Inventory of approaches to account for site effects: methodologies and regulations

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Summary

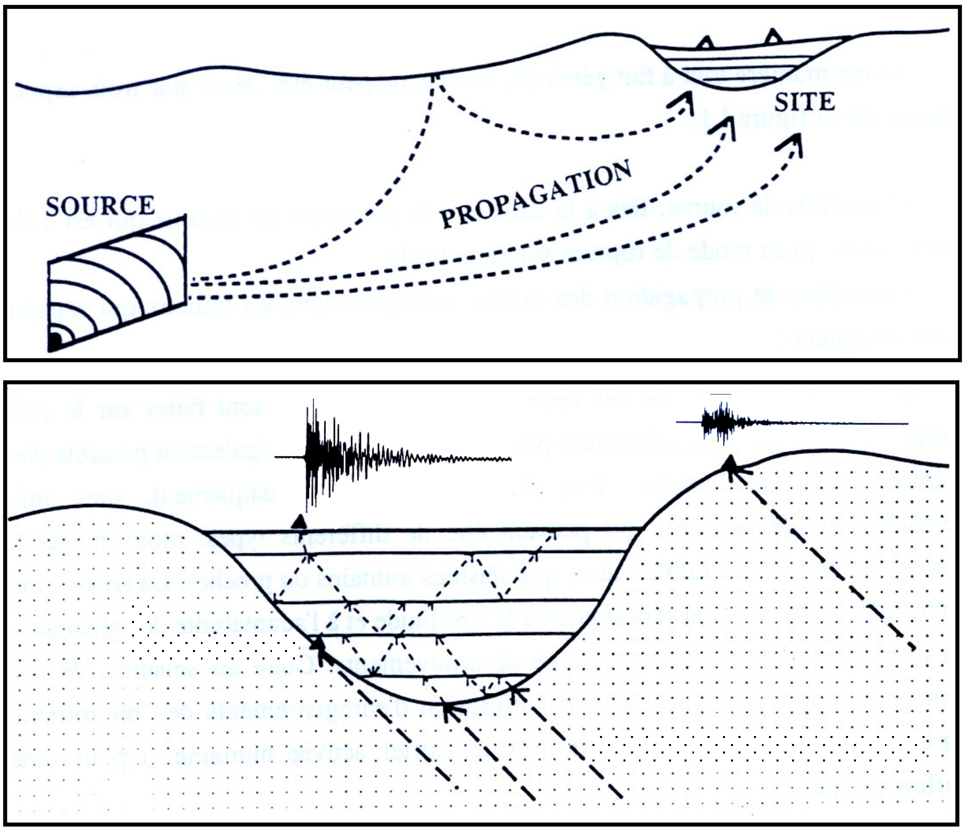
The principal and ultimate goal of program SIGMA WP3 is to provide one (or several) operational method(s) to account for site effects. These methods have to be relevant and must produce robust estimations and should be flexible enough to be adapted to site complexity.

A first step toward this target is to dispose of a general overview of the existing approaches to account for site effects in both 1/ methodologies for the evaluation of amplification and 2/ regulations. The present report aims to do this overview.

In the first section of the present report, experimental and numerical techniques are presented that are available to estimate the amplification due to site effects with a final synthesis of all described methodologies, with comparison criteria. This section presents the most well-known and used methodologies for site effects evaluation throughout the world. They are presented in three categories: experimental, numerical and empirical or semi-empirical methods. The presentation is not exhaustive at all. Indeed, it has not been possible to describe all available methods throughout the world, in the framework of the present compilation. The different categories of methods are described with, in most cases, some examples which are presented in more details.

The second section is devoted to the taking into account for site effects in seismic regulations. It deals with building codes from different countries (USA, Europe, NewZeland). It also addresses the issue of site effects in regulation for nuclear facilities (IAEA recommendations, practices in France, Germany, Japan, Switzerland, UK and USA). Since soil classification is often a central issues in these practice, a discussion on research for “improved soil classification” is also proposed.

Inventory of approaches to account for site effects: methodologies and regulations



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1. Introduction and objectives

It is now well known, and widely accepted amongst the earthquake engineering community, that the effects of surface geology on seismic motion exist and can be large. Nearly all destructive earthquakes bring evidences of the dramatic importance of site effects. Accounting for such "site effects" in seismic regulations, land use planning or design of critical facilities thus became one goal of earthquake hazard reduction programs (Bard, 1997).

The main goal of the French research programme "Sigma" (funded by EdF, CEA, AREVA and Enel) is to establish stable and robust seismic hazard estimations. This implies a better characterisation of uncertainties, which will probably contribute to future regulations. One of the five work packages of this program is devoted to the account for site effects. In this framework, Résonance Ingénieurs-Conseils SA (Carouge, Switzerland) was asked to compile an inventory of existing methodologies available to account for site effects.

In the first section of the present report, experimental and numerical techniques are presented that are available to estimate site effects, with a final synthesis of all described methodologies, with comparison criteria. The second section is devoted to the account for site effects in seismic regulations.

2. Methods for estimating site effects

This section presents the most well-known and used methodologies for site effects evaluation throughout the world. They are presented in three categories: experimental, numerical and empirical or semi-empirical methods. The following presentation is not exhaustive at all. Indeed, it has not been possible to describe all available methods throughout the world, in the framework of the present compilation. The different categories of methods are described with, in most cases, some examples which are presented in more details.

2.1 Experimental methods

Experimental methods to estimate site effects are based either on weak and strong motion earthquake recordings or on ambient vibration recordings. Particularly in low and moderate seismicity areas, the use of ambient vibrations has become increasingly popular. Nevertheless, it should be kept in mind that methods based on real recordings are much more reliable if recordings of several events are available. That's why, for critical facilities, it is strongly recommended to install high quality broad-band seismographs in order to evaluate site effects with better reliability. Such seismographs allow to significantly reduce the uncertainties of site effect evaluations.

A concise overview on the different experimental methods to investigate site effects, with an extensive reference list, is given by Parolai (2012). An interesting comparison of the quality of the principal experimental methods in a specific case study can be found in Drouet et al. (2008-b).

More and more recordings throughout the world are available nowadays. This allows more and more sophisticated experimental evaluations of site effects. However, data of very dense arrays that capture the spatial variability of ground motion at the scale of typical foundations are still extremely sparse – although this variability should be known in order to elaborate how much of the high frequency content of ground motion is filtered out by typical massive foundations of critical facilities.

2.1.1 H/V noise spectral ratio

Among the empirical methods, the H/V spectral ratio technique on ambient vibrations has become the probably most popular approach – in spite of its limitations – at least in Japan and Europe. The H/V ratio, i.e. the ratio between the Fourier spectra of the horizontal and vertical components of ambient vibrations (often called "microtremors" or "ambient noise"), was introduced in the early seventies by several Japanese scientists (Nogoshi and Igarashi, 1971; Shiono et al., 1979; Kobayashi, 1980; Nakamura, 1989). Since then, many investigators in different parts of the world have conducted a large number of applications (see SESAME, 2004, for example).

An important requirement for the implementation of the H/V method is a good knowledge of engineering seismology combined with background information on local geological conditions supported by geophysical and geotechnical data. The method is typically applied in microzonation studies and in the investigation of the local response of specific sites.

In general, due to the experimental character of the H/V method, the absolute values obtained for a given site require careful examination. In this respect visual inspection of the data both during data collection and processing is necessary. Especially during the interpretation of the results, there should be frequent interaction with regard to the choices of the parameters for processing.

In the framework of the European research project SESAME (Site Effects Assessment Using Ambient Excitations), the use of ambient vibrations in understanding local site effects has been studied in detail. The SESAME guidelines (SESAME, 2004) outline the recommendations that should be taken into account in studies of local site effects using the H/V technique on ambient vibrations. The recommendations given apply basically for the case where the method is used alone in assessing the natural frequency of sites of interest and are therefore based on a rather strict set of criteria. The recommended use of the H/V method is, however, to combine several other geophysical and geotechnical approaches with sufficient understanding of the local geological conditions. In such a case, the interpretation of the H/V results can be improved significantly in the light of the complementary data.

In spite of its limitations, the H/V technique is a very useful tool for microzonation and site response studies. This technique is most effective in estimating the natural frequency of soft soil sites when there is a large impedance contrast with the underlying bedrock. The method is especially recommended in areas of low and moderate seismicity, due to the lack of significant earthquake recordings, as compared to high seismicity areas.

Although Nakamura's qualitative physical explanation of the method looked at least questionable (as indicated in Lachet and Bard, 1994, and again in Kudo, 1995), various sets of experimental data confirmed that these ratios are much more stable than the raw noise spectra. In addition, on soft soil sites, they usually exhibit a clear peak that is well correlated with the fundamental resonant frequency. These observations are supported by several theoretical investigations (Field and Jacob, 1993b; Lachet and Bard, 1994; Lermo and Chavez-Garcia, 1994; Cornou, 1998; Fäh et al., 2001; SESAME, 2004), showing that synthetics obtained with randomly distributed, near surface sources lead to horizontal-to-vertical ratios sharply peaked around the fundamental S-wave frequency (Figure 1a), whenever the surface layers exhibit a sharp impedance contrast with the underlying stiffer formations.

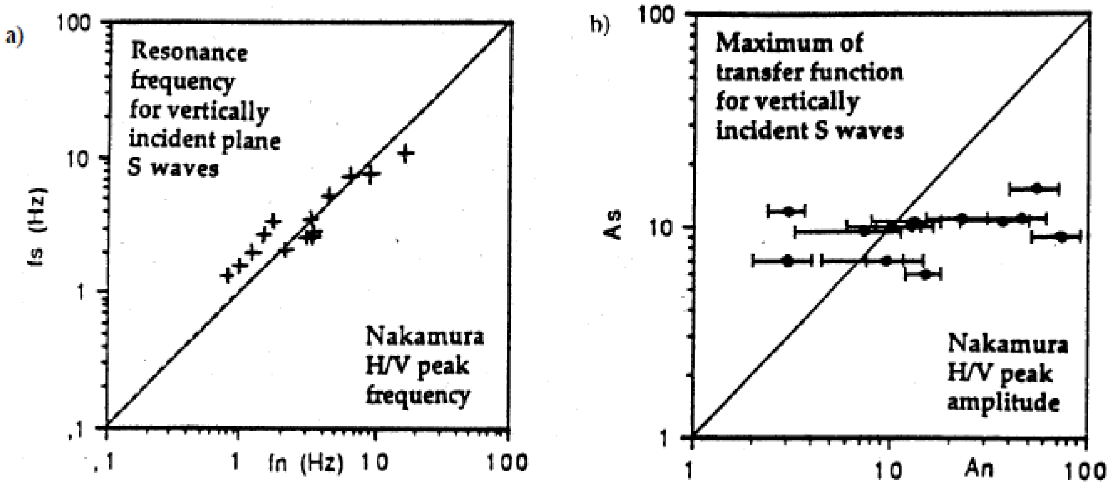


Figure 1: Theoretical checks of the H/V ratio technique. Numerical horizontal to vertical spectral ratios were computed from noise models in various soil profiles. a) Comparison between the S-wave resonance frequency (fs, computed for vertically incident S-waves) and the peak frequency "observed" in theoretical H/V ratios (fn): the agreement is very satisfactory. b) Same thing for the spectral amplitude at the resonant frequency (As is the amplification for vertically incident S waves, An is the amplitude of the H/V peak obtained from noise modeling): the agreement is very poor... (Reproduced from Lachet and Bard, 1994).

However, the first three studies mentioned above also conclude that the amplitude of this peak is not well correlated with the S wave amplification at the site's resonant frequency (Figure 1b). Instead, it is highly sensitive to some parameters such as Poisson's ratio near the surface. Furthermore, Lachet and Bard (1994) proposed that the good match at the fundamental frequency is due to the horizontal-vertical polarisation of the Rayleigh waves, an interpretation that is in agreement with the early Japanese studies (Kudo, 1995). According to this view, no straightforward relation exists between the H/V peak amplitude and the site amplification. However, this opinion is not shared unanimously. For instance, a one to one average correlation is claimed by Konno and Ohmachi (1998) on the basis of a comparison between observed H/V peaks and numerical estimates of 1D transfer functions.

Furthermore, an empirical relationship between H/V peak amplitude and local intensity increment (MM scale) was argued in Toshinawa et al. (1997) from a strictly experimental viewpoint. A thorough comparison (Bard et al., 1997; Bard, 1999; SESAME, 2004) between observed amplifications derived from earthquake recordings and observed H/V peak amplitudes at more than 30 sites demonstrates that the H/V peak amplitude is almost always smaller than the observed amplification (Figure 2). Such an experimental result, although not yet explained by theoretical or numerical work, despite the computations performed by Cornou (1998), could be very useful indeed. It would mean that the H/V ratio technique could provide a lower-bound estimate to the actual weak motion amplification. This view needs to be confirmed, however, by a larger set of experimental data.

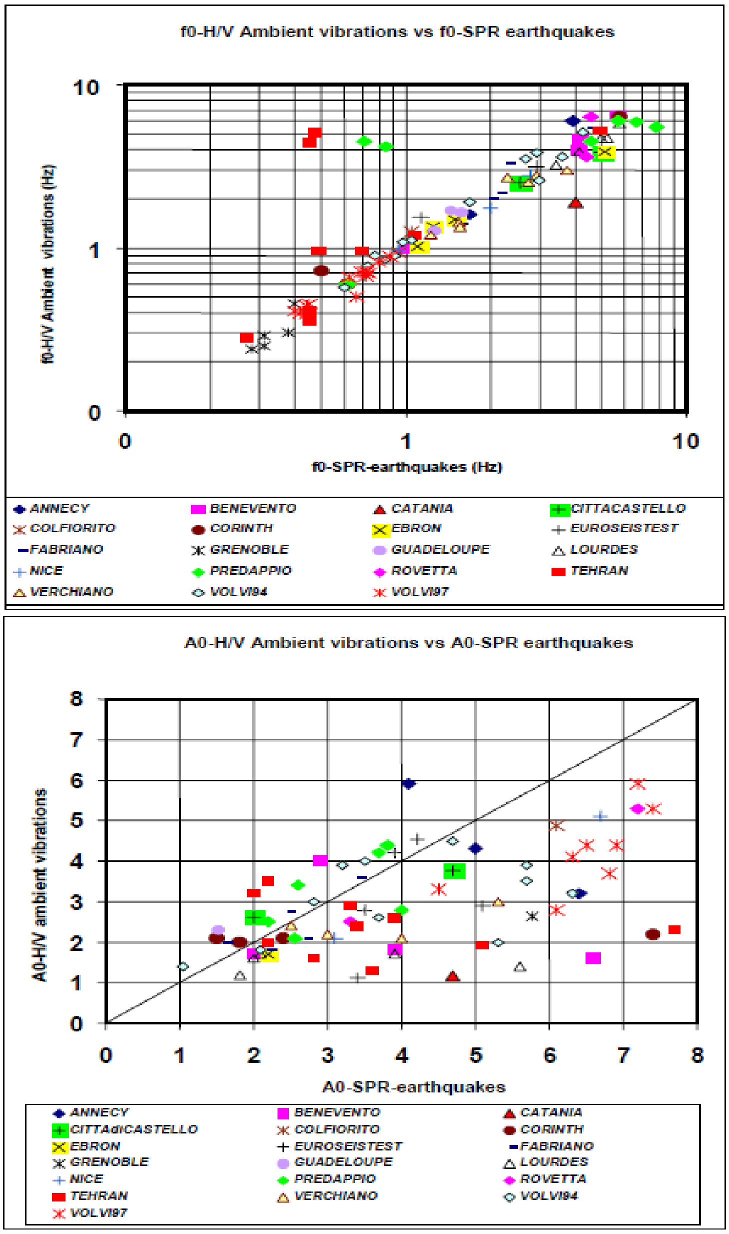


Figure 2: Comparison between H/V ratio of ambient vibrations and standard spectral ratio of earthquakes. Top: comparison of the frequencies f0, bottom: comparison of the amplitudes A0. From SESAME (2004).

Other examples of estimates obtained with this technique are also displayed in Figure 3, for comparison with the results of other estimates, presented later. They show that the H/V ratio technique allows obtaining, very simply, the fundamental resonant frequency, but fails for higher harmonics, and that peak amplitude is often different from amplification measured on standard spectral ratios.

The interpretation of the H/V spectral ratio is intimately related to the composition of the seismic wave-field responsible for the ambient vibrations, which in turn is dependent both on the sources of these vibrations, and on the underground structure. It is also related to the effects of the different kinds of seismic waves on the H/V ratio. See Bonnefoy-Claudet et al. (2006) and SESAME (2004) for a comprehensive review, and Kawase et al. (2011) for recent theoretical developments.

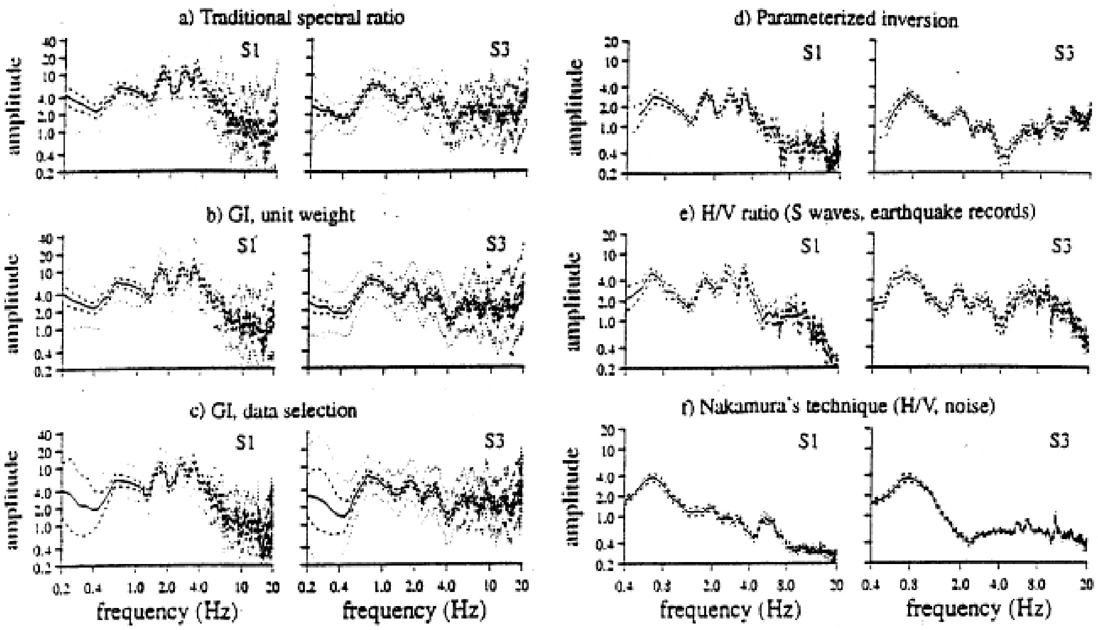


Figure 3: *Comparison between various techniques for the estimation of site response transfer function, for two sites in Oakland (California). Adapted from Field and Jacob (1995). a) Traditional spectral ratios; b) Generalized Inversion spectral ratios whatever the noise ratio); c) Generalized Inversion spectral ratios obtained when only data with signal to noise ratio larger than 3 are kept (and then given an equal weight). d) Parameterized inversion estimates; e) Average Horizontal-to-vertical component spectral ratios for S wave part of earthquake records. f) Nakamura's estimates (average horizontal-to-vertical spectral ratio of ambient vibrations) Curves a) to c) correspond to site-reference techniques, while curves d) to f) correspond to non-reference site techniques. The dashed-lines represent 95 % confidence limits of the mean.*

Theoretical investigations on the nature and use of H/V ratios of ambient vibrations are still going on. De Rubeis et al. (2011), for instance, proposed a strategy based on statistical methods to reconstruct the standard spectral ratios (SSR) at a target site using the spectral ratios on ambient vibration measurements at the same site. From a practical point of view, this method seems to be highly promising. However, further research efforts are necessary before it is ready to be applied for practical purposes.

2.1.2 Standard spectral ratio (SSR)

The most obvious procedure (the principle of which is illustrated in Figure 4) consists in comparing recordings at nearby sites (where source and path effects are believed to be identical) through spectral ratios. These spectral ratios constitute a reliable estimate of site response if the "reference site" is free of any site effect, which means that it should fulfil the two following conditions: First, it should be located near enough to the examined station to ensure that differences between each site are only due to site conditions, and not to differences in source radiation or travel path. Secondly, it should also be unaffected by any kind of site effect, which is the case when the reference site is located on an unweathered, horizontal bedrock (Steidl et al., 1996). These two conditions prove to be rather restrictive in practice. The SSR technique, introduced first by Borcherdt (1970), is still widely used, often without enough critical check of the reference site.

