed significantly to the breakthrough in the understanding of site effects during the last three decades. They allow for parametric studies and more important the study of uncertainties of the seismic ground response at a site, considering the incomplete knowledge regarding the mechanical and geometrical characteristics of the site under consideration. However, there is still an important lack of reliable and detail validations.

Topic 21

Development of Response/Design Spectrum

- Classification of sites based on the average shear wave velocity of the top 30 meters of the subsoil is popular among engineers as a quick way of understanding how ground motion during an earthquake differs on rock sites and soil sites. Standard documents such as IBC- 2009, can be referred for classifying sites based on borehole data or velocity profiling. The standard site classification definitions are shown in Table 14.1.

Table 14.1: Site Class Definitions (Ref: International Building Code IBC-2009)

Site class	Average shear wave velocity (v_{s1})	Average standard Penetration resistance (N1 or N_{ch1})	Average undrained shear strength in the case of cohesive soils (s_{u1})
A : Hard Rock	>1500 m/s	Not applicable	Not applicable
B: Rock	760 to 1500 m/s	Not applicable	Not applicable
C:Very dense soil or soft rock	370 to 760 m/s	>50	>100kPa
D: Stiff soil	180 to 370 m/s	15 to 50	50 to 100 kPa
E: Soft soil	<180 m/s	<15	<50 kPa
	Any profile with more than 3 m of soil having Plasticity Index PI>20, Moisture content $\omega \geq 40\%$ Average undrained shear strength s_u < 24 kPa		
F: Soils requiring site-specific evaluation	Soils vulnerable to potential failure or collapse (liquefiable, quick- or highly sensitive clays, collapsible weakly cemented soils) More than 3 m of peat and/or highly organic clays More than 7.5m of very high plasticity clays (PI>75) More than 37m of soft to medium clays		

- When the soil properties are not known in sufficient details to determine the site class, site class D is used unless it can be established that E or F type soil is likely to be present at the site. After the local soil classification is carried out and the soil type is fixed up, the design spectrum can be constructed following the approach of IBC briefly illustrated below.

- IBC-2009 defines two site coefficients Fa and Fv corresponding to the 2500-year spectral acceleration (5% damping) value for representative short and long period ranges as shown in Tables 14.2 and 14.3

Table 14.2: Site coefficients Fa for short period range

SITE CLASS	Mapped spectral response acceleration at short periods				
	Ss ≤ 0.25	Ss = 0.50	Ss = 0.75	Ss = 1.0	Ss ≥1.25
A	0.8	0.8	0.8	0.8	0.8
B	1.0	1.0	1.0	1.0	1.0
C	1.2	1.2	1.1	1.0	1.0
D	1.6	1.4	1.2	1.1	1.0
E	2.5	1.7	1.2	0.9	0.9
F	Site-specific analysis shall be performed				

.

Table 14.3: Site coefficients Fv for 1-second period

SITE CLASS	Mapped spectral response acceleration at 1 sec period				
	Ss ≤ 0.25	Ss = 0.50	Ss = 0.75	Ss = 1.0	Ss ≥1.25
A	0.8	0.8	0.8	0.8	0.8
B	1.0	1.0	1.0	1.0	1.0
C	1.7	1.6	1.5	1.4	1.3
D	2.4	2.0	1.8	1.6	1.5
E	3.5	3.2	2.8	2.4	2.4
F	Site-specific analysis shall be performed				

Response Spectrum

Step 1: Determine, maximum considered earthquake spectral response acceleration at 0.2s period and 1s period as

$$S_{MS} = F_a \; S_s \qquad (14.9)$$

$$S_{M1} = F_v \; S_1 \qquad (14.10)$$

SS and S1 are mapped spectral accelerations for short period and 1 s period

Step 2: Determine design basis earthquake spectral response acceleration at 0.2s period and 1s period using the equations

$$S_{DS} = \; 2/3 \;\; S_{MS} \qquad (14.11)$$

$$S_{D1} = \; 2/3 \;\; S_{M1} \qquad (14.12)$$

Step 3: Calculate characteristic time periods To and Ts

$$T_O = 0.2\frac{S_{D1}}{S_{DS}} \qquad (14.13)$$

$$T_S = \frac{S_{D1}}{S_{DS}} \qquad (14.14)$$

Step 4: Design spectra construction:
Let T is the fundamental time period of the structure

a) For periods less than or equal to To, design spectral response acceleration, Sa is given by

$$S_a = 0.6\ S_{DS}/T_O\ T + 0.4 S_{DS} \qquad (14.15)$$

b) For periods greater than or equal to To and less than or equal to Ts,

$$S_a = S_{DS} \qquad (14.16)$$

c) For periods greater than or equal to Ts

$$S_a = S_{D1}/T \qquad (14.17)$$

Lecture 14 Concept of ground response; local site effects and evaluation methods; ground motion amplifications and estimation; development of response/design spectrum