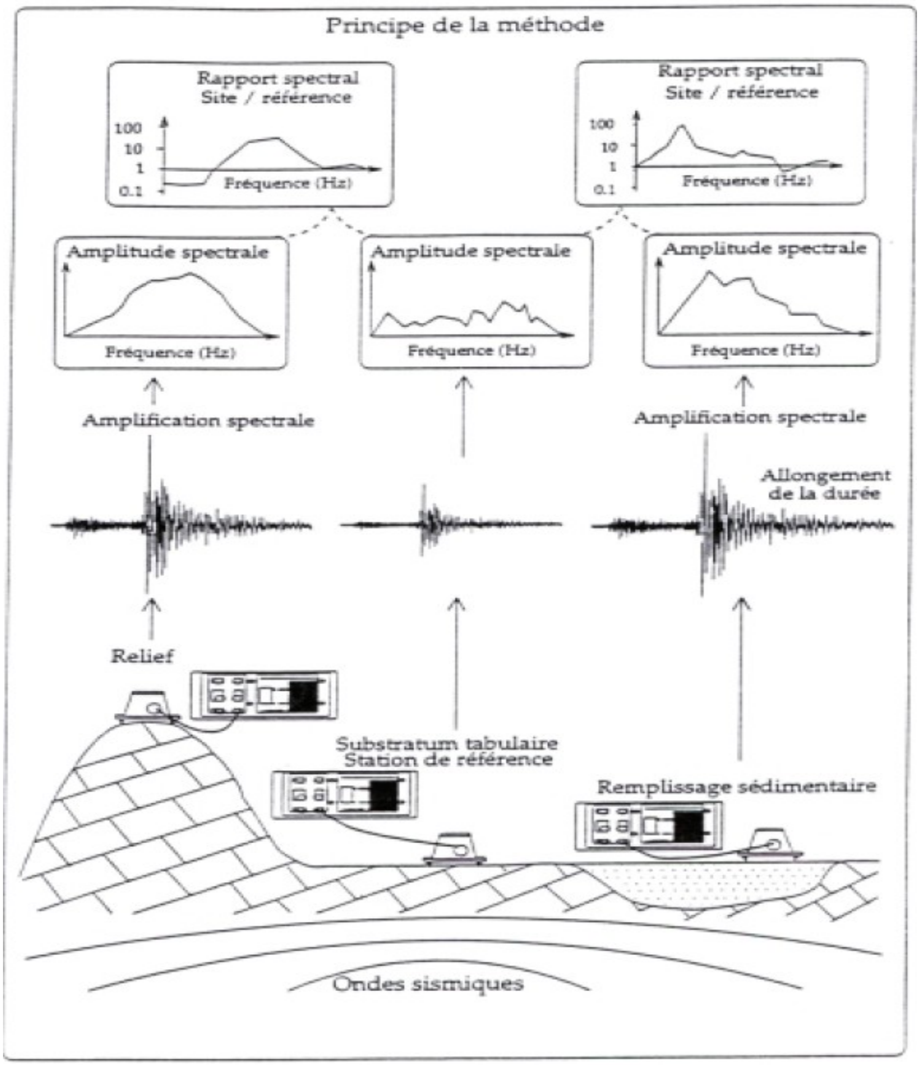


Figure 4: An example of use of the standard spectral ratio technique, for the evaluation of site effects and topographic effects.

From a practical point of view, two main difficulties linked with the SSR method can be identified:

- Measurements are usually available only for events weaker – much weaker indeed – than the events engineers are interested in. Therefore, due to non-linearity, the site effects estimated by SSR techniques may be considered as an overestimation or upper limit of the actual site effects at high frequencies, and, correlatively, a slight underestimation at frequencies below the "elastic" fundamental frequency.
- Even if the reference site is an "ideal" flat and unweathered rock site, the site response resulting of the SSR technique is obviously only valid with respect to the specific rock characteristics of this reference site. Therefore, this site response can only be convolved with rock hazard values that have been elaborated with GMPEs valid for rock of the same characteristics – which is rarely the case. Otherwise, corrections have to be taken into account for the differences in shear wave velocities and kappa values (different frequency contents of the rock ground motion: see, for instance, Silva & Darragh, 1995, or Van Houtte et al., 2011).

2.1.3 Generalised Inversion Technique (GIT)

The ground motion at a given site can be understood as a product of a source, path and site term. If several events have been recorded by a relatively dense array, the source, path and site terms can be found for all stations with the aid of a simultaneous inversion. Some simplifying assumption, however, have to be made with respect to the path term, accounting for attenuation (intrinsic and scattering). For a very concise description as well as further references, see Parolai (2012). In the inversion, either a specific rock site or the average of several rock sites within the array may be considered as a reference, free of site effects.

On the one hand, the GIT has the appealing advantage over the SSR technique that site effects can be extracted for sites without any nearby reference rock station. On the other hand, recordings of a whole array and non-negligible analysis efforts are necessary.

The difficulties mentioned with respect of the SSR technique, namely the non linear soil behaviour for strong motion of engineering interest and the reference rock characteristics (Vs_{30} and kappa), remain the same.

As early as 2000, Parolai et al. (2000), applied the GIT to a microzonation study for stations of a small urban network. In the French context, Drouet et al. (2008-a), applied the GIT with success to the French Accelerometric Network.

2.1.4 Vertical Array data analysis

The probably most reliable determination of site effects is possible if at least one accelerometer is located within the base rock below the site of interest. However, when calculating spectral ratios between the surface and the base rock recordings, some corrections have to be applied since ground motions at depth and at the surface are not identical, even for identical rock conditions. This is due to the reflection at the free surface; the interference between incoming and reflected wave trains is not the same at the free surface and at depth. Cadet et al. (2012-a) propose some correction for the transformation of a surface to depth spectral ratio into a classical surface (soil) to surface (rock) ratio, corresponding to what would result from the SSR technique.

Again, the problems of non linear soil behaviour for strong motion of engineering interest and different reference rock characteristics (Vs_{30} and kappa) remain the same as for the SSR technique and the GIT.

From a practical point of view, it has to be mentioned that the budgets to install borehole instruments will rarely be available, except – hopefully – for critical facilities. In fact, many Japanese NPPs have installed vertical arrays on their sites.

2.1.5 H/V spectral ratio of weak motion

Another simple technique consists in taking the spectral ratio between the horizontal and the vertical components of the shear wave part of weak earthquake recordings. This technique is in fact a combination of Langston's (1979) "receiver-function" method for determining the velocity structure of the crust from the horizontal to vertical spectral ratio (HVSR) of teleseismic P waves, and the H/V ratio on recordings of ambient vibrations (H/V noise spectral ratios).

This method is obviously interesting, since it does not need any reference station. It was first applied to the S wave portion of the earthquake recordings obtained at three different sites in Mexico by Lermo and Chavez-Garcia (1993). These recordings exhibit very encouraging similarities between the classical spectral ratios and these HVSR, with a good fit in both, the frequencies and amplitudes of the resonant peaks. The same technique was also checked on various sets of weak and strong motion data (see Chavez-Garcia et al., 1996; Lachet et al., 1996; Riepl et al., 1998; Theodulidis et al., 1996; Bonilla et al., 1997; Yamazaki and Ansary, 1997; Zaré et al., 1999, Kawase et al., 2011), from which several conclusions appear well established:

- The HVSR shape exhibits a very good experimental stability.
- It is also well correlated with surface geology, and much less sensitive to source and path effects (a warning should be issued however for near field recordings of large events, because of the strong directivity of the near-source "fling" or "killer pulse").
- However, comparisons with classical spectral ratios (including surface / down-hole recordings), as well as with theoretical 1D computations (see also Lachet and Bard, 1994), also agree on the fact that the absolute level of HVSR depends on the type of incident waves. It follows that the determination of the absolute level of amplification from only HVSR is not straightforward.

Field and Jacob (1995) also applied this technique in their systematic comparisons, and found that the method reproduces very well the shape of the site response, but underestimates the amplification level (see Figure 3e). They also found very different results when applying this technique to the P-wave part of the recordings. They therefore conclude that HVSR, when applied to the S-wave signals, reveals the overall frequency dependence. Based on our own investigations, we agree only partly with this conclusion, since in some cases we did find a good similarity in "spectral shapes", but in a few other HVSR we were only able to identify the fundamental resonance frequency. Furthermore, it should be pointed out that this technique has been applied and checked for soft soil sites only, and might not be valid for other kinds of sites.

2.1.6 Use of the coda wave for site effect estimation

During the last decades, the signal processing community has developed, for digital communication, different methods of blind deconvolution making it possible to retrieve the unknown convolutive components of one known signal. Sèbe (2003) applied these techniques to the codas of seismic recordings in order to retrieve seismic source time functions and site effects. His work has the character of a feasibility study and should be further developed before it might one day be applied in a practical context.

2.2 Numerical methods

When the geotechnical characteristics of the site or of the area are known, site effects can be, in principle, estimated through numerical analysis. The prerequisite of a sufficient geotechnical knowledge generally implies that such ground response analyses be made on a site by site basis, but the density of boreholes and geotechnical information in some large cities may be sufficient to allow a numerically-based zoning. Such an approach, however, requires an in-depth understanding both of the analytical models and of the numerical schemes that are used. When the required expertise is lacking, it may occur that sophisticated numerical analyses lead to less reliable results than simpler and cruder, but more robust approximations.

Methods presented in the following sections are given one after the other as they are, most of the time, a combination of different aspects:

- dimension of the problem (1D, 2D, 3D);
- type of seismic solicitation (in plane or out of plane wave, point or extended source, inside model or far source, etc.);
- account for material behaviour (linear, equivalent-linear, non linear).

Douglas and Aochi (2008) present an article that summarises existing methods and the most important references, provides a family tree showing the connections between different methods (Figure 5) and, most importantly, discuss the advantages and disadvantages of each method. This paper by Douglas and Aochi (2008) contains a comprehensive comparison of most available methods, pointing out the advantages, limitations, inputs, outputs, references, type of usage, available codes, etc.

As concluding remarks from this wide comparison review, Douglas and Aochi (2008) state that, over time, the preferred techniques will tend to move to the top of Figure 5 (more physically based approaches requiring greater numbers of input parameters) since knowledge of faults, travel paths and sites will become sufficient to constrain input parameters. Such predictions will be site-specific as opposed to the generic estimations commonly used at present. However, Douglas and Aochi (2008) say that, due to the relatively high cost and difficulty of ground investigations, detailed knowledge of the ground subsurface is likely to continue to be insufficient for fully numerical simulations for high-frequency ground motions, which require data on 3D velocity variations at a scale of tens of metres. The authors state that, in the distant future, when vast observational strong-motion databanks exist including records from many well studied sites and earthquakes, more sophisticated versions of the simplest empirical technique, that of representative accelerograms, could be used where selections are made not just using a handful of scenario parameters but many, in order to select ground motions from scenarios close to that expected for a study area.

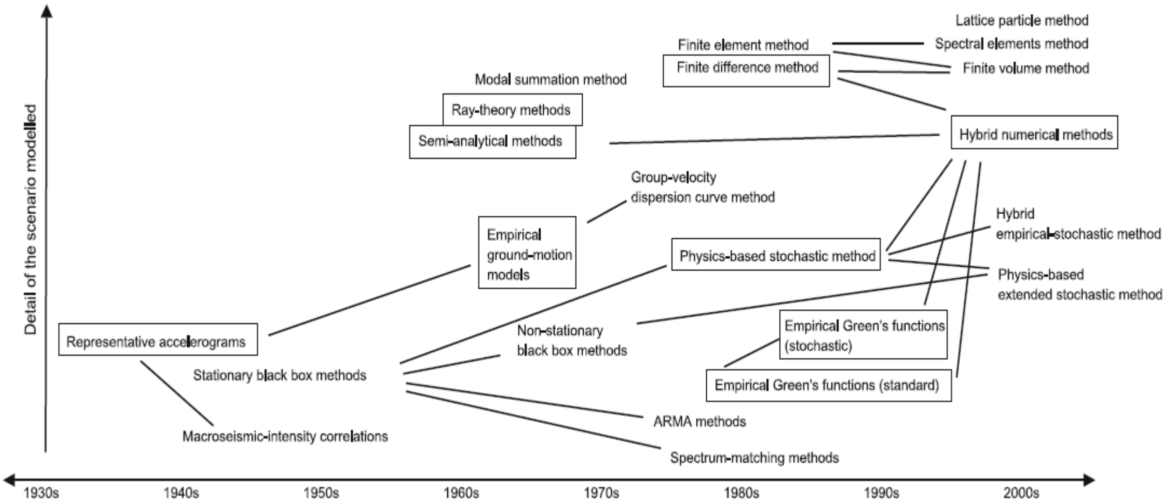


Figure 5: Summary of the approximate date when a method was developed on the x-axis, links to other approaches and the level of detail of the scenario modelled on the y-axis. Boxes indicate those methods that are often used in research and/or practice (Douglas and Aochi, 2008).

2.2.1 1D response of soil columns

There exist a number of simple analytical methods which allow computation of the seismic response of a given site with only the help of a small personal computer. Amongst these, the most widely used make use of the multiple reflection theory of S waves in horizontally layered deposits, very often referred to as "1D analysis of soil columns".

Such a soil column is excited by an incoming plane S wave, generally considered as vertically incident, and corresponding to a surface bedrock motion representative of what is likely to occur in the area. The specific parameters required for such an analysis are shear wave velocity, density, damping and thickness of each layer. These parameters may be obtained either through direct in situ measurements, or from drillings and subsequent laboratory measurements, or from known approximate relationships with other, more usual geotechnical parameters such as the results of cone penetration tests (CPT) or standard penetration tests (SPT).

These analyses may be performed considering either a linear or a non-linear behaviour for the soil. The non-linearity is very often approximated by a "equivalent-linear" method that uses an iterative procedure to adapt the soil parameters (i.e., rigidity and damping) to the actual strain it undergoes, according to the curves depicted in Figure 6. The SHAKE program is one of the most widely used for such calculations (Schnabel et al., 1972).

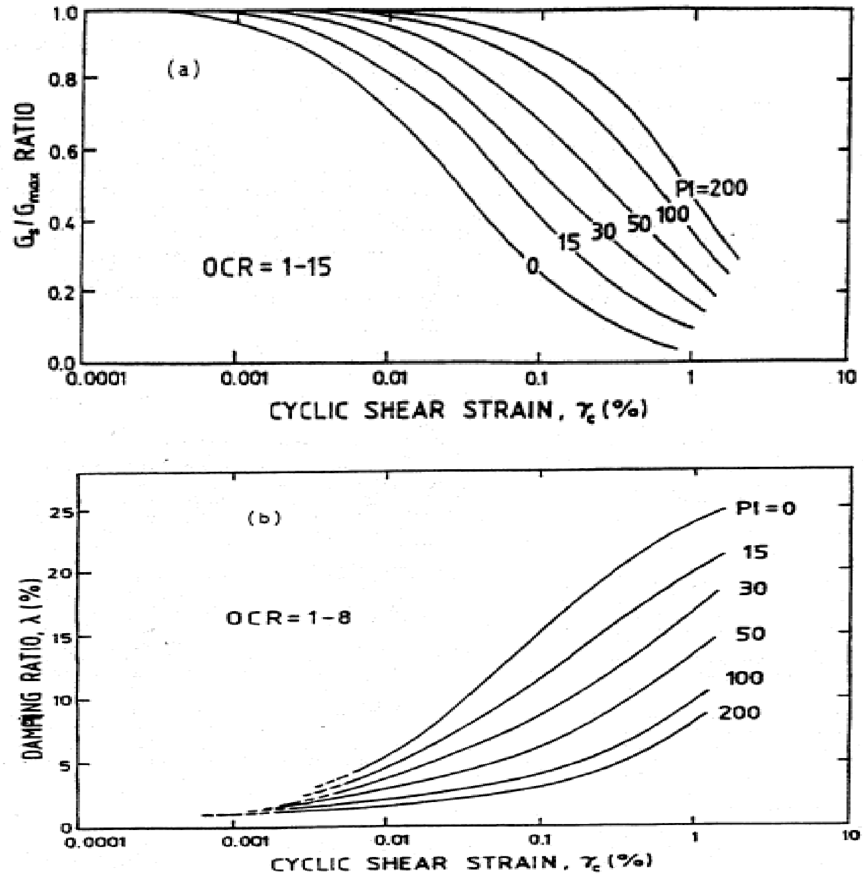


Figure 6: An example of strain dependency of normalized shear modulus (top) and damping (bottom), for soft soils with varying plasticity index PI (after Dobry and Vucetic, 1987).

Recently developed packages incorporating true non-linear constitutive models are now available, that also allow accounting for liquefaction phenomena (example: CyberQuake program, 1998). However, these non-linear analyses require a quantitative knowledge of the actual nonlinear material behaviour, which can only be obtained by means of sophisicated laboratory tests. Some generic average curves have been proposed for different types of material, as sand or clay, but the actual behaviour of a given soil at a given site may strongly depart from these averages. This was precisely the case in Mexico City where the clays, with high plasticity index, proved indeed to behave almost linearly despite of the large strains experienced during the 1985 event, while they were previously believed to be highly non-linear because of their very low rigidity.

Random vibration theory (RVT) equivalent-linear site response analyses, along with profile randomization, was developed by Walt Silva to provide a method for accommodating random variability in dynamic material properties that occur across a site (or within a generic site category) in developing site specific motions (EPRI, 1993). The fully probabilistic approach leads to unbiased estimates of mean (linear or log) amplification or site response along with the associated aleatory variability in site effects due to site-specific parametric aleatory variability. The motivation for the development of equivalent-linear RVT was to eliminate the use of multiple time histories. Pacific Engineering has extended the RVT approach to vertical motions using incident inclined P-SV wave motions (EPRI, 1993, Silva, 1997). The approach has been validated with recorded motions (EPRI, 1993).

Rathje and Kottke (2008) present a report that focuses on the RVT approach for equivalent-linear site response analysis. Figure 7 shows the advantages and disadvantages of different methods of site response analysis. RVT-based site response analysis is an extension of stochastic ground motion simulation procedures developed by seismologists to predict peak ground motion parameters as a function of earthquake magnitude and site-to-source distance (e.g. Hanks and McGuire 1981, Boore 1983). The RVT procedure consists of characterizing the Fourier Amplitude Spectrum (FAS) of a motion and using RVT to compute peak time domain values of ground motion from the FAS. When site response is included in the calculation, the FAS developed for rock is modified to account for the soil response before RVT is applied.

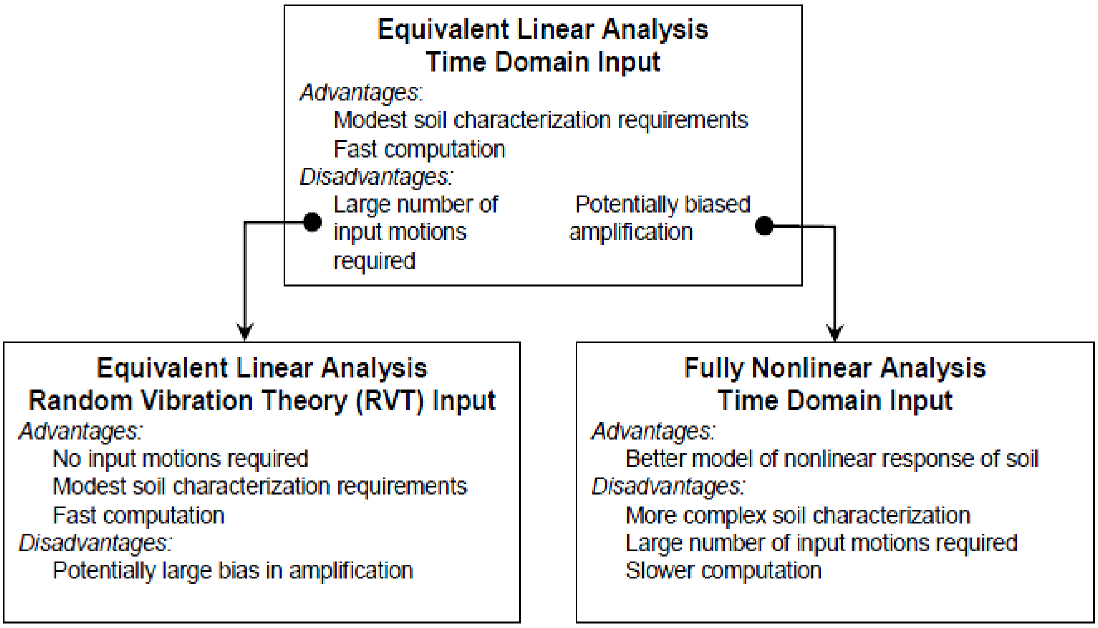
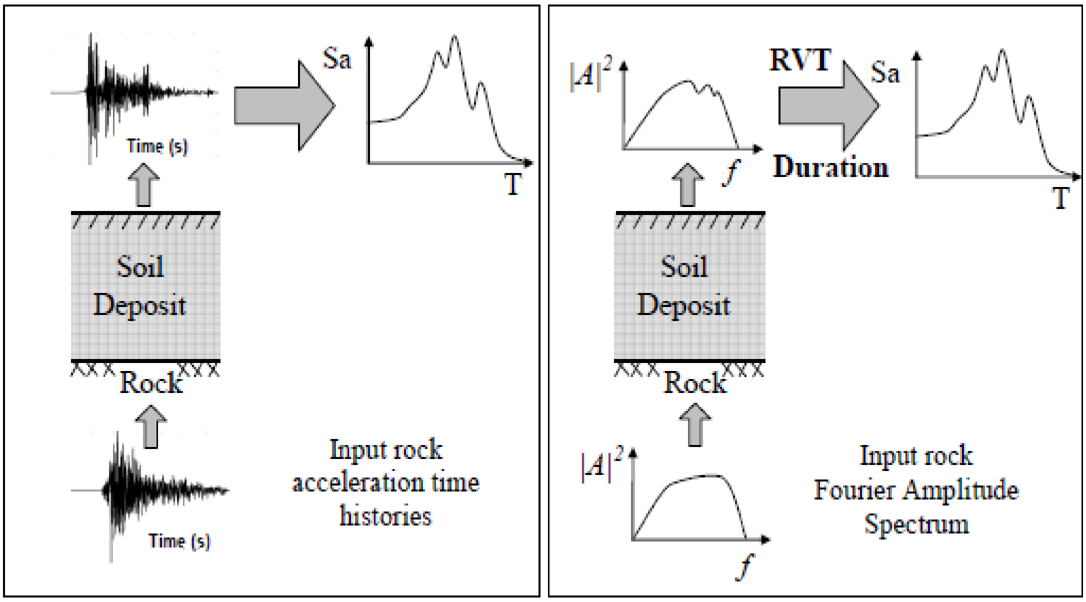


Figure 7: Advantages and disadvantages of different methods of site response analysis (Rathje and Kottke, 2008).

As reported in details by Rathje and Kottke (2008), Random Vibration Theory represents an alternative to selecting a suite of motions for equivalent-linear analysis. In the RVT approach, the input to the site response analysis is a single Fourier Amplitude Spectrum (FAS) that represents the input rock motion. This spectrum contains only the Fourier amplitudes, without the accompanying phase angles, and thus cannot be used to compute directly an acceleration-time history. However, RVT can be used to estimate peak time domain values (e.g., peak acceleration) from the Fourier amplitude information. A schematic of RVT-based site response analysis is shown in Figure 8 (b). Transfer functions (the same frequency domain transfer functions used in equivalent-linear analysis with time history input motions) are used to propagate the rock FAS through the soil column to obtain the FAS of the motion at the ground surface, and RVT is utilized to calculate peak time domain parameters, such as peak ground acceleration and spectral acceleration, from the FAS. The RVT calculation requires an estimate of the ground motion duration, a parameter that is not required in traditional equivalent-linear analysis with time domain input motions. The product of an RVT-based site response analysis is an acceleration response spectrum calculated from the surface FAS, rather than an acceleration time history.

As described by Rathje and Kottke (2008), the key to RVT analysis is the prediction of peak time domain motions from only a Fourier amplitude spectrum representation of the motion and its duration. Parseval's theorem and extreme value statistics (EVS) are used to relate the frequency domain motion with the peak time domain motion. EVS was first used in seismology by Hanks and McGuire (1981) to predict peak ground acceleration (PGA) from the rms (root-mean-square) acceleration, a_{rms}. Parseval's theorem is used to compute a_{rms} from the FAS, and a peak factor is used to relate a_{rms} to the peak ground acceleration. More details on the RVT theory can be found in Rathje and Kottke (2008).



(a) (b)

Figure 8: (a) Time History Seismic Site Response Analysis, and (b) Random Vibration Theory Based Seismic Site Response Analysis (Rathje and Kottke, 2008).

Kottke and Rathje (2008) developed the computer program Strata which performs equivalent-linear site response analysis in the frequency domain using time domain input motions or random vibration theory (RVT) methods, and allows for randomization of the site properties. However, the randomization of soil velocity profiles addresses the question of the real representativeness of such a procedure: are there enough borehole data to propose appropriate models for vertical spatial correlations? Strata is distributed under the GNU General Public License which can be found here: http://www.gnu.org/licenses/. The manual can be found in Kottke and Rathje (2008).

As underlined by Kottke and Rathje (2008), for the large magnitude events (Mw 7.5, R = 50 km), the point source Fourier Amplitude Spectrum (FAS) matches the Inverse RVT (IRVT) FAS over frequencies from 0.4 to 15 Hz, but it is significantly larger than the IRVT FAS at lower frequencies. This difference results in significantly larger spectral accelerations at long periods. The discrepancies between the input rock response spectra and the FAS from the seismological point source model are certainly affected by the shortcomings of the point source model. A better fit to the target spectrum could be obtained from more sophisticated source models or finite fault simulations. Nonetheless, the differences obtained reveal that it is critical that the input rock FAS used in RVT site response calculations be converted to a rock response spectrum such that its match to a target spectrum can be assessed.

2.2.2 Account for non-linear behaviour

As stressed by Bonilla et al. (2011), most nonlinear studies are performed either by using equivalent-linear approximations or using complex constitutive models that require a detailed soil characterization. Indeed, the problem of estimating nonlinear site response is the number of parameters needed to describe the dynamic material properties. For this reason, the majority of "true" nonlinear analyses is limited to one-dimensional computations.

For example, the program CyberQuake, (CyberQuake, 1998), allows two kinds of direct and one inverse analysis:

1. Cyber Analysis (transient analysis),
2. Equivalent-Linear Analysis,
3. Deconvolution.

In 1, soil layers may be considered as elastoplastic materials (with isotropic linear elasticity as a special case). True transient nonlinear analyses are carried out and, following the version, two or three-dimensional kinematics are assumed. In 2 and 3, soil layers are treated by equivalent-linear assumption and viscoelastic analyses are performed while the dependence of the shear modulus, as well as the damping, on distortion is incorporated. The computations are done in the frequency domain. It is also possible to perform direct linear (visco)elastic analyses in 2 and deconvolution in 3. The boundary conditions are defined by current engineering language (e.g. water table position, deformable / rigid bedrock, etc.) instead of using numerical modelling terminology. Therefore, standard boundary conditions are easily prescribed on the boundaries. The rigid bedrock assumption simplifies computational aspects, as no absorbing boundaries have to be taken into account. With this assumption, the calculation can be done in a moving reference frame that results in a fixed base. The seismic loading is modelled as a prescribed displacement time history of the rigid bedrock, which results from the double integration of the input acceleration with respect to time.

DYNAFLOW (Prévost, 2002), is a finite element analysis program for the static and transient response of linear and nonlinear two- and three-dimensional systems. In particular, it offers transient analysis capabilities for both parabolic and hyperbolic initial value problems in solid, structural and fluid mechanics. There are no restrictions on the number of elements, the number of load cases, the number of load-time functions, and the number or bandwidth of the equations. Despite large system capacity, no loss of efficiency is encountered in solving small problems. In both static and transient analyses, an implicit-explicit predictor-(multi)corrector scheme is used. The nonlinear implicit solution algorithms available include: successive substitutions, Newton-Raphson, modified Newton and quasi-Newton (BFGS and Broyden updates) iterations, with selective line search options. Although

DYNAFLOW can be a very powerful analysis tool, it should be emphasized that its use requires a thorough understanding of the underlying field theories used, and of the integration techniques (both in space and time) employed. Furthermore, the main problem in accounting for soil full non-linearity, especially in more than 1D problems, is to obtain the input soil characteristics.

Another example is SUMDES (Li et al, 1992), a computer program to perform dynamic response analyses of Sites Under Multi-Directional Earthquake Shaking. The basic assumptions made in deriving the formulations are as follows:

- The site is horizontally layered and it extends infinitely in horizontal directions
- Waves travel along the vertical direction only
- The ground surface is free of stresses
- The bottom boundary is impermeable
- Soil below the water table is fully saturated

As explained by Li et al. (1992), in practice, these assumptions conform to large free-field soil deposits that are water saturated, essentially levelled, and subjected to earthquake shaking originating primarily from their underlying rock formation. As for DYNAFLOW, the procedure is formulated on the basis of effective stress principle, vectored motion, transient pore fluid movement, and generalized material stiffness; therefore, it is capable of predicting three-directional motions and the pore water pressure build-up and dissipation within the soil deposits. Each soil layer can be individually modelled using either linear elasticity or other built-in nonlinear inelastic constitutive models.

Bonilla et al. (2011) point out the fact that site characterization studies have different goals for seismologists and earthquake engineers. Traditionally, seismologists work on elastic and viscoelastic wave propagation in complex media. This means, that P and S wave speeds, density, Q_P and Q_S values characterize the media (e.g. Magistrale et al., 2000). In addition to these parameters, earthquake engineers also need information about the dynamic properties of the different materials. To name a few, lithology composition to see the type of material, water content, cohesion and friction angle, liquefaction resistance laboratory tests, shear modulus reduction and damping ratio curves (e.g. Heuze et al., 2004). The type and number of geotechnical parameters depend on the constitutive soil model used in the numerical simulations.

Bonilla et al. (2011) studied the 2D response of a small basin with an inclined incident wavefield. In order to reduce the model's size, they propagate a plane wave with three angles of incidence into a relatively small basin in Nice, France, which has a 3D velocity model and whose soil nonlinear dynamic parameters have been estimated from literature. They use a 2D P-SV finite differences scheme as proposed by Saenger et al. (2000). The nonlinear soil behaviour is the one proposed by Towhata and Ishihara (1985) and Iai et al. (1990). Figure 9 shows the basin response for the linear (left) and nonlinear (right) cases. Top panels correspond to the basin amplification for an incident plane wave at 35° to the right; the second panels show the results for an inclined wave at 35° to the left; the third panels correspond to the case of vertical incidence, and the bottom panels display the S wave velocity model. The first thing that can be observed is the deamplification of the ground motion for the nonlinear case. However, nonlinear basin responses for the inclined wavefield are not as much deamplified compared to the vertical incidence. As explained by Bonilla et al. (2011), this is due to the fact that inclined waves do not traverse the nonlinear media as if they were impinging vertically.

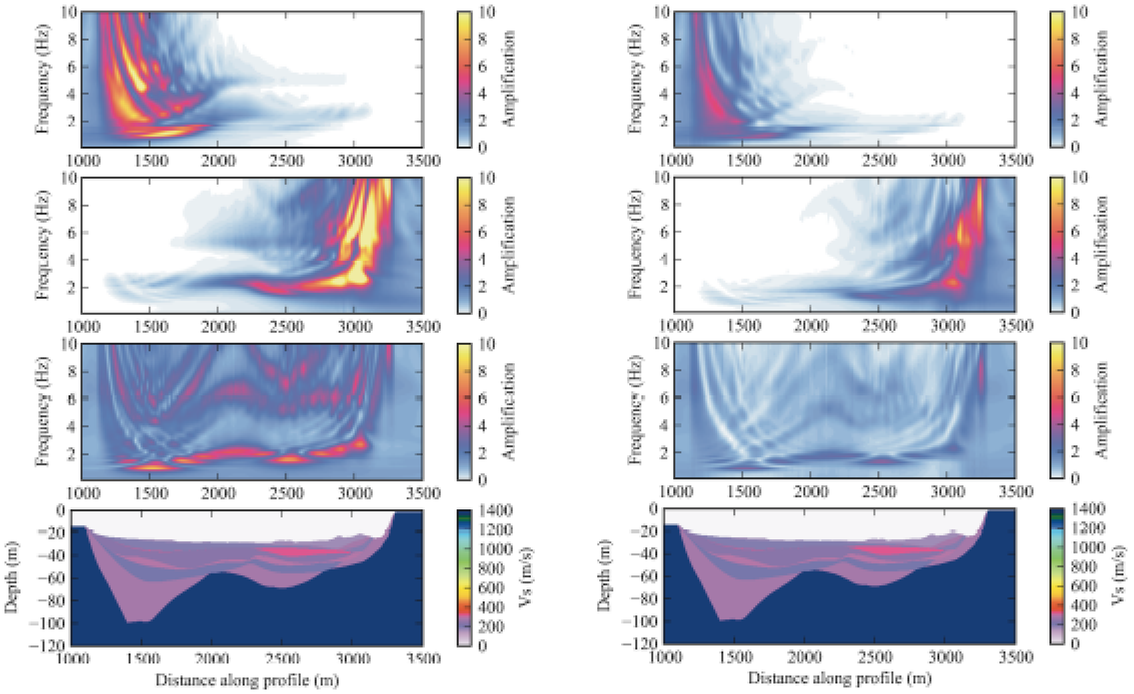


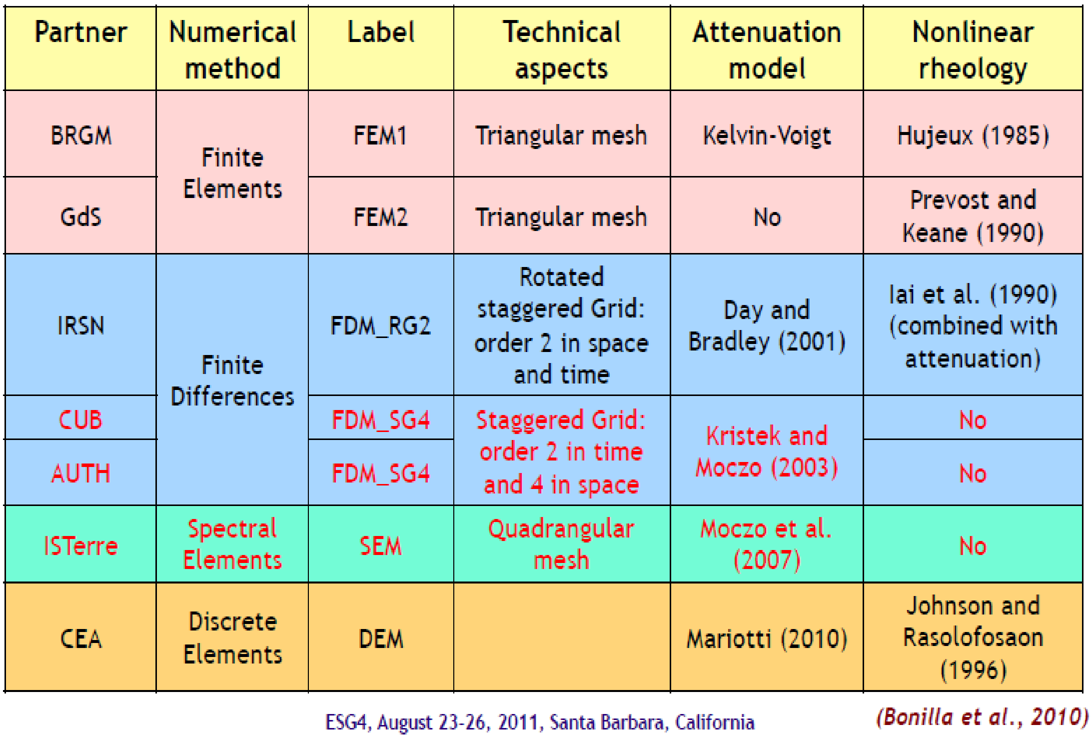
Figure 9: 2D linear (left) and nonlinear (right) basin response of Nice, France (Bonilla et al., 2011).

Bonilla et al. (2011) show, on different examples, that soil nonlinearity has a broadband effect. Thus, there is a need of computing broadband time histories so that nonlinear effects can be triggered, which all seismologists know is not a trivial problem. On the contrary, their analysis of the 2011 Tohoku records at KiK-net stations suggests that nonlinear behaviour may be shallow. This is good news because there is no need for expensive material dynamic characterization down to the bedrock. Finally, since the resulting ground motion depends on the source and soil dynamic properties, there is a need to quantify the uncertainty of the numerical predictions. Finally, Bonilla et al. (2011) conclude that one-dimensional studies can be easily done, but 2D and 3D analyses present a challenge and there is still a lot of work to be done.

Bard et al. (2011) show the main results of the "EuroseisTest Verification and Validation Project" (E2VP), employing a wide range of different 2D non-linear numerical methods (see Table 1). Even 2D linear modelling is not yet straight-forward and needs iterations and cross-checks with other techniques. Bard et al. (2011) also show a key importance of damping in non-linear models: the classical "Seed like" curves yield strong non-linear effects at least in deep deposits which are already significant at 0.05 g (0.12 g surface). Results of the project also show large effects at high frequencies because of damping; are those realistic? Finally, they observe a large variability in the non-linear results: a) an identical G-ζ-γ curve implemented in different codes yields different results, with large differences in time histories, strain / pga / pgv profiles; b) the effects on 5% response spectra are less apparent.

Finally, it has to be noted here that non linear codes often become numerically unstable in the case of very high level seismic solicitations (for example with multi-component excitation and vertical accelerations over 1 g).

Table 1: Applied 2D non-linear methods used by the participants of the E2VP (from Bard et al., 2011). For cited references, see Bard et al. (2011).



Partner	Numerical method	Label	Technical aspects	Attenuation model	Nonlinear rheology
BRGM	Finite Elements	FEM1	Triangular mesh	Kelvin-Voigt	Hujeux (1985)
GdS		FEM2	Triangular mesh	No	Prevost and Keane (1990)
IRSN	Finite Differences	FDM_RG2	Rotated staggered Grid: order 2 in space and time	Day and Bradley (2001)	Iai et al. (1990) (combined with attenuation)
CUB		FDM_SG4	Staggered Grid: order 2 in time and 4 in space	Kristek and Moczo (2003)	No
AUTH		FDM_SG4			No
ISTerre	Spectral Elements	SEM	Quadrangular mesh	Moczo et al. (2007)	No
CEA	Discrete Elements	DEM		Mariotti (2010)	Johnson and Rasolofosaon (1996)

ESG4, August 23-26, 2011, Santa Barbara, California (Bonilla et al., 2010)

The computation of the two-dimensional response of alluvial basins can be based on the discrete wavenumber method proposed by Aki and Larner (1970). The basis of this method lies on the transposition of the direct problem in space and time domain to the horizontal wavenumber and frequency domain, achieved by a double Fourier transform. To solve the problem numerically, a discretization in both space and time, and thus in wavenumber and frequency, is operated.

The account for equivalent-linear behaviour is practically achieved by fitting the modulus and damping of the linear viscoelastic model to the effective modulus and damping of the non-linear material under loading. These effective values are generally given by experimental modulus and damping degradation curves obtained by laboratory tests. In Seed and Idriss' visco-elastic model, modulus and damping values are computed from these degradation curves by an iterative algorithm, until a convergence limit is reached, between the effective strain at two consecutive iterations. Seed and Idriss' equivalent-linear model, widely used in the well-known 1D SHAKE program (Schnabel et al., 1972), was implemented in the extended Aki and Larner method, for SH waves. In the 2D computation, it is assumed that the shear modulus and damping are constant inside each layer, with the strain amplitude being variable (2D computation). In the 2D equivalent-linear frame, the mean strain amplitude, computed at several points across the valley within each layer, is used to compute the new shear modulus and damping at each iteration step.

Some of the simplifying assumptions on which this method is based impose a frequency limitation which is approximately in the range between 4 × f0 and 8 × f0, f0 being the fundamental resonance frequency of the considered basin. The iterative equivalent-linear formulation forces to estimate the time domain response and associated peak and effective strains for each iteration. Thus, the response is needed over the whole frequency range covered by the input motion, which very often exceeds this 8 × f0 upper bound. To overcome this frequency limitation, the computation is combined with a classical 1D computation, for frequencies higher than 8 × f0. Between 4 × f0 and 8 × f0, a hybrid solution if linearly interpolated between the 1D and the 2D solutions, as shown on Figure 10. The hybrid transfer function can be written as:

$TFhybrid = \alpha\, TF2D + (1 - \alpha)\, TF1D$, with:

$\alpha = 1$ for $f \leq 4f0$,

$\alpha = 2 - f/4f0$ for $4f0 < f \leq 8f0$,

$\alpha = 0$ for $f > 8f0$

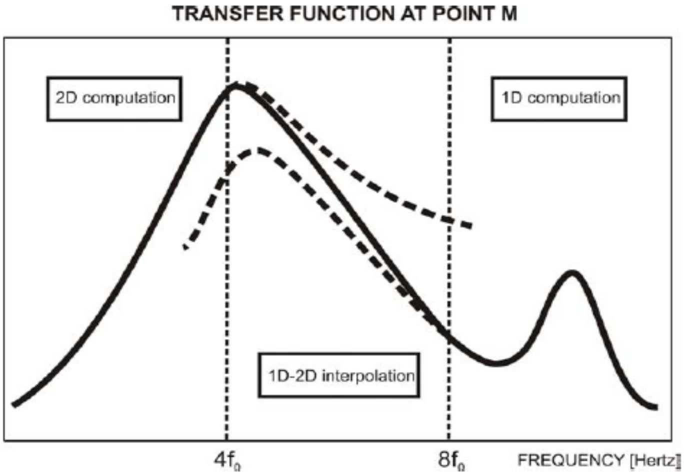


Figure 10: Approximation of the 2D basin response by the extended Aki and Larner's method.

2.2.3 Modelling of distant earthquakes

In areas of low to moderate seismicity, it is necessary to account for distant sources. Few local earthquake recordings are available in such areas. Hybrid methods composed of two models with different scales are proposed to optimise the modelling of distant sources.

As pointed out by Fäh and Suhadolc (1994), many of the numerical techniques used for seismic zonation studies treat one-dimensional structural models and/or the incidence of plane polarized body waves. These techniques are often not adequate for laterally heterogeneous structures and for sources that are not located beneath the site of interest. In such cases, a more rigorous treatment of the combined effects of the source, the path and the site response is needed. This is the reason why Fäh and Suhadolc (1994) developed a hybrid approach combining modal summation and the finite-difference technique, as shown on Figure 11. Each of the two techniques is applied in that part of the structural model where it works most efficiently. Modal summation is applied to simulate wave propagation from the source position to the detailed two-dimensional structure of interest. The path is approximated by a one-dimensional structure composed of a series of flat, homogeneous, anelastic layers. The finite-difference method, applied to treat wave propagation in the two-dimensional part of the structural model, permits wave propagation modelling in complicated and rapidly varying velocity structures. The hybrid approach allows the simulation of the complete wavefield characterized by given frequency and phase-velocity bands, and, in these bands, it can automatically account for all surface waves and body waves characterized by any incidence angle consistent with the bands considered.

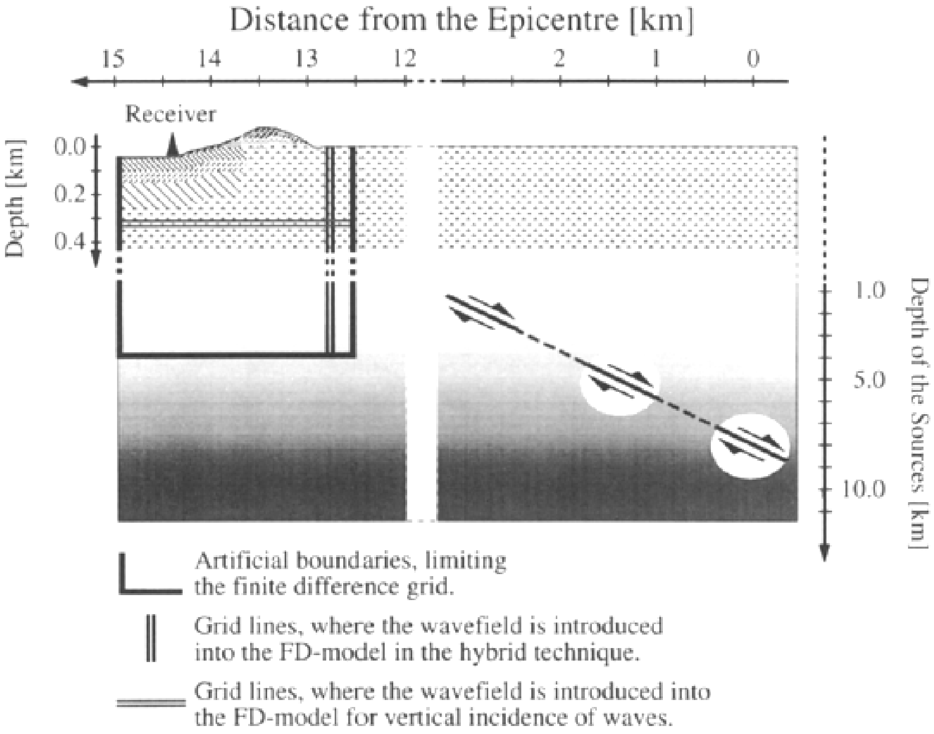


Figure 11: Geometry used for the numerical modelling, both for the vertical incidence of plane polarized body waves in one- and two-dimensional structural models, and for the application of the hybrid technique. In the right part of the Figure, the spatial representation of the used extended source is schematized (Fäh and Suhadolc, 1994).

Fäh and Suhadolc (1994) compare the results obtained with one- and two-dimensional structural models for vertical incidence of plane polarized body waves with those obtained with the hybrid approach for two-dimensional structural models. For the same site, these differences consist of strong variations in amplitude and in the shape of the spectral amplifications. For a seismic source which is not located beneath the site, vertical incidence of waves significantly overestimates the local hazard in a laterally homogeneous structure. For a laterally heterogeneous area, Fäh and Suhadolc (1994) can conclude that one-dimensional modelling fails to estimate the seismic hazard, whereas for a seismic source which is not located beneath the site of interest, two-dimensional modelling with vertical incidence of plane polarized body waves may not allow reliable estimates to be made of the frequency bands at which amplifications occur.

Moczo et al. (2007) present a monograph providing tutorial and detailed introduction to the application of the finite-difference (FD), finite-element (FE), and hybrid FD-FE methods to the modelling of seismic wave propagation and earthquake motion.

As described in details by Moczo et al. (2007), the application of the finite-difference (FD) method to a particular differential problem includes:

– construction of a discrete FD model of the problem (coverage of the computational domain by a space-time grid, FD approximations to derivatives, functions, initial and/or boundary conditions at all the grid points, construction of a system of the finite-difference),
– analysis of the FD model (consistency and order of the approximation, stability, convergence),
– numerical computations.

The analysis of the FD model or numerical computations may lead to a redefinition of the grid and FD approximations, if numerical behaviour is not satisfactory.

For the finite-element (FE) method, the need is to develop a discrete approximation to the equation of motion in its weak formulation. Moczo et al. (2007) present an alternative approach based on the idea of Michlin (1970), in directly deriving the semi-discrete weak form of the equation of motion from the strong (differential) form of the equation of motion.

As pointed out by Moczo et al. (2007), in many wavefield-medium problem configurations, it is advantageous to combine two or even more computational methods in order to solve the problem with a reasonable level of accuracy and computational efficiency. In some cases, it is advantageous to solve time dependence of the displacement using one method and spatial dependence using some other method. In some other cases, it is reasonable to split the computational domain into two or more parts and solve each part by the best suited method. Several hybrid methods were developed in an effort to achieve reasonable computational efficiency in applications to relatively complex structural models. The FE method more easily incorporates boundary conditions at the free surface and material interfaces compared to the FD method. This is especially true about non-planar surfaces and interfaces. From this point of view, the FE method is better suited for simulation of the traction-free condition and rupture propagation. This is the reason why Moczo et al. (2007) developed a hybrid combination of the two methods (Figure 12), to comprise both the dynamic earthquake source and the wave propagation in the complex heterogeneous medium.

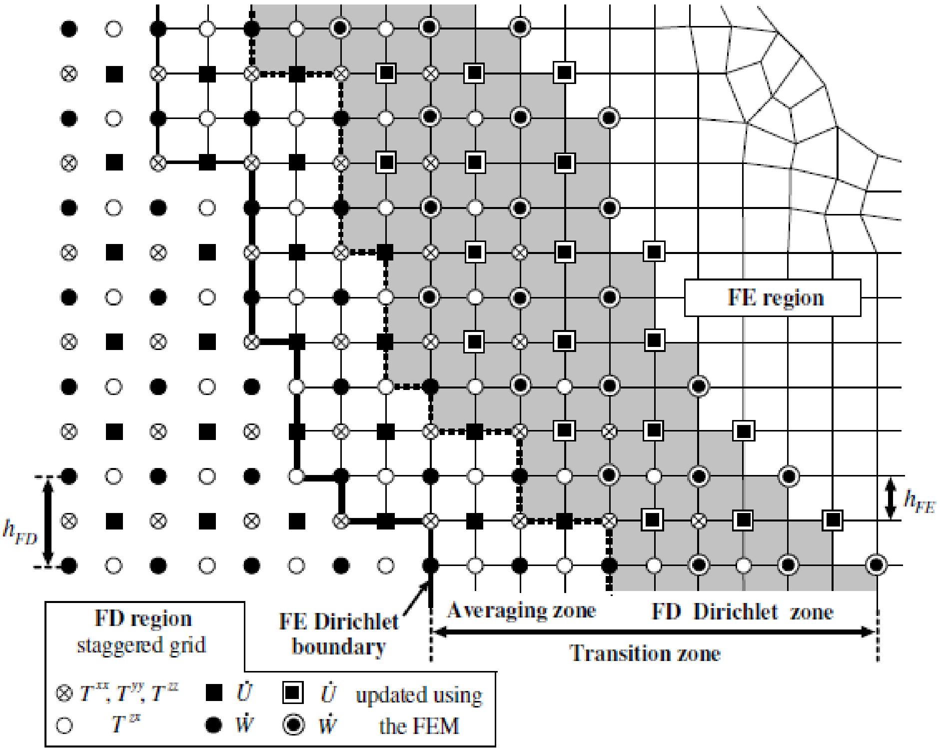


Figure 12: *The FD-FE transition zone in the FD-FE hybrid modelling. For simplicity, only the vertical grid plane with the x- and z-components of the particle velocity is shown.* h_{FD} *is the spatial grid spacing in the FD grid,* h_{FE} *is the spatial grid spacing in the uniform part of the FE grid near the transition zone (the rest of the FE grid can be non-uniform). Each grid point in the FE region, that is, each intersection of the grid lines in the FE region, is a position of all components of the displacement vector (Moczo et al., 2007).*

Bielak et al. (2003) developed a modular two-step, finite-element methodology for modelling earthquake ground motion in highly heterogeneous localized regions with large contrasts in wavelengths. Their aim is to model complex geological structures such as sedimentary basins, some distance away from the earthquake source. Bielak et al. (2003) overcome the problem of multiple physical scales by subdividing the original problem into two simpler ones. The first is an auxiliary problem that simulates the earthquake source and propagation path effects with a model that encompasses the source and a background structure from which the localized feature has been removed. The second problem models local site effects. Its input is a set of equivalent localized forces derived from the first step. These forces act only within a single layer of elements adjacent to the interface between the exterior region and the geological feature of interest. This enables to reduce the domain size in the second step. If the background subsurface structure is simple, one can replace the finite-element method in the first step with an alternative efficient method. This methodology, called the Domain Reduction Method (DRM), is illustrated in Figure 13 and in the paper by Yoshimura et al. (2003) for several 3D problems of increasing physical and computational complexity. They consider first a flat-layered, stratigraphic system. For this simple case, the first step can be carried out by means of 3D Green's function evaluations. An extension to more general problems is illustrated by Bielak et al. (2003), with the same background stratigraphy. Verifications and applications are presented in Yoshimura et al. (2003). The method can be applied in the elastic, anelastic and inelastic cases.

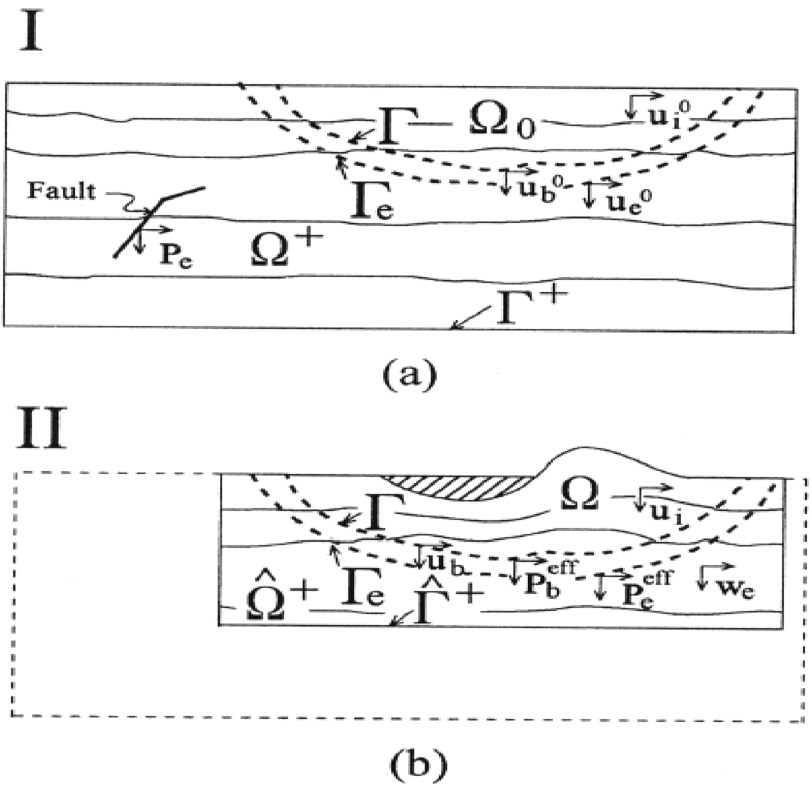


Figure 13: Summary of the two-step domain reduction method (DRM). (a) Step I defines the auxiliary problem over background geological model. Resulting nodal displacements within Γ, Γ_e and the region between them are used to evaluate effective seismic forces P^{eff} required for step II. (b) Step II, defined over reduced region made up of Ω and Ω^+ (a truncated portion of Ω+). The effective seismic forces P^{eff} are applied within Γ and Γ_e. The unknowns are: the total displacement fields u_i in Ω and u_b on Γ, and the residual displacements w_e in Ω^+. (Bielak et al., 2003).

2.2.4 Spectral elements modelling (2D and 3D)

Smerzini et al. (2011) present a comparison of different numerical approaches using the Spectral Element Method (SEM) software package GeoELSE (GeoELastodynamics by Spectral Elements, http://geoelse.stru.polimi.it). GeoELSE is a Spectral Elements code for the study of wave propagation phenomena in 2D or 3D complex domain, developed by CRS4 (Center for Advanced Research and Studies in Sardinia) and the Politecnico di Milano, DIS (Department of Structural Engineering). Some of the main features of the code are:

- naturally oriented to large scale applications (millions of grid points);
- dealing with externally created 3D unstructured meshes;
- native parallel implementation;
- implementing of complex constitutive behaviour like visco-plasticity or non linear elasticity.

The spectral discretization of the spatial domain is performed as follows (Figure 14):

1– The domain is split into quadrilaterals in 2D (or hexahedrals in 3D)

2– Each subdomain is mapped onto a reference element

3– Legendre Gauss Lobatto (LGL) nodes are introduced

4– Spectral grid-points are mapped back onto the domain

Comparisons performed by Smerzini et al. (2011) include:

- a 3D model, including a kinematic model of the extended seismic source, a layered crustal structure, and a simplified homogeneous velocity profile;
- a 2D model of a longitudinal and transversal cross-section of a basin, subject to vertical and oblique incidence of plane waves with time dependence at bedrock obtained by 3D simulations.

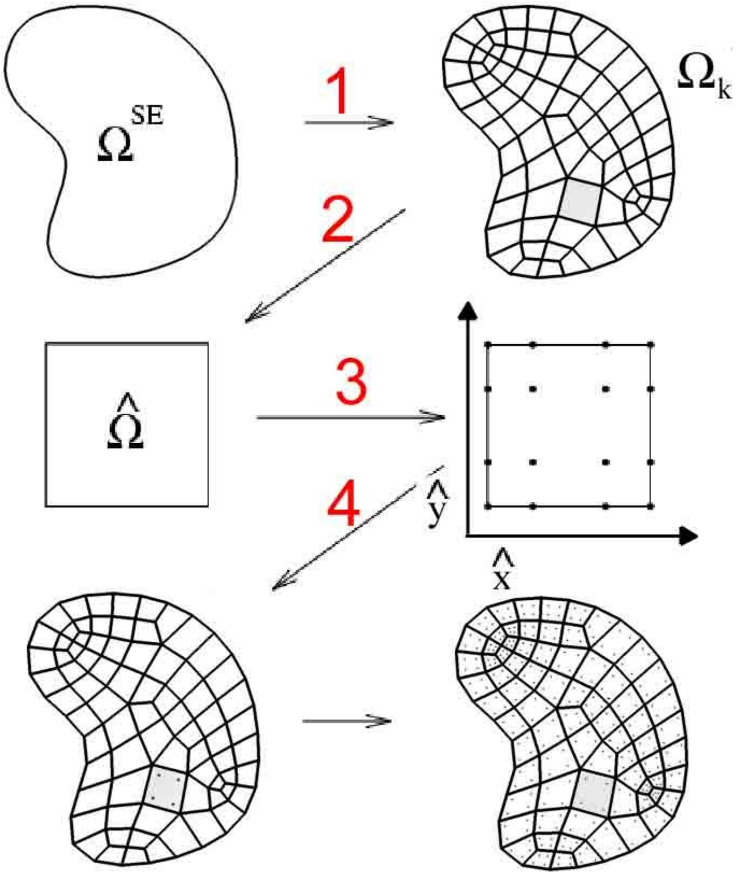


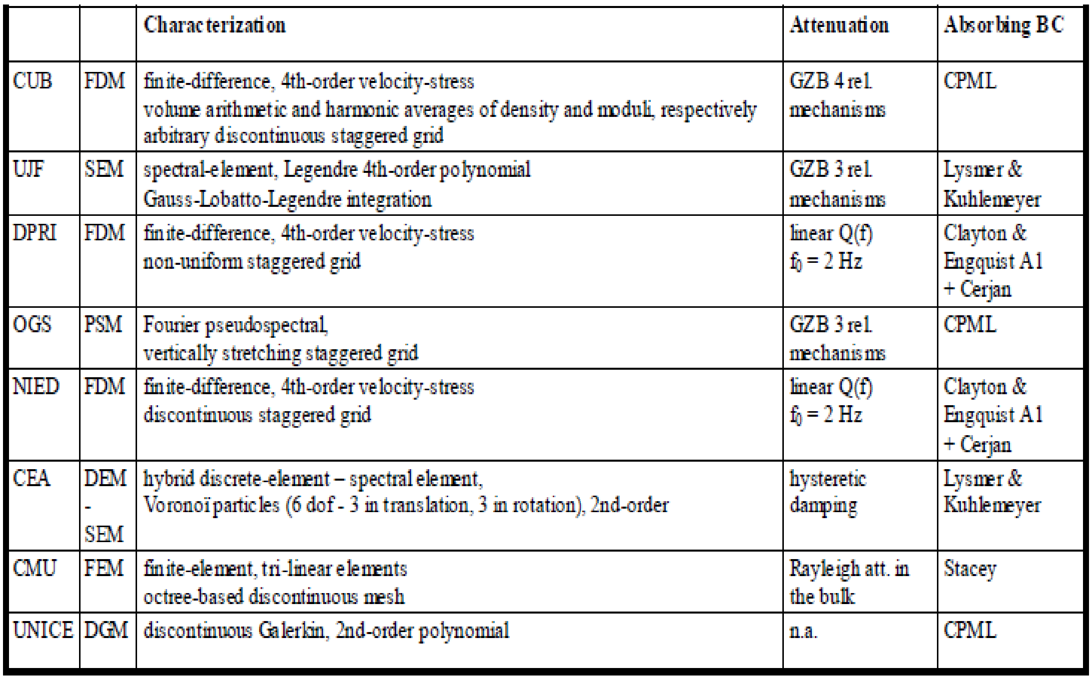
Figure 14: The spectral discretization of the spatial domain applied in GeoELSE code (Faccioli et al., 2007).

As reported by Smerzini et al. (2011), 3D numerical simulations were successful to predict the observed large amplification of ground motion at periods beyond about 1 s, due to the predominant onset of surface waves originated at the southern edge of the 3D basin and propagating northwards. More specifically, the difference between 3D and 2D modelling results was remarkable, since the latter ones failed to approach such large amplification levels, even when an oblique incidence of plane waves was considered.

2.2.5 3D linear modelling

Bard et al. (2011) and Chaljub et al. (2011) present the results of the "EuroseisTest Verification and Validation Project" (E2VP), employing a wide range of different numerical methods – finite-difference, finite-element, global pseudospectral, spectral-element, discrete-element and discontinuous Galerkin (see Table 2), in an unprecedented effort in assessing the reliability of 3D numerical simulation to model earthquake ground motion in realistic configurations. In the framework of this project, Chaljub et al. (2011) conclude that the results achieved show that a proper method and implementation of a continuous and discontinuous material heterogeneity, large Poisson's ratios, attenuation, non-reflecting boundary and free-surface condition are the key elements of a reasonable numerical simulation. The project confirms that still some important methodological questions remain to be addressed and answered before the 3D methods are confronted with data, and highlights the necessity of a continuing methodology development of the traditional and new methods in their application to the complex 3D realistic models.

Table 2: Applied 3D methods used by the participants of the E2VP. All are 2nd order in time. GZB stands for Generalized Zener Body (from Chaljub et al., 2011).



		Characterization	Attenuation	Absorbing BC
CUB	FDM	finite-difference, 4th-order velocity-stress volume arithmetic and harmonic averages of density and moduli, respectively arbitrary discontinuous staggered grid	GZB 4 rel. mechanisms	CPML
UJF	SEM	spectral-element, Legendre 4th-order polynomial Gauss-Lobatto-Legendre integration	GZB 3 rel. mechanisms	Lysmer & Kuhlemeyer
DPRI	FDM	finite-difference, 4th-order velocity-stress non-uniform staggered grid	linear Q(f) $f_0 = 2$ Hz	Clayton & Engquist A1 + Cerjan
OGS	PSM	Fourier pseudospectral, vertically stretching staggered grid	GZB 3 rel. mechanisms	CPML
NIED	FDM	finite-difference, 4th-order velocity-stress discontinuous staggered grid	linear Q(f) $f_0 = 2$ Hz	Clayton & Engquist A1 + Cerjan
CEA	DEM - SEM	hybrid discrete-element – spectral element, Voronoï particles (6 dof - 3 in translation, 3 in rotation), 2nd-order	hysteretic damping	Lysmer & Kuhlemeyer
CMU	FEM	finite-element, tri-linear elements octree-based discontinuous mesh	Rayleigh att. in the bulk	Stacey
UNICE	DGM	discontinuous Galerkin, 2nd-order polynomial	n.a.	CPML

In the framework of the E2VP project, results show a good match up to 4 Hz obtained between various simulation techniques, indicating a very encouraging level of maturity.

Final conclusions from Bard et al. (2011) state that neither 3D, linear nor (2D) non linear numerical simulations are yet "press-button" procedures. Too fast applications may yield very wrong results (and large un-trust from end-users); there is still a need for improvements. However, very similar results are possible even with completely different numerical schemes (3D, linear). Recommendations proposed by Bard et al. (2011) are to never use only one method, prefer at least two, use quantitative assessments of the mismatch between predictions, use only well-validated techniques and codes, by well trained users, with careful model implementation, external review and cross-check with data.

2.3 Empirical and semi-empirical methods

2.3.1 Ground motion prediction equations

Many ground motion prediction equations (GMPEs) have been derived on the basis of available strong motion recordings. They all relate a given ground motion parameter (pga, pgv, Sa, duration, Arias intensity, etc.) to the magnitude and distance of the seismic event, and they also very often take into account a site parameter. A report by Douglas (2011) summarizes all empirical ground-motion prediction equations (GMPEs), to estimate earthquake peak ground acceleration (PGA) and elastic response spectral ordinates, published between 1964 and 2010 (inclusive). This report summarizes, in total, the characteristics of 289 empirical GMPEs for the prediction of PGA and 188 empirical models for the prediction of elastic response spectral ordinates. In addition, many dozens of simulation-based models to estimate PGA and elastic response spectral ordinates are listed, but no details are given.

Very often the site parameter is simply a binary descriptor, such as "rock" and "non-rock". In some newer GMPEs, the site geology is characterized in a more refined manner, for instance with distinction between thin and thick deposits, or with S-wave velocity values (Vs_{30}): the reason is that detailed information on strong motion recording sites is generally missing. Significant efforts are presently made throughout the world, however, to fill this gap: the most striking example is the K-NET network installed in Japan after the Kobe event, for which a 20 m deep borehole has been drilled at each of the 1000 sites, and the S and P wave velocity profile has been obtained.

It is thus possible to modify the ground motion parameters according to the site geology. However, as these modifications are based on a very crude classification of soils, and on statistical studies which, in essence, smooth out the extreme values, such an approach may lead to a dangerous underestimation of amplifications at sensitive sites. Conversely, there is a significant probability of overestimating the motion at common sites.

2.3.2 Empirical Green's functions technique (EGF)

The empirical Green's functions (EGF) technique is known essentially in the seismological community, as a tool for studying the source process of past large earthquakes using records from both mainshock and aftershocks (e.g. Mueller, 1985 ; Courboulex et al., 1998). It is far less known in the engineering community, where its potential to predict the expected strong ground motion during future large events has not yet been sufficiently exploited. A key feature of the EGF technique is its capability to synthesise physically realistic, site specific acceleration time histories. This is of particular interest for the seismic analysis of critical facilities.

Since critical facilities should withstand strong earthquakes with long return periods, typically of the order of 10 000 years or more, it is common that no recording of such an event is available for the facility's site. This lack of appropriate time histories can elegantly be overcome with the aid of the EGF technique. Its basic idea is to interpret recordings of small seismic events at the site of interest as reasonable approximations of Green's functions and to convolute them suitably, using earthquake scaling laws, in order to simulate time histories that correspond to larger earthquakes. The EGF technique was first put forward by Hartzell (1978) and has since been further developed by numerous scientists. Its main interest is that the true propagation and site effects are automatically accounted for; its main disadvantage is that it cannot, on its own, account for non-linear soil behaviour. If non-linear soil behaviour cannot be neglected, the EGF technique should be combined with geotechnical methods, as outlined by Heuze et al. (1995).

There are, roughly speaking, two different "families" of EGF techniques. In both cases, the EGF is taken at several times and added up so that a larger earthquake, referred to as the "target" event, of the same focal mechanism is synthesized (see Figure 15). The difference lies in the way how the summing up of the EGF is performed: with or without kinematic modelling of the target event's rupture process. Irikura (1983, 1986), Hutchings (1994) and Irikura and Kamae (1994) are all representatives of the family of kinematic modelling techniques. The other family uses essentially statistical tools that allow to sum up the EGFs in a way that the relevant earthquake scaling laws will be respected. An overview on this family is given by Tumarkin and Archuleta (1994).

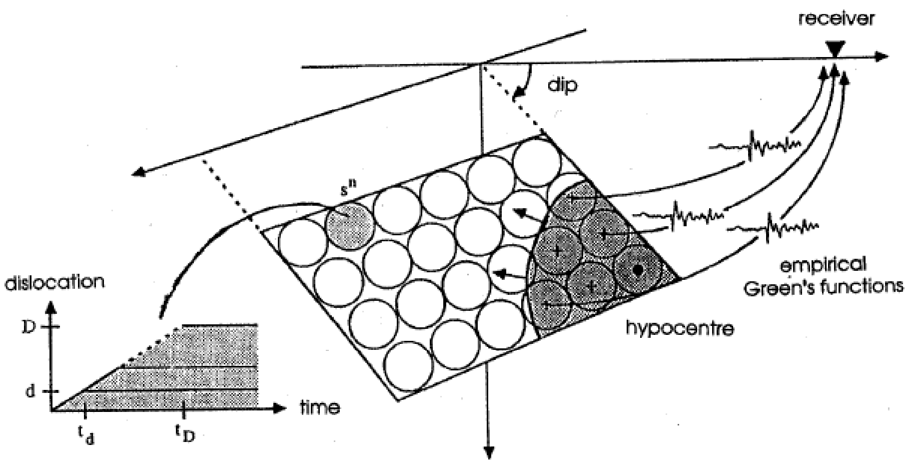


Figure 15: Schematic representation of the different sources of time delays in the summation of the EGF : path length, finite rupture velocity and dislocation rise time (after Bour, 1993).

Kohrs-Sansorny et al. (2005) present a two-stage method to simulate the ground motions produced by an earthquake, using stochastic summation of small earthquakes. In this method, identical small earthquakes are multiplied by a scaling factor and summed together with time delays randomly distributed, during the two stages, over the source duration, as shown on Figure 16. The summation scheme is characterized by four fundamental parameters: the number of summed small earthquakes, the scaling factor, and both probability densities of time delays used in the first and second stages. By a proper choice of these parameters, this method generates a large number of synthetic time histories that, on average, agree exactly with the ω^{-2} model in the whole frequency band. The produced time histories are sufficiently realistic and different from each other to be associated with a multitude of rupture processes that could happen during an earthquake. However, because the extended target fault is approximated by a point source, this method does not take into account possible directivity effects and is not appropriate to simulate ground motions for near-source sites.

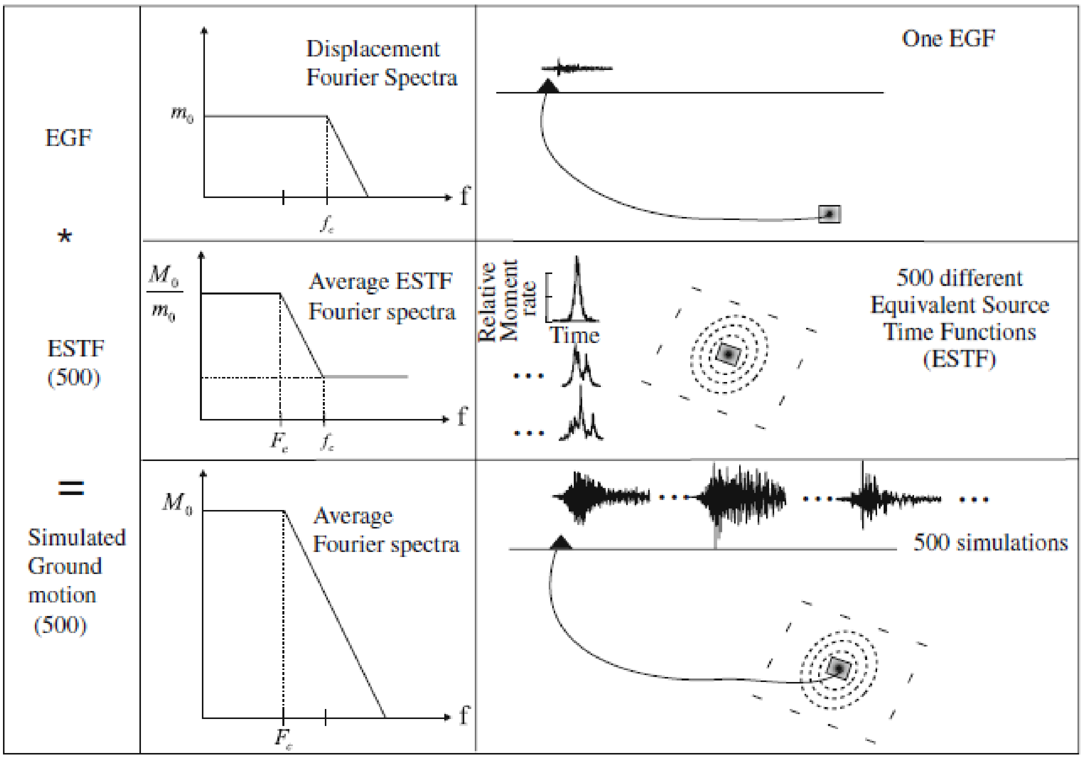


Figure 16: Schematic view of the EGF summation method. The EGF is the waveform recorded during a small event. The source is modelled by an ω^{-2} Brune spectra. 500 different ESTFs are constructed that account for different rupture processes, for a larger event. Each ESTF is convolved by the EGF to give the 500 simulated accelerograms (Salichon et al., 2010).

Salichon et al. (2010) used the above described stochastic empirical Green's functions (EGFs) summation method to produce a population of realistic accelerograms on rock and soil sites in the city of Nice (Southern France). The ground motion simulations are calibrated on a rock site with a set of ground motion prediction equations (GMPEs) in order to estimate a reasonable stress-drop ratio between the EGF and the target earthquake. Their results show that the combination of the GMPEs and EGF techniques is an interesting tool for site-specific strong ground motion estimation.

The EGF method is based on the assumption of soil response linearity. Therefore, the acceleration values found in the aforementioned study at sediment sites should be considered as upper bound estimations of expected ground motion related to the target earthquake. The method developed by Salichon et al. (2010) complements well the empirical ground motion prediction equations by accounting for the regional and 3D local site effects in the high frequency domain at any instrumented site and by providing statistically realistic waveform data sets. Finally, some improvement should be addressed by considering the nonlinearity of the soil response in the method by accounting for the site dynamic properties.

2.3.3 Hybrid 3D spectral elements and empirical Green's functions (EGF) technique

Causse et al. (2009) present a new approach for performing broad-band ground motion time histories (0.1–30 Hz) of a future earthquake in a sedimentary basin. Synthetics are computed with an hybrid scheme combining reciprocity-based 3D-spectral element method simulations at low frequencies and empirical Green's functions (EGF) at high frequencies. The combination between both deterministic and empirical parts results in a set of hybrid Green's functions, summed according to a new k^{-2} kinematic model algorithm. The summation technique enables to remove the high-frequency artefacts that appear above the EGF corner frequency. The ground motion variability is assessed by generating a variety of source parameter sets selected from a priori probability density functions. This leads to a population of response spectra, from which the median spectral acceleration and standard deviation values are derived.

In particular, Causse et al. (2009) point out the fact that for deep sediment sites, the simulated response spectra significantly differ from one station to the other. At some sites simulations present large response spectra both at high-frequency (>1 Hz) and low-frequency (≈ 0.3 Hz) exceeding EC8 spectra. This points out the interest of coupling EGFs and 3D numerical simulations in such deep valleys.

2.4 Synthesis and comparison

Table 3 presents a synthesis and comparison of the main available approaches to evaluate site effects. Some information is also given about the main advantages and drawbacks of the considered methods.

Table 3: Synthesis and comparison of the main approaches available to evaluate site effects.

Name	**Type**	**Advantages**	**Drawbacks**	**Status (Research / Engineering practice)**
H/V noise spectral ratio	Experimental	Easy experimental work, even in low seismicity areas.	Only valid for determination of site f_0. To be combined with other technique for amplification determination.	Standard engineering practice.
Standard spectral ratio (SSR)	Experimental	Direct evaluation of site effect for weak and moderate events.	Need for earthquake recordings. Time consuming in low and moderate seismicity areas. Non linear behaviour for strong motion not accounted for.	Standard practice when available instruments and data. Rather used for comparison when possible.
Generalised Inversion Technique (GIT)	Experimental	No need for a nearby reference site.	Need of recordings on a whole array. Quite heavy analysis efforts necessary.	Rather institutional practice.
Vertical Array data analysis	Experimental	Reliable determination of site effects.	Need for borehole instruments.	Easily applicable when available instruments and data
H/V spectral ratio of weak motion	Experimental	Easy, does not need any reference station.	Need for earthquake recordings. Time consuming in law and moderate seismicity areas. Non linear behaviour for strong motion not accounted for.	Only very little used, in research activities.
Coda wave site effect estimation	Experimental	Of scientific interest.	Heavy analysis efforts needed, not yet ready for practical purposes.	Research work only.
1D response of soil column	1D – Numerical – equivalent-linear	Available computer codes (SHAKE, CyberQuake, etc.). Input data reasonably easily available.	1D, no full non-linear behaviour computation.	Standard engineering practice.
Random vibration theory (RVT)	1D – Numerical – equivalent-linear	No need for earthquake input motion. Site-specific parametric aleatory variability. Available computer code (Strata)	1D, no full non-linear behaviour computation. Limitations in the low frequency domain.	Can be applied in the framework of engineering practice; particularly popular in the US.
1D non-linear response of soil column	1D – Numerical – Non-linear	Available computer codes (CyberQuake, DYNAFLOW, SUMDES, etc.).	Difficult and expensive acquisition of input parameters.	Standard engineering practice.
2D non-linear computations	2D – Numerical – Non-linear	Account for both 2D site configuration and non-linear soil behaviour.	Difficult and expensive acquisition of input parameters.	1D studies can be easily done, but 2D and 3D analyses present a challenge and there is still some work to be done.
Equivalent-linear Aki-Larner approach	2D – Numerical – Equivalent-linear	Combination of 2D and equivalent-linear approach.	Implemented only for plane layering.	Can be applied in the framework of engineering practice.
Combined mode summation	2D – Numerical – Anelastic layers	No need for earthquake input motion.	Flat homogeneous anelastic layers. Requires knowledge or estimates of parameters for the definition of the source-receiver path and source rupture process.	Difficult for engineering practice where input motion is defined by a uniform hazard spectrum rather than specific source scenarios.
Finite-difference and finite-element modelling	1D, 2D, 3D – Numerical – Viscoelastic	Account for site geometry (1D, 2D or 3D). Accurate strong motion prediction.	Complex input grids. Need for a high skills in numerical simulation.	Too heavy to become standard engineering practice.
Spectral elements modelling (2D and 3D)	2D, 3D – Numerical - Visco-plasticity or non linear elasticity	Account for 2D or 3D effects in visco-plasticity or non linear elasticity domains. Available code (GeoELSE).	Heavy parallel computing for the 3D code. 2D modelling fails to predict amplification levels in a 3D basin.	Heavy 3D parallel computing.
3D domain reduction method	3D – Numerical – Elastic, anelastic and inelastic	Account for 3D basin geometry.	Heavy programming and computing (duration and memory size).	Too heavy to become standard engineering practice.
3D linear modelling	3D – Numerical - Linear	Account for 3D basin geometry.	Difficult and expensive acquisition of input parameters. Code validation still needed. Linear computation.	Still need for research and validation. Use only well-validated techniques and codes, by well trained users, with careful model implementation.
Ground motion prediction equations	Empirical and semi-empirical	Many available GMPEs. Easy and fast use.	Very rough site characterization. For rock sites, rock characteristics (Vs and kappa) often not sufficiently well known.	Standard engineering practice.
Empirical Green's functions technique (EGF)	Empirical and semi-empirical - Linear	Site effect included in weak motion recordings.	Need for earthquake recordings. Non linear behaviour for strong motion not accounted for.	Remains in the research domain, but could be used in practice without major difficulties.
Hybrid 3D spectral elements and EGF technique	Hybrid empirical and numerical	Site effect included in weak motion recordings. Wide frequency band.	Need for earthquake recordings. Non linear behaviour for strong motion not accounted for.	Mainly research work.

3. Account for site effects in regulations

3.1 Account for site effects in present building codes

3.1.1 Uniform Building Code - UBC 1997 (USA)

The Uniform Building Code of 1997 (UBC, 1997) was the first code that used a soil classification based on the average shear wave velocity in the uppermost 100 feet as the key parameter. This concept was based on the publication of Borcherdt and Glassmoyer (1994). Today, this average shear wave velocity is commonly denoted by Vs_{30}, 30 standing for the top 30 m.

The UBC 1997 classifies all sites into six different Soil Profile Types S_A through S_F. The essential parameter for the first five types is Vs_{30}. For soils of unknown shear wave velocities, the classification can be made with the aid of standard penetration resistance or undrained soil shear strength. Different response spectra are determined depending on the Seismic Zone and the Soil Profile Type. The latter is taken into account with the aid of two Seismic Coefficients, C_a and C_v, for the short (constant acceleration) and long (constant velocity) period range, respectively. In addition, the response spectra are multiplied by short and long period Near-Fault Factors for sites close to a seismic fault.

At long periods, the spectral acceleration decreases for all Soil Profile Types with 1/T, T being the period. This means that the spectral displacement increases with T without any limit, which is physically not satisfactory.

The Soil Profile Type S_F groups all soils requiring a site-specific evaluation of the design ground motion. This type includes liquefiable soils, quick and highly sensitive clays, collapsible weakly cemented soils, peats, highly organic clays, high plasticity clays and soft/medium stiff clays.

3.1.2 International Building Code - IBC 2003 (USA)

The International Building Code 2003 (IBC, 2003) replaced the UBC 1997. The classification of the soils, however, is the same, with different notation. The response spectra are determined by means of mapped spectral acceleration values for short and medium periods and two Site Coefficients which depend on the Site Class. The acceleration spectra still decrease with 1/T.

The present version of the IBC (IBC, 2012) refers to the ASME 7 (2010), for the definition of the seismic design motion.

3.1.3 Eurocode 8 (Europe)

Eurocode 8 (Eurocode 8, 2005) classifies seven "Ground Types", A trough E as well as S_1 and S_2., For the Ground Types A to E, the main parameter for the classification is Vs_{30}. If the shear wave velocity is unknown, the values of the standard penetration resistance or the undrained soil shear strength can be used for the ground type classification. Different spectra, depending on the Ground Type, account for the influence of local ground conditions on seismic action. The response spectra are determined by means of the reference peak ground acceleration on rock soil and the Soil Factor, which depends on the Ground Type. The specific periods of the spectra also depend on the Ground Type.

The Ground Types S_1 and S_2 group deposits of at least 10 m thick soft clays or silts with high plasticity and deposits of liquefiable soils and sensitive clays. These sites require special studies for the definition of the design seismic actions.

Most European countries adopted or will adopt Eurocode 8 for the seismic design of structures.

3.1.4 DIN 4149 (Germany)

The building code DIN 4149 (DIN 4149, 2005) has a soil classification scheme that is based on both the deep geological structure and the superficial soil conditions. Three geological "subsoil classes", R, T and S, are mapped in the code, and three "groundsoil classes", A, B and C, are defined, mainly based on a geological description of the soil down to a depth of about 20 m. There are six combinations that are geologically meaningful, and for each such combination, a response spectrum is defined whose shape mathematically corresponds to an Eurocode 8 spectrum.

For loose sands or silts, soft clays, sea bed deposits etc., with "dominant" S wave velocities < 150 m/s in the uppermost 20 m, special studies for the definition of the seismic actions are required.

3.1.5 NZS 1170.5:2004 (New Zealand)

The Structural Design Code NZS 1170.5:2004 (2004) classifies five Site Subsoil Classes A trough E, which are used to account for the influence of local ground conditions on design seismic action.

The classes A and B, "strong rock" and "rock", respectively, are distinguished based on Vs_{30}. Class C, "shallow soil sites", and class D, "deep or soft soil sites", are distinguished with the aid of the low-amplitude natural period (C: ≤ 0.6 s; D: > 0.6 s) the soil depth or undrained shear strength or SPT-values. Finally, class E, "very soft soil sites", are defined by more than 10 m of soil with Vs < 150 m/s or with low undrained shear strength or low PST-values (< 6). Therefore, the Structural Design Code NZS 1170.5:2004 does not classify the soils solely based on V_{S30}.

The response spectra are determined by means of mapped value of the "hazard factor" and the "spectral shape factor" depending on the subsoil class. In addition the response spectra are multiplied by a "near-fault factor" for sites within 20 km of a seismic fault.

3.2 Research for improved soil classifications

According to Borcherdt and Glassmoyer (1994), Vs_{30} turned out to be a good proxy for the physical conditions governing site amplification in California, where weak base rock conditions dominate. However, Vs_{30} was not meant to be a sufficient physical parameter to capture site effects. Nevertheless, the Californian correlations of Borcherdt and Glassmoyer (1994) were taken up by the UBC 1997 (UBC, 1997) for soil classification without any geographical or geological restriction. This can be explained, at least partly, by the fact that there was no better alternative to this classification scheme. It has to be remembered that at that time, most codes in the world, including PS 92 (PS 92, 1995) or the first drafts of Eurocode 8, still had plateaus of spectral accelerations for soft soils that were not higher, sometimes even lower, than those for rock sites. Therefore, the new spectra of UBC 1997 represented a clear progress even for areas where the Vs_{30} concept was problematic.

As can sometimes be observed in engineering practice, approximations start being applied outside their domain of validity, and once established, it may become extremely difficult to get rid of them. This is exactly what happened with the Vs_{30} concept. Today, two opposite trends can be observed. On the one hand, further developments towards either an improvement or a simplification of the Vs_{30} concept for soil classification (see point 3.2.1), and on the other hand, developments to replace the Vs_{30} concept by similarly simple, but physically more satisfactory concepts (see points 3.2.2 to 3.2.4).

3.2.1 Further developments based on Vs_{30}

As pointed out by Crouse (2011), a great amount of research has been conducted during the last 40 years on the effects of local geology on earthquake ground motion. During this period, analytical methods for computing site response have evolved from simple one-dimensional (1D) linear or equivalent-linear models to 2D and 3D nonlinear models. The empirical ground-motion database, consisting of motions recorded at a variety of soil and rock sites, has also grown tremendously. Studies of these data, supplemented with results from numerical modelling, have led to improvements in the way the effects of local geology are included in the seismic provisions of the International Building Code (IBC), which contains site-coefficient tables (Fa and Fv) to account for local geological effects at short and long natural periods. However, Crouse (2011) points out the fact that the validity of the Fv table for long periods, greater than about 2 sec, is questionable because these longer period motions are influenced by the regional geology. One solution proposed by Crouse (2011) is to eliminate the IBC site-coefficient tables altogether and incorporate the effects of the local and regional geologies directly into a new generation of region-specific ground-motion equations for predicting response spectra to 10 s period. These equations, developed from simulations and available strong motion data, would be inputs to probabilistic and deterministic seismic hazard analysis (PSHA and DSHA) methods presently used to develop the ground motion maps in the IBC. Alternatively, Crouse (2011) suggests that simulations, directly modelling the 3D regional geology, could be used exclusively to develop the maps for periods greater than 2 s. The feasibility of either approach has been tested by Crouse (2011) in a pilot study for the Los Angeles region, where the 3D geology is well known and where a reasonable amount of ground motion data has been recorded.

Pitilakis et al. (2012) present a study where the validity and accuracy of the elastic response spectra, defined in Eurocode 8 provisions, is checked against a large worldwide dataset of strong motion records, in terms of both PGA-normalized spectra and soil factors.

Concerning the shape of normalized elastic response spectra, Pitilakis et al. (2012) found that for soil classes A, B and C the spectral shapes provided by EC8 are in good agreement with the derived empirical data for both seismicity types (1 and 2) prescribed in EC8. For soil classes D and E, the sample of data is not as rich as for the other soil classes and hence the results may not be as convincing as for soil classes A, B and C. However, Pitilakis et al. (2012) found a clear tendency in soil class D spectral shapes to differ substantially from the EC8 shapes. Equally important differences are found in soil class E where the EC8 spectra seem to be conservative enough for medium and high periods, but probably in short period the plateau should be somehow increased. In conclusion, considering all the above analyses, observations and comments, Pitilakis et al. (2012) believe that, on average, the EC8 spectral shapes are in good agreement with the empirical data and the proposition of improved shapes is not really justified for the moment.

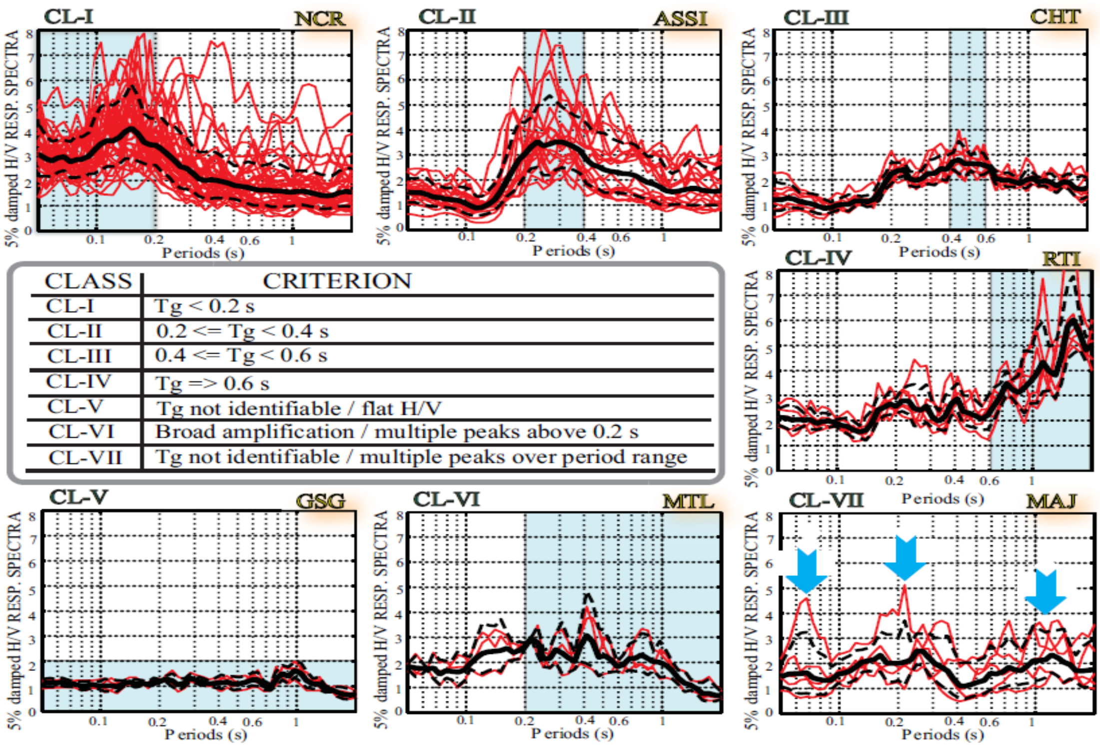
Concerning the amplification factors, Pitiliakis et al. (2012) found that EC8 factors for class B are in good comparison to the empirical data for both seismicity types, while for soil class C, the S factors are higher compared to EC8. For soil class D the estimated soil factors, which were derived from a limited dataset, are also higher than the EC8 factors for Type 2 seismicity but relatively close to the EC8 factors for Type 1 seismicity. For soil class E, the weighted average soil factors are found quite low for Type 1 seismicity, a result, which is attributed to both the limited data and the averaging process. Based on the results derived from this comprehensive study, Pitiliakis et al. (2012) propose improved soil factors S, for potential use in an EC8 update, supposing that no further changes are made in the definition of soil classes and seismicity types and the shape of normalized design spectra.

In the past few years, a series of articles have been published concerning the use of topographic slope from digital elevation models (DEMs) constructed through remote sensing (satellite imaging) to give first-order estimates of NEHRP site classes based on the average shear wave velocity in the top 30 m, Vs_{30} (Wald and Allen, 2007). Lemoine et al. (2012) evaluate the potential applicability of these methods taking advantage of a large new database of measured and estimated Vs_{30} values and their topographic slopes for locations in Europe and the Middle East. Novel statistical tests are performed to evaluate the predictive power of the procedure in this region. Lemoine et al. (2012) evaluate the percentage of sites correctly-classified / misclassified for each site class for active and stable regimes. Their results show that the method does a better job than blind chance for all site classes in active regions but only for class B (rock) and, to a lesser extent, class C (stiff soil) sites located in stable areas. Based on their findings, Lemoine et al. (2012) recommend that site classifications based on the Vs_{30}-slope correlations proposed by Wald and Allen (2007) are only used for regional or national (and not local or site-specific) first-order studies in active parts of Europe, and only in the absence of other more detailed information (e.g. microzonation studies), excluding small basins, special geological conditions that may affect results. The test case of the city of Thessaloniki, conducted by Lemoine et al. (2012), confirms that site classifications based on Vs_{30} slope correlations are not sufficiently accurate to replace actual field measurements and they should not be used for site-specific studies.

3.2.2 Predominant-Period site classification

Di Alessandro et al. (2012) propose a site classification scheme based on the predominant period of the site, as determined from the average horizontal-to-vertical (H/V) spectral ratios of ground motion (Figure 14). This classification is investigated by using 5%-damped response spectra from Italian earthquake records. Di Alessandro et al. (2012) computed H/V ratios for a selected dataset and used these to classify each site into one of six classes. They then investigate the impact of this classification scheme on empirical ground motion prediction equations by comparing its performance with that of the conventional rock/soil classification. Although the adopted approach only results in a small reduction of overall standard deviation, the use of H/V spectral ratios in site classification does capture the signature of sites with flat frequency response, as well as deep and shallow soil profiles, characterized by long- and short-period resonance, respectively; in addition, the classification scheme is relatively quick and inexpensive, which is an advantage over schemes based on measurements of shear wave velocity.

On the contrary, the disadvantage of this method is the need for instrumentation and earthquake recordings, which is difficult in low to moderate seismicity areas, as well as from a financial point of view.



CLASS	CRITERION
CL-I	Tg < 0.2 s
CL-II	0.2 <= Tg < 0.4 s
CL-III	0.4 <= Tg < 0.6 s
CL-IV	Tg => 0.6 s
CL-V	Tg not identifiable / flat H/V
CL-VI	Broad amplification / multiple peaks above 0.2 s
CL-VII	Tg not identifiable / multiple peaks over period range

Figure 14: *Proposed classification criterion based on the predominant period identified from the average H/V spectral ratio (thick solid line) of the 5%-damped response spectra recorded at each site (thin curves). The light shaded area indicates the interval of validity in which each class is defined. Tg is the site natural period (in seconds) as inferred from the H/V spectral ratios. (Di Alessandro et al., 2012).*

3.2.3 f_0 and Vsz classification

As stressed by Cadet et al. (2012-b), in an economically constrained context, the estimation of site effects is made through physical parameters used as proxies. The time-average shallow velocity parameter Vs_{30} is commonly accepted as a convenient such proxy in many European and American regulation codes. However, as this single parameter does not satisfactorily capture the physics of site amplification (especially for deep, stiff sites and thin, soft sites), the engineering seismology community has long faced the challenge to find alternative cost-effective, simple and physically relevant proxies. Cadet et al. (2012-b) propose one such possible alternative, consisting in a two-parameter characterization: the time-averaged shear wave velocity Vs_z of the first z meters, with z being equal to 5, 10, 20 or 30 m, and the fundamental resonance frequency f_0 of the studied site. This combination carries shallow information with Vs_z, depth and frequency content information with f_0.

Cadet et al. (2012-b) present empirical correlations between amplification factors and simple site parameters derived from a large subset of the KiK-net data. They estimate the amplification factor from ratios between surface and down-hole horizontal response spectra, corrected for varying depths and impedance of the down-hole sites (Cadet et al., 2012-a). The amplification factors are then correlated with each of the individual site parameters; four other “twin-parameter” – couples (f_0, Vs_z) – are also considered and the correlation with amplification factors is performed through a normalization of the frequencies by each site fundamental frequency. The largest variance reduction is obtained with twin-parameter characterizations, out of which the couple (f_0, Vs_{30}) proves to provide the lowest misfit. The performance of single parameter correlations is relatively lower; however, the best single parameter proves to be the fundamental frequency, which provides smaller misfit than the Vs_z parameters. Cadet et al. (2012-b) also perform a comparison with the amplification factors recommended in European regulations, showing that it is possible to significantly improve both site characterization criteria and associated amplification factors, for use in building codes and microzonation studies.

Moreover, Cadet et al. (2012) point out the fact that this classification is not more expensive than the classical Vs_{30} classification, coming from the fact that the fundamental frequency is most generally provided by single point microtremor measurements and H/V processing.

3.3.4 VFZ classification

As underlined by Castellaro (2011), recently, several examples of highly detailed site response calculations have been proposed. In principle, these offer a superior accuracy. However, they require a knowledge of the relevant parameters which is hardly realised in daily practice. Acknowledging this, Castellaro (2011) looks for a simplified - yet as physically meaningful as possible - method, which has to be practically and widely applicable. The soil classification based on Vs_{30} was developed on a purely empirical basis, and has been shown to suffer from statistical and physical problems. In particular, Vs_{30} does not take into account impedance contrasts, which cause the amplification. Vs is an estimator of soil stiffness, however, SH stratigraphic amplification is ruled by impedance contrasts, Z, not simply by absolute stiffness. As pointed out by Castellaro (2011), the information on the impedance contrast is lost in all site classes but in the E site class (EC8 / Italian classification system). 30 m might be insufficient (or might be too much) to describe the amplification in the frequency range of engineering interest. Several combinations of stiffness-thickness may result in different Vs_{30} (i.e. different soil classes) but substantially in the same amplification function and vice-versa.

To investigate the relevance of the impedance contrasts, rather than the absolute velocity in the first 30 m depth, to the amplification function expected at a site, Castellaro (2011) studies a dataset of subsoils with the following properties:

- Layer 1: Vs_0 = [100, 600] m/s, thickness H = [3, 300] m,
- Layer 2: Vs > Vs_0, Vs = [200, 2000] m/s,

- Layer 3 to 30: Vs increases in an exponentially decaying way down to the bedrock, located at 2 km depth,
- The maximum impedance contrast Z is between layer 1 and layer 2,
- 45 different Vs profiles for each layer 1 thickness,
- 585 subsoil models investigated.

Castellaro (2011) runs a 1D equivalent-linear site response simulation for each of the 585 models. For each tested Vs_0, she plots the maximum amplification as a function of the frequency at which it occurs, which depends on the bedrock depth, and obtains a plot like the ones shown in Figure 15. Each line in this plot connects the points characterized by the same impedance contrast between layer 1 and layer 2. These plots therefore represent a way to get a quick estimate of the expected SH amplification factor (Fa), from (Vs_0, f_0, Z). Vs_0, f_0 and Z are the basic parameters of the classification scheme (FaSH proxy) proposed by Castellaro (2011).

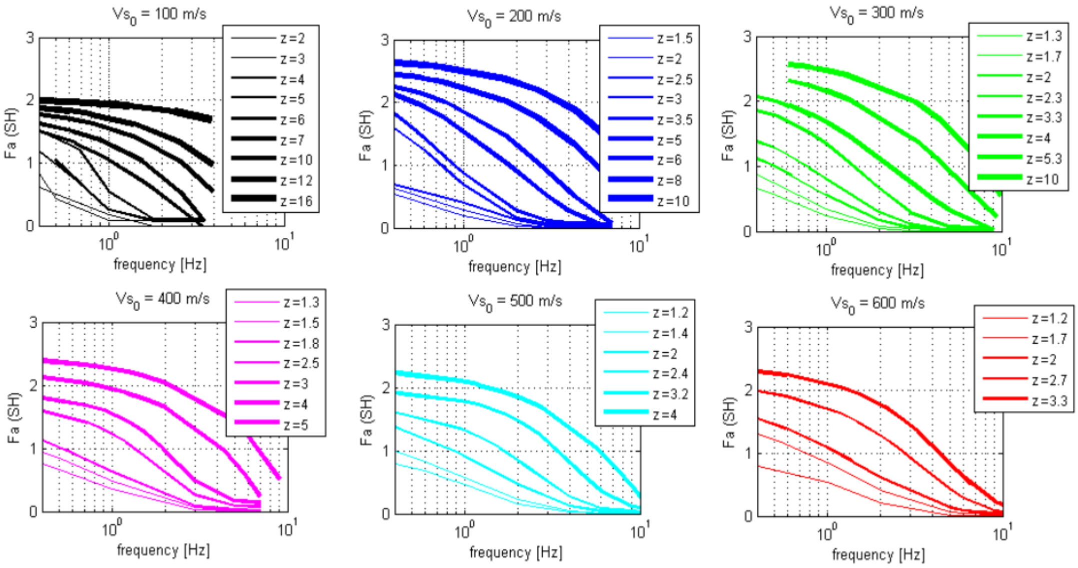


Figure 15: Plots of the maximum amplification as a function of the frequency at which it occurs, which depends on the bedrock depth. Each line in these plots connects the points characterized by the same impedance contrast between layer 1 and layer 2. These plots therefore represent a way to get a quick estimate of the expected SH amplification factor (Fa), from (Vs_0, f_0, Z).

There is no need to fix any boundary between new site classes because this procedure – if rigidly instead of statistically interpreted – adds up problems at the class boundaries (Mulargia and Castellaro, 2009). However, just to discuss the benefits of a classification based on Vs_0, f_0 and Z, Castellaro (2011) groups the 585 soil models as shown on Figure 16. As expected, $f_0 < 1$ Hz classes are related to subsoils with strong impedance contrasts at larger depths. However, several different models give the same amplification factors and a description of the different classes in terms of subsoil profile is not straightforward. This confirms the advantages of an alternative classification method that does not take into account only Vs depth but the VFZ matrix.

The final goal of site effect assessment is to predict the behaviour of an oscillator (the structure) founded on another oscillator (the subsoil). Castellaro (2011) therefore proposes to shift the reasoning from a depth dependent approach (Vs_{30}) to a frequency dependent approach (f_0). By observing that the main cause for stratigraphic seismic amplification is the existence of impedance contrasts in the subsoil, Castellaro (2011) proposes a simplified seismic site classification scheme (the VFZ matrix) based on: Vs_0, f_0 and Z, which are measurable in the whole frequency range of engineering interest (0.1-20 Hz). In the VFZ matrix approach, there is no need to set threshold values to characterize what bedrock is. By numerically studying the 1D soil response on different soil models (all characterized by Vs increasing with depth), Castellaro (2011) creates the 4D function that relates the expected SH-wave amplification factor Fa to (Vs_0, f_0, Z).

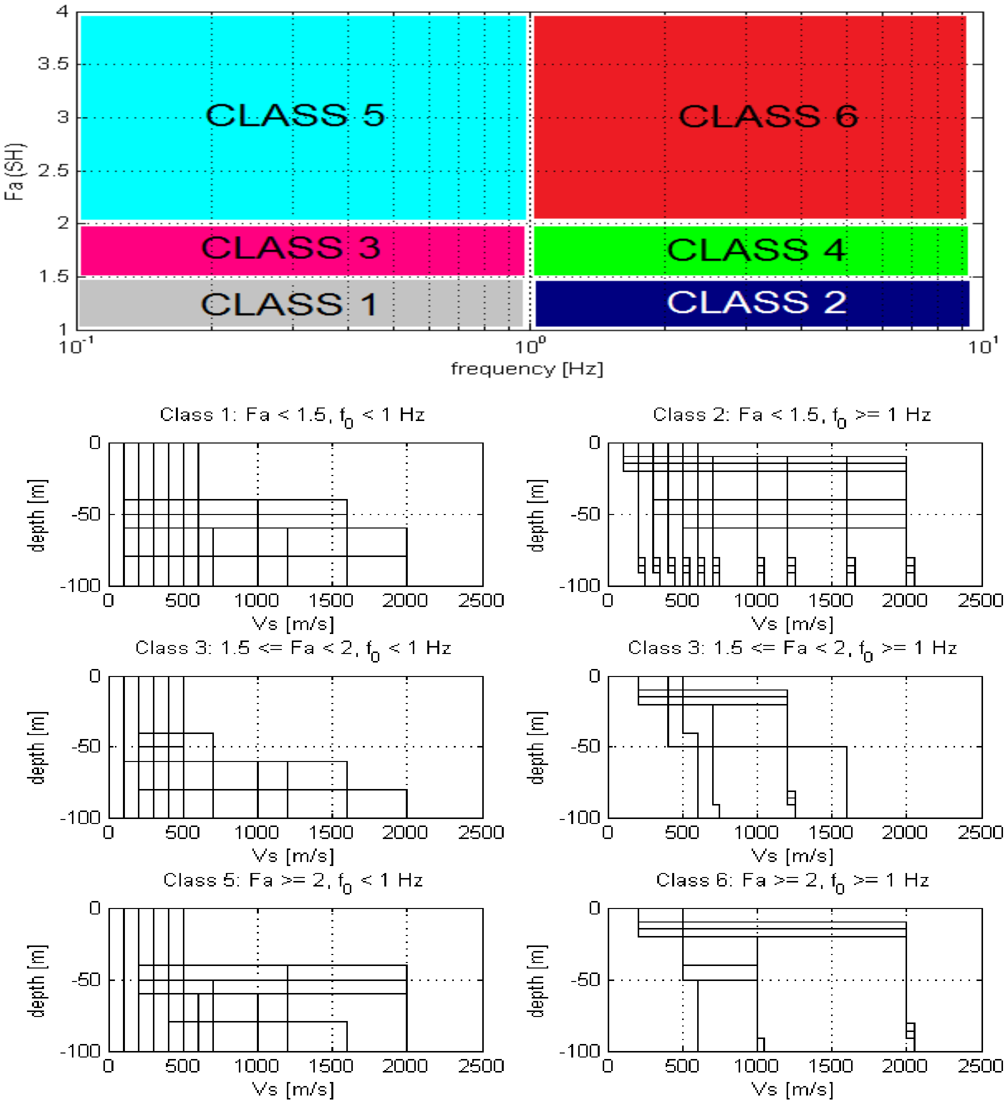


Figure 16: *Site classification based on the VFZ matrix as proposed by Castellaro (2011). Fa is the expected SH amplification factor.*

Several methods exist to estimate (Vs_0, f_0, Z). However, the microtremor H/V technique is preferred by Castellaro (2011) to assess (f_0, Z) because there are no techniques as easy as H/V to get a first order idea of the soil stiffness trends in the subsoil in the whole frequency domain of interest. Finally, Castellaro (2011) also suggests that the proposed classification scheme based on the VFZ matrix can be used also on sites where no specific resonances are measured (due to the absence of sharp impedance contrasts) and on soils presenting several resonances.

3.3 Account for site effects for nuclear facilities

3.3.1 IAEA recommendations

The International Atomic Energy Agency (IAEA) has published safety standards of different categories: safety fundamentals, safety requirements and safety guides. These safety standards are not legally binding on Member States but may be adopted by them, at their own discretion, for use in national regulations in respect of their own activities.

The former safety guide NS-G-3.3 (IAEA, 2002), entitled "Evaluation of Seismic Hazards for Nuclear Power Plants", described good practice for seismic hazard studies. No reference was given to explicit site resonse studies. This safety guide has been superseded by the specific safety guide SSG-9 (IAEA, 2010).

The safety guide NS-G-3.6 (IAEA, 2004), entitled "Geotechnical Aspects of Site Evaluation and Foundations for Nuclear Power Plants", defines three site categories:

- Type 1 sites: Vs > 1100 m/s;
- Type 2 sites: 1100 m/s > Vs > 300 m/s;
- Type 3 sites: 300 m/s > Vs;

where Vs is the best estimate shear wave velocity just below the foundation level in the natural condition. The site categorization is valid on the assumption that the shear wave velocity does not decrease significantly with depth; otherwise, particular analyses should be carried out according to the best practices.

Paragraph 3.7 states:

> "A computation of site response under free field conditions should be carried out for sites other than Type 1 sites. This computation of site response may be needed for the assessment of settlement or liquefaction as well as for soil-structure interaction analyses. The site response computation may also be required for developing specific site response spectra. ..."

Therefore, according to this paragraph, site response computations "should" be carried out for Type 2 and Type 3 sites, whereas their results only "may" be required for developing specific site response spectra.

Paragraph 3.14 is formulated more stringently, but applies only to Type 3 sites. It states:

> "In the case of a Type 3 site, site specific response spectra should be determined; they should be at least representative of the response of the profile at the surface level."

Paragraph 3.11 explicitly states that SHAKE type 1D-models and computations with vertically propagating body waves is an acceptable model.

The specific safety guide SSG-9 (IAEA, 2010), entitled "Seismic Hazards in Site Evaluation for Nuclear Installations", is less stringent than (or even in contradiction to) the safety guide NS-G-3.6. Paragraph 9.3 states:

> A number of approaches can be taken, in order to take into account the geological and geotechnical conditions at a site as part of the estimation of ground motion. The first approach is to utilize ground motion attenuation relationships appropriate for the site conditions (i.e. attenuation relationships that have been developed for subsurface conditions of the type that prevails at the site). The second approach is to conduct a site response analysis compatible with the geotechnical and dynamic characteristics of the soil and rock layers beneath the site. This also includes incorporating site response into the calculations for seismic hazard analysis (in the case of a probabilistic analysis). In both of these approaches, uncertainties should be taken into account. However, site profile related uncertainty contributions that are already inherent in the ground motion attenuation relationships used in the seismic hazard analysis should be identified and disregarded so as not to be included more than once."

Since attenuation relationships depend at best on Vs_{30} (many relationships only distinguish between rock, stiff soil and soft soil), this leaves the door open for crude ways of taking into account site effects, without any site response analyses, for nuclear installations – in contradiction to the safety guide NS-G-3.6.

3.3.2 Practice in France

RFS 2001-01

Seismic hazard assessment for nuclear facilities in France is guided by the French regulation RFS2001-01 (ASN, 2001), based on a deterministic approach. The RFS2001-01 is presented and discussed in detail in Berge-Thierry et al. (2004).

The seismic design input is represented by an acceleration response spectrum. The regulation differentiates the site situation according Vs_{30} but also the geometry. In case of 1D geometry ("plane geometry") and for site with Vs_{30} >300 m/s, this spectrum is computed with the aid of the mean motion prediction of a single empirical GMPE, given in the RFS2001-01, distinguishing only between two site classes, rock (Vs_{30} > 800 m/s) and soil (300 m/s < Vs_{30} < 800 m/s) conditions.

However, for sites exhibiting shear wave velocities lower than 300 m/s, or for sites associated with particular geometries (sedimentary basins that could lead to so-called 2D amplification affects, or steep hills that could lead to so-called topographical amplifications), "specific studies are necessary". For this case, introduced as the concept of "*particular* site effect", the RFS2001-01 stipulates:

> "In these situations, the use of the response spectrum calculated according to the relationship 2 [the above mentioned GMPE] can be usefully completed by

> other indicators of the seismic movement that are specific at the site considered."
>
> Original text in French: "Dans ces situations, l'utilisation du spectre de réponse calculé avec la loi 2 peut être complété utilement par d'autres indicateurs du mouvement sismique spécifique au site considéré."

In practice, this extremely vague formulation seems to be interpreted more stringently, since specific site response analysis can be asked for, although the term "site response analysis", or similar, does nowhere appear in the RFS2001-01.

"Cashima" approach

In 2003, the French nuclear regulation authority (ASN) asked the CEA to develop a methodology to account for site effects for the Cadarache site. The "Cashima" program was launched to work in this framework (among other subjects).

The CEA proposed in 2008 a methodology to identify, on the one hand, the sites for which the "standard" response spectra of RFS 2001-01 could be used without modification and, on the other hand, the sites where site-specific spectra have to be considered. This methodology proposed the computation of a so-called "aggravation" factor, which is the ratio between the transfer function of all site effects (empirically estimated or computed with 2D or 3D models depending on the geometry of the site) and the 1D soil response (computed using the geotechnical property profile beneath the studied location). If this ratio – a function of frequency – is not significantly higher than 1, then the standard response spectra can be used.

The ASN proposed to CEA in 2011 to use the aggravation factor as an increase factor of response spectra and specified that this aggravation factor should be computed using response spectra, taking into account the uncertainties.

3.3.3 Practice in Germany

The German nuclear safety rule KTA 2201.1 (2010), "Design of nuclear power plants against seismic actions: principles", describes how a design earthquake has to be defined. The only article that refers to local site effects, article 3.5 (3), states (translated): "... The corresponding soil profile of the geological underground and of the construction ground has to be taken into account with the dynamical soil parameters and their variation." Nothing is said about how this has to be done. In particular, KTA rule 2020.1 does not mention at all specific site amplification studies. Nevertheless, the KTA rules state in their introductions that state of the art methods should be applied.

Leydecker et al. (2005) of the Federal Institute for Geosciences and Natural Resources presented a study in which the seismic design action was determined for 13 temporary waste disposals on German NPP sites. This study was carried out for the German safety authorities, the Federal Office for Radiation Protection.

Deterministic and probabilistic studies were carried out, both types of studies exclusively with the aid of GMPE's formulated in intensities. Response spectra were then associated with the resulting intensities; these response spectra depended not only on the intensities, but also on three underground classes: class A (loose sediments) with Vs < 400 m/s, class M (overconsolidated or cemented sediments) with Vs between 400 m/s and 1100 m/s and class R (rock) with Vs > 1100 m/s.

Leydecker et al. (2005) do not mention the possibility of specific site amplification studies.

The nuclear safety rule KTA 2020.2 (1990), "Design of nuclear power plants against seismic actions: construction ground", gives a list of methods that can be used to determine dynamic soil parameters. However, nothing is explicitly said about the use of these parameters; it seems that they have to be determined to enable the design of foundations. Furthermore, some indications are given with respect to soil liquefaction. Specific site amplification studies are not mentioned in the KTA rule 2020.2 neither.

3.3.4 Practice in Japan

The Japanese Nuclear Safety Commission (NSC, 1981) published a safety guide in July 1981: "Regulatory Guide for Aseismic Design of Nuclear Power Reactor Facilities". It gives general principles for seismic design in about 30 pages. Concerning soil properties, it is mentioned:

> "Important (nuclear) buildings and structures shall be supported on bedrock..."

In the Commentary, it is written that the

> "Base stratum is firm bedrock which was formed in general in the Tertiary or earlier era and which is not significantly weathered."

In a paragraph related to static analysis, an equivalent acceleration is proposed; it depends on soil conditions, with three types. Type I is bedrock, Type II is "soft and humid" alluvial soil and Type II is in between. In addition to this text, the use of the so-called "Oshaki" response spectrum is often mentioned, which is defined for soils with Vs > ~700m/s.

In parallel, industry under the impulsion of NISA (regulator) published so-called application guides: JAEG4601-XXXX – "Technical Guidelines for Aseismic Design of NPP by Japan Electric Association", XXXX being the year of revision. After the 1981 safety guide, the revision is : JAEG4601-1987, which was translated in English by USNRC as NUREG/CR-6241 (Park & Hofmayer, 1994). In this document, it is clearly stated that the input is defined at the "free surface of the base stratum (rock outcrop)… the base stratum has a Vs higher than 700m/s…"

In September 2006, NSC (2006) issued a new version of the safety guide: the "Regulatory Guide for Reviewing Seismic Design of Nuclear Power Reactor Facilities" with the companion JAEG issued in 2010 in Japanese, not (yet?) translated in English. In this safety guide, there is no mention of rock properties or site effects.

As far as we know, soil characteristics of the different plants are in general corresponding to rock, with Vs > 1200 m/s. Some exceptions are (the list may not be exhaustive):

- Kashiwazaki-Kariwa where Vs is about 450 m/s under the reactor and turbine buildings. The first unit started commercial operation in 1985, with construction starting before 1981,
- Fukushima Diichi, with Vs of 500 to 600m/s (started in the 70ties),
- Hamaoka 1 and 2, with Vs of about 630m/s (started in the 70ties).

3.3.5 Practice in Switzerland

The Swiss licence practice is primarily based on USNRC regulations, and to a minor extent on German KTA rules.

Since the 70ties, shortly after the release of the computer code SHAKE, 1D site response analysis with SHAKE became the standard practice – although all Swiss NPP sites exhibit Vs_{30} values > 300 m/s. At first, nonlinear soil behaviour was modelled based on published nonlinearity curves, suitable for equivalent-linear calculations. In the 80ties, extensive laboratory testing (resonant column tests, etc.) was undertaken in view of seismic requalifications of the older NPPs.

In 2001, the PEGASOS project was launched with the objective of redefining the seismic hazard at the four Swiss NPP sites according to the highest standards of science, the SSHAC level 4 requirements (SSHAC, 1997). More than 20 internationally renowned European and US-American experts were involved during four years.

Extensive soil response analyses were carried out, taking into account all kinds of uncertainties. The main calculations were done with SHAKE and an equivalent-linear 1D-RVT code. For the strongest ground motions considered, true nonlinear 1D-calculations in effective stresses were performed as well. Furthermore, for one of the sites, linear viscoelastic 2D-calculations were carried out in order to estimate the importance of "2D-effects" on site amplification. The methodology of integrating soil hazard into the PSHA corresponded to approach 3A of table X.1 of the present report, taken from McGuire et al. (2001).

At the 10^{-4}/a probability of exceedence level, the hazard resulting from PEGASOS was nearly twice as large as what was found in earlier PSHAs, for all NPP sites. This difference is mainly due to the fact that the earlier studies had not included the aleatory variability of the GMPEs in the hazard integral, a methodical error that was widespread before the end of the 20tiest century (Bommer and Abrahamson, 2006). For lower probabilities of exceedence, the differences in hazard became even larger than a factor of 2.

It was recognised that aleatory variability and epistemic uncertainty drive the hazard the more the lower the probability of exceedence. In fact, at extremely low probabilities, ground motion corresponding to the median plus 2 or 3 standard deviations become more and more "possible". Therefore, the so-called PEGASOS Refinement Project (PRP) was launched in 2008 with the objective of reducing the variabilities and uncertainties, particularly in the GMPEs, but also in the soil amplification. This project is scheduled to finish by the end of 2012.

During the PRP, many more site investigations were undertaken, applying about all possible methods of measuring shear wave velocities in order to reduce the uncertainties in the soil profiles. Subsequently, the soil response calculations were repeated, taking care of not taking into account uncertainties that are already included in the rock ground motion.

3.3.6 Practice in the United Kingdom

In the UK, the Health and Safety Executive's Nuclear Installations Inspectorate (abbreviations HSE and NII, respectively) assesses the safety of nuclear facilities by examination against a series of rather general Safety Assessment Principles (SAPs) (HSE, 2006). How the SAPs are respected is up to the licensees. The very open UK practice is well described in a brochure of the HES (HES, 2008) discussing the safety assessments in an international context. It states:

> "We believe that reactors built in the UK should be at least as safe as modern reactors anywhere else in the world. ... Unlike other countries we do not prescribe which standards must be used – we leave that choice to the designers. The standards may be from UK or elsewhere. We just expect to see their choice of codes and standards justified to convince us that they are relevant and represent modern good practice."

Therefore, there are no UK regulations on how local site effects have to be considered neither. However, in practice, reference is made to the IAEA safety guides as well as to foreign national standards, and particularly to US standards. According to I. Tromans, with respect to earthquake ground motion, reference would certainly be made to the USNRC Regulatory Guide (RG) 1.208 (USNRC, 2007). RG 1.208 contains precise requirements with respect to local site amplification studies (see point 3.3.7, Practice in the USA).

3.3.7 Practice in the USA

The Code of Federal Regulations, 10 CFR Part 100 (USNRC, 1996), Section 100.23, "Geologic and Seismic Siting Criteria", defines the so-called "Safe Shutdown Earthquake Ground Motion (SSE)" which is used for the design of nuclear facilities. 10 CFR 100.23 requires that "uncertainty inherent in estimates of the SSE be addressed through an appropriate analysis, such as probabilistic seismic hazard analysis or suitable sensitivity analysis".

There were two "Regulatory Guides (RG)" that provide general guidance to satisfy the requirements of 10 CFR 100.23: RG 1.165 (USNRC, 1997), and RG 1.208 (USNRC, 2007). Although RG 1.165 was withdrawn in 2010, it is interesting to discuss it.

RG 1.165 states that

> "Past licensing experience ... has demonstrated the need to formulate procedures that quantitatively incorporate uncertainty (including alternative scientific interpretations) in the evaluation of seismic hazards. A single deterministic representation of seismic sources and ground motions at a site may not explicitly provide a quantitative representation of the uncertainties in geological, seismological, and geophysical data and alternative scientific interpretations."

As a consequence, the regulatory position 3, "Probabilistic Seismic Hazard Analysis Procedures" (PSHA), states:

> "A PSHA should be performed for the site as it allows the use of multiple models to estimate the likelihood of earthquake ground motions occurring at a site, and a PSHA systematically takes into account uncertainties that exist in various parameters (such as seismic sources, maximum earthquakes, and ground motion attenuation). Alternative hypotheses are considered in a quantitative fashion in a PSHA. Alternative hypotheses can also be used to evaluate the sensitivity of the hazard to the uncertainties in the significant parameters and to identify the relative contribution of each seismic source to the hazard. ..."

Within the regulatory position 4, "Procedures for Determining the SSE", it is stated that after completing the PSHA for reference rock site conditions and determining the controlling earthquakes by deaggregation of the median probabilistic hazard, a site study has to be performed:

> "For nonrock sites, perform a site-specific soil amplification analysis considering uncertainties in site-specific geotechnical properties and parameters to determine response spectra at the free ground surface in the free field for the actual site conditions."

RG 1.208 (USNRC, 2007) was first an alternative to RG 1.165 and finally superseded it, the latter being withdrawn in 2010. RG 1.208 regulates a performance-based approach to define the site specific earthquake ground motion. The desired performance is the onset of significant inelastic deformation for a mean annual probability of exceedence of 10^{-5}/a. This guide explicitly asks for "a site response analysis to incorporate the effects of local geology and topography":

> "Seismic wave transmission (site amplification) procedures are necessary to obtain appropriate UHRS at the free-field ground surface if the shear wave velocity of the surficial material is less than the generic rock conditions appropriate for the rock-based attenuation relationships used in the PSHA."

Appendix E of RG 1.208 describes the requirements for such a site study. Among other prescriptions, it states:

> "Due to the non-linear nature of the analyses and the heterogeneity of the soil, sufficiently capturing the variability of the soil response at the site requires that at least 60 randomized shear velocity profiles are paired with 60 sets of randomized shear modulus and damping curves (i.e., one shear velocity profile with one set of modulus reduction and damping curves). The use of 60 profiles is generally adequate to determine a reliable estimate of the standard deviation of the site response. To determine the UHRS at the free-field ground surface, the site amplification functions (spectral ratios) for each input earthquake are computed. The mean site amplification function is obtained for each input earthquake scenario by dividing the response spectrum from the computed surface motion by the response spectrum from the input hard-rock surface motion, and computing the arithmetic mean of these 60 individual response spectral ratios."

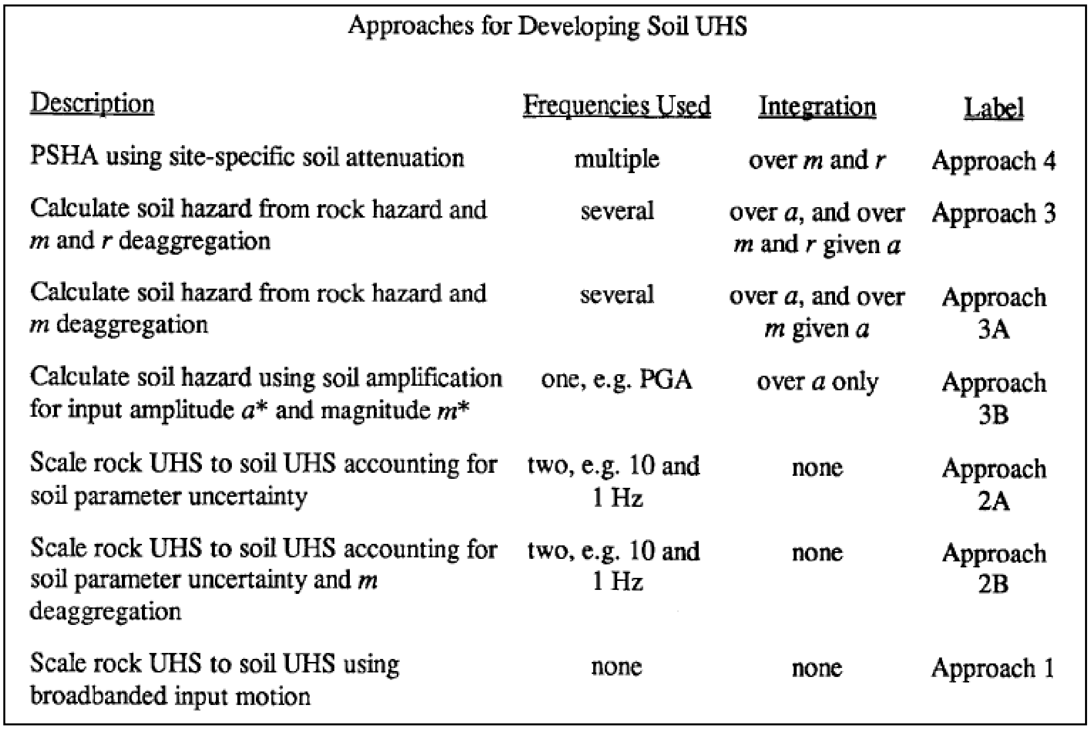
It is somewhat astonishing that the arithmetic mean has to be used. In fact, site amplification functions are more or less lognormally distributed. Hence, the geometric or logarithmic mean would be more appropriate, and indeed, it seems that nowadays, the geometric mean is used rather than the arithmentic one.

It is important to know that the NRC regulatory guides are not applied in a rigid manner. With adequate justification, it is possible to deviate from these guides. The RG 1.165, for instance, states at the end:

> "Except in those cases in which the applicant proposes an acceptable alternative method for complying with the specified portions of the Commission's regulations, this guide will be used in the evaluation of applications for construction permits, operating licenses, early site permits, or combined licenses ..."

A similar formulation is included at the end of RG 1.208.

Table 4: Overview of the essentially four levels of approaches to produce soil motions consistent with uniform rock hazard spectra, taken from McGuire et al. (2001), table 6-1.



Approaches for Developing Soil UHS

Description	Frequencies Used	Integration	Label
PSHA using site-specific soil attenuation	multiple	over *m* and *r*	Approach 4
Calculate soil hazard from rock hazard and *m* and *r* deaggregation	several	over *a*, and over *m* and *r* given *a*	Approach 3
Calculate soil hazard from rock hazard and *m* deaggregation	several	over *a*, and over *m* given *a*	Approach 3A
Calculate soil hazard using soil amplification for input amplitude *a** and magnitude *m**	one, e.g. PGA	over *a* only	Approach 3B
Scale rock UHS to soil UHS accounting for soil parameter uncertainty	two, e.g. 10 and 1 Hz	none	Approach 2A
Scale rock UHS to soil UHS accounting for soil parameter uncertainty and *m* deaggregation	two, e.g. 10 and 1 Hz	none	Approach 2B
Scale rock UHS to soil UHS using broadbanded input motion	none	none	Approach 1

In the early 2000, new states of best practice for the definition of design spectra for the evaluation of nuclear facilities were developed (McGuire et al., 2001) and tested (McGuire et al., 2002) for the USNRC, documented in the reports NUREG-CR-6728 and NUREG-CR-6769, respectively. In particular, McGuire et al. (2002) developed recommendations for conducting site response analyses to produce uniform hazard spectra (UHS) for soil motions consistent with rock outcrop hazard results from PSHA. They distinguished approaches of essentially 4 levels, level 4 to level 1, with decreasing accuracy from 4 to 1. A rough overview, without further explanations, is given in table 4. It would be far beyond the scope of the present report to go into the details of these approaches, inherently linked to the PSHA methodology. Essential in the present context is that site response analyses according to best practice are carried out in all cases.
In conclusion, since the 90ties at least, detailed site response analyses, for virtually all site classes, represent the state of practice in the context of US nuclear facilities.

4. Conclusions

One of the main points of this overview is that the instrumental approach based on analyses of earthquake recordings is principally a reliable technique. However, the existence of non-linear soil effects – a firmly established reality – compromises the validity of amplification factors obtained from weak motion measurements to a certain extent. Whenever non-linear effects must be taken into account in numerical approaches, however, the computations are significantly impaired by the uncertainties in the measurement or estimation of the non-linear constitutive characteristics of the soil. These uncertainties are at least as large as those that affect the measurement or estimation of the soil characteristics at small deformations. The need for seismic recordings also constitutes a strong limitation to experimental techniques in areas of low to moderate seismicity.

Numerical approaches remain of primary importance to help understand the physics of site effects. Their advantages for practical estimations of amplification factors at specific sites must not be overlooked, since the instrumental approach may not always be applicable, for instance in urban areas with weak seismicity. However, sensitivity studies (see Field and Jacob, 1993a) draw attention to the need for multiple, redundant geotechnical measurements (which increases the actual cost of numerical estimations).

Ambient vibration methods are clearly important because of their low expense, as the H/V ratio technique based on horizontal to vertical spectral ratios, for example. However, they should be used with lots of care, as they are able to provide only limited information.

The main lessons learned on the physics of site effects are i) the growing reconciliation of seismologists' and engineers' viewpoints on non-linear soil effects and ii) the accumulating experimental and numerical evidence on the engineering importance of 2D or 3D effects (wave diffraction by surface or subsurface topography).

Much work, both in research and of regulatory character, remains to be done in order to transfer the accumulated knowledge about site effects to the engineering practice.

In summary, although significant advances have been achieved in recent years, some issues regarding the physics of site effects as well as the manner in which to consider them in engineering practice remain unresolved (Bard, 1997):

- Basic research is needed, with both theoretical and experimental approaches, in order to better understand some particular aspects of site effects: surface topography effects, effects of strong lateral discontinuities, actual importance of non-linearity in soil response, actual level and effects of differential motion on structures, site-city interaction effects in densely urbanized areas.
- Methodological work is required to better assess and compare the reliability, cost and usefulness of the various methods available for the prediction of site effects.
- Last, but not least, some regulatory work is needed to better account for site effects in seismic codes.

Recommendations proposed by Bard et al. (2011) are to never use only one method, prefer at least two, use quantitative assessments of the mismatch between predictions, use only well-validated techniques and codes, by well trained users, with careful model implementation, external review and cross-check with data.

The extreme importance of site effects in recent damaging earthquakes calls for special efforts to apply right now what we already know regarding site effects – without waiting for results of further research. The state of the art is such that it is now possible to perform "present day" site amplification studies.

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6. References

Aki K. and K.L. Larner, 1970, Surface motion of a layered medium having irregular interface due to incident plane SH waves, J. Geophys. Res., 75, pp. 933-954.

ASME 7, 2010. Minimum Design Loads for Buildings and Other Structures. American Society of Civil Engineers. 658 pages. ISBN: 9780784410851.

ASN, 2001. RFS2001-01, Règle fondamentale de sûreté n°2001-01 relative à la determination du risque sismique pour la sûreté des installations nucléaires de base de surface, Paris.

Asten, M. W., Dhu, T., and Lam,N., 2004. Optimised array design for microtremor array studies applied to site classification; observations, results and future use: Proceedings of the 13th World Conference of Earthquake Engineering, Vancouver, August 2004.

Bard, P.-Y., 1997. Local effects on strong ground motion: Basic physical phenomena and estimation methods for microzoning studies, Advanced study course on seismic risk (SERINA), Thessaloniki, Greece, pp. 229-299.

Bard, P.-Y., A.-M. Duval, B. Lebrun, C. Lachet, J. Riepl and D. Hatzfeld, 1997. Reliability of the H/V technique for site effects measurement: an experimental assessment. In: Seventh International Conference on Soil Dynamics and Eathquake Engineering, July 19-24, Istanbul, Turkey.

Bard, P.-Y., 1999. Microtremor measurements: a tool for site effect estimation ?, State-of-theart paper, Second International Symposium on the Effects of Surface Geology on seismic motion, Yokohama, December 1-3, 1998, Irikura, Kudo, Okada & Sasatani, (eds), Balkema 1999, 3, 1251-1279.

Bard P.-Y., F. Hollender, E. Chaljub, P. Moczo, J. Kristek, N. Theodoulidis and K. Pitilakis, 2011. Verification and validation of numerical simulation techniques: lessons from the E2VP project and ongoing studies in Europe (Euroseistest Verification and Validation Project). 4th IASPEI / IAEE International Symposium: Effects of Surface Geology on Seismic Motion. University of California Santa Barbara.

Berge-Thierry C., E. Cushing, O. Scotti et F. Bonilla, 2004. Determination of the Seis¬mic Input in France for the Nuclear Power Plants Safety: Regulatory Context, Hypothesis and Uncertainties Treatment, NEA/CSNI/R 22, Tsukuba, Japan.

Bielak J., K. Loukakis, Y. Hisada and C. Yoshimura, 2003. Domain Reduction Method for Three-Dimensional Earthquake Modeling in Localized Regions, Part I: Theory. Bull. Seism. Soc. Am., vol. 93, no. 2 817-824, doi: 10.1785/0120010251.

Bommer, J,J, and N.A. Abrahamson, 2006. Why do modern seismic hazard analyses often lead to increasedhazard estimates?, Bull. Seism. Soc. Am., Vol 96, no 6, 1967-1977.

Bonilla, L.F., J.H. Steidl, G.T. Lindley, A.G. Tumarkin and R.J. Archuleta, 1997. Site amplification in the San Fernando valley, California: variability of site-effect estimation using the S-wave, coda, and H/V methods, Bull. Seism. Soc. Am. 87-3, 710-730.

Bonilla L. F., C. Gelis and J. Regnier, 2011. The challenge of nonlinear site response: field data observations and numerical simulations. 4th IASPEI / IAEE International Symposium: Effects of Surface Geology on Seismic Motion. University of California Santa Barbara.

Bonnefoy-Claudet S., F. Cotton and P.-Y. Bard, 2006. The nature of noise wavefield and its applications for site effects studies: A literature review. *Earth-Science Reviews* 79 (2006) 205–227.

Boore, D.M., 1983. Stochastic simulation of high-frequency ground motions based on seismological models of the radiated spectra. Bull. Seism. Soc. Am., Vol. 73, No. 6, pp. 1865-1894.

Boore D.M., 1994. Can Site Effects Be Predicted? Journal of Earthquake Engineering, Vol. 8, Special Issue 1, 1-41, Imperial College Press.

Borcherdt, R.D. 1970. Effects of local geology on ground motion near San Francisco Bay. Bull. Seism. Soc. Am. 60, 29-61.

Borcherdt, R. D. and Glassmoyer, G.,1994. Influences of local geology on strong and weak ground motions in the San Francisco Bay region, California and their implications for site-specific code provisions, in The Loma Prieta earthquake of October 17, 1989 -- strong ground motion, R. D. Borcherdt, (ed.), U.S. Geol. Survey Prof. Paper 1551-A, A77-A108.

Bour, M., 1993. Simulation de forts mouvements du sol à partir de petits séismes utilisés comme fonctions de Green empiriques, PhD thesis, Université Louis Pastuer, Strasbourg.

Cadet H., P.-Y. Bard, A. Rodriguez-Marek, 2012-a. Site effect assessment using KiK-net data: Part 1. A simple correction procedure for surface/downhole spectral ratios. Volume 10, Number 2, 421-448, DOI: 10.1007/s10518-011-9283-1.

Cadet H., P.-Y. Bard, A.-M. Duval and E. Bertrand, 2012-b. Site effect assessment using KiK-net data: part 2—site amplification prediction equation based on f0 and Vsz. Bulletin of Earthquake Engineering, Volume 10, Number 2, 451-489, DOI: 10.1007/s10518-011-9298-7.

Causse M., E. Chaljub, F. Cotton, C. Cornou and P.-Y. Bard, 2009. New approach for coupling k^{-2} and empirical Green's functions: application to the blind prediction of broad-band ground motion in the Grenoble basin. *Geophys. J. Int.* doi: 10.1111/j.1365-246X.2009.04354.x.

Castellaro S., 2011. The VFZ matrix: simplified seismic soil classification from a different perspective. 4th IASPEI / IAEE International Symposium: Effects of Surface Geology on Seismic Motion. University of California Santa Barbara.

Chaljub E., P. Moczo, J. Kristek, P.-Y. Bard and F. Hollender, 2011. Relevance of ground motion numerical simulations: what have we learned since the ESG'

2006 benchmark? 4th IASPEI / IAEE International Symposium: Effects of Surface Geology on Seismic Motion. University of California Santa Barbara.

Chavez-Garcia, F.J., L.R. Sanchez and D. Hatzfeld, 1996. Topographic site effects and HVSR. A comparison between observations and theory. Bull. Seism. Soc. Am., 86-5, 1559-1573.

Cho, I., T. Tada, Y Shinozaki, 2004. A new method to determine phase velocities of Rayleigh waves from microseisms, Geophysics, 69, 6, 1535-1551.

Cornou, C. 1998. Etudes théoriques et numériques sur la méthode de Nakamura-Nogoshi. Mémoire de Diplôme d'Ingénieur, EOST Strasbourg-LGIT Grenoble, 132 pp. (in French).

Cornou C., M. Ohrnberger, D. M. Boore, K. Kudo and P.-Y. Bard, 2006. Derivation of structural models from ambient vibration array recordings: results from an international blind test. Third International Symposium on the Effects of Surface Geology on Seismic Motion, Grenoble, France, Paper Number: NBT.

Courboulex, F., A. Deschamps, M. Cattaneo, F. Cosli, J. Deverchere, J. Virieux, P. Augliera, V. Lanza and D. Spallorossa, 1998. Source study and tectonic implications of the 1995 Ventimiglia (border of Italy and France) earthquake (Ml= 4.7), Tectonophysics, 290, 245-257.

Crouse C. B., 2011. Effects of local geology on earthquake ground motions: from research to engineering practice and building codes. 4th IASPEI / IAEE International Symposium: Effects of Surface Geology on Seismic Motion. University of California Santa Barbara.

CyberQuake, 1998. User's Guide, Version 1.1 (Version 2 in Arbeit), BRGM, Orléans.

De Rubeis V., G. Cultrera, H. Cadet, P.-Y. Bard and N. Theodulidis, 2011. Statistical Estimation of Earthquake Site Response from Noise Recordings. Proc. 4th IASPEI/IAEE Int. Symp., University of California Santa Barbara.

Di Alessandro, C., Bonilla, L. F., Boore, D. M., Rovelli, A. and Scotti, O., 2012. Predominant-period site classification for response spectra prediction equations in Italy. Bulletin of the Seismological Society of America, Vol. 102, No. 2, pp. 680-695, DOI: 10.1785/0120110084.

DIN 4149, 2005. Buildings in German earthquake areas – Design loads, analysis and structural design of buildings, DIN Deutsches Institut für Normung, Berlin.

Dobry, R. and M. Vucetic, 1987. Dynamic properties and seismic response of soft clay deposits, Proc. Int. Symp. on Geotech. Eng. of Soft Soils, Mexico city, Vol. 2, pp. 51-87.

Douglas, J., 2011. Ground-motion prediction equations 1964–2010, BRGM/RP-59356-FR, 444 pages, 9 illustrations.

Douglas J. and H. Aochi, 2008. A Survey of Techniques for Predicting Earthquake Ground Motions for Engineering Purposes. *Surv Geophys* (2008) 29:187–220, DOI 10.1007/s10712-008-9046-y.

Drouet, S., S. Chevrot, F. Cotton and A. Souriau, 2008-a. Simultaneous Inversion of Source Spectra, Attenuation Parameters, and Site Responses: Application to the Data of the French Accelerometric Network, Bull. Seism. Soc. Am., 98, 198-219.

Drouet, S., P. Triantafyllidis, A. Savvaidis and N. Theodulidis, 2008-b. Comparison of Site Effects Estimation Methods Using the Lefkas, Greece, 2003 Earthquake Aftershocks, Bull. Seism. Soc. Am., 98, 2349-2363.

EPRI (Electric Power Research Institute), 1993. Guidelines for determining design basis ground motions. Palo Alto, Calif: Electric Power Research Institute, vol. 1-5, EPRI TR-1 02293.

Eurocode 8, 2005. Design of structures for earthquake resistance Part 1: General rules, seismic actions and rules for buildings, European Committee for Standardization, Brussels.

Faccioli E., Fotia G., Maggio F., Massidda L., Paolucci R., Quarteroni A., Siddi G., Stupazzini M., Scandella L., Vanini M., Zambelli C., 2007. GeoELSE software package. http://geoelse.stru.polimi.it

Fäh D. and P. Suhadolc, 1994. Application of numerical wave-propagation techniques to study local soil effects: the case of Benevento (Italy), PAGEOPH, Vol. 134, No. 4, pp. 513-536.

Fäh D., F. Kind and D. Giardini, 2001. A theoretical investigation of average H/V ratios. Geophys. Jour. Int., Vol. 145, Issue 2, pp. 353-549.

Fäh, D., F. Kind and D. Giardini, 2003. Inversion of local S-wave velocity structures from average H/V ratios, and their use for the estimation of site-effects, Journal of Seismology, 7, 449-467.

Fäh D., G. Stamm and H.-B. Havenith, 2008. Analysis of three-component ambient vibration array measurements. Geophys. J. Int. 172, pp. 199–213 doi: 10.1111/j.1365-246X.2007.03625.x.

Field, E.H. and K. Jacob, 1993a. Monte Carlo simulation of the theoretical site response variability at Turkey Flat, California, given the uncertainty in the geotechnically derived input parameters, Earthquake Spectra, 9-4, 669-702.

Field, E.H. and K. Jacob, 1993b. The theoretical response of sedimentary layers to ambient seismic noise. Geophysical Res. Lett. 20-24, 2925-2928.

Field, E.H., and K. Jacob, 1995. A comparison and test of various site response estimation techniques, including three that are non reference-site dependent, Bull. seism. Soc. Am., 85, 1127-1143.

Hanks, T. and McGuire, R., 1981. The character of high-frequency strong ground motion.Bull. Seism. Soc. Am., Vol. 71, No. 6, pp. 2071-2095.

Hartzell, S.H., 1978. Earthquake aftershocks as Green's functions. Geophys. Res. Letters, 5, 104-107.

Heuze, F.E., T.S. Ueng, L.J. Hutchings, S.P. Jarpe, P.W. Kasemeyer, 1995. A New Seismic- Geotechnical Strong Motion Approach, Proc. 3rd Int. Conf. on Recent Advantages in Geotechnical Earthquake Engineering and Soil Dynamics, Vol. III, Paper No 8.11, St. Louis, Missouri: 1311-1318.

Heuze, F., R.J. Archuleta, L.F. Bonilla, S. Day, M. Doroudian, A. Elgamal, S. Gonzales, M. Hoehler, T. Lai, D. Lavallee, B. Lawrence, P.C. Liu, A. Martin, L. Matesic, B. Minster, R. Mellors, D. Oglesby, S. Park, M. Riemer, J.H. Steidl, F. Vernon, M. Vucetic, J. Wagoner, Z. Yang [2004]. Estimating site-specific strong earthquake motions, Soil Dyn. and Earth. Eng., Vol. 24, pp. 199-223.

HSE, 2006. Safety Assessment Principles for Nuclear Facilities, Revision 1, http://www.hse.gov.uk/nuclear/saps/saps2006.pdf.

HSE, 2008. New nuclear power stations – safety assessments in an international context", Version 2, 24 June, http://www.hse.gov.uk/newreactors/international.pdf.

Hutchings, L. , 1994. Kinematic earthquake models and synthesized ground motion using empirical Green's functions. BSSA, 84, 1028-1050.

IAEA, 2002. Evaluation of Seismic Hazards for Nuclear Power Plants, Safety Guide, IAEA Safety Standards Series No. NS-G-3.3, Vienna.

IAEA, 2004. Geotechnical Aspects of Site Evaluation and Foundations for Nuclear Power Plants, Safety Guide, IAEA Safety Standards Series No. NS-G-3.6, Vienna.

IAEA, 2010. Seismic Hazards in Site Evaluation for Nuclear Installations, Specific Safety Guide No. SSG-9, Vienna.

Iai, S., Y. Matsunaga, and T. Kameoka, 1990. Strain Space Plasticity Model for Cyclic Mobility, Report of the Port and Harbour Research Institute, Vol. 29, pp. 27-56.

International Building Code, 2003. International Code Council®, ISBN 9781609830403.

Irikura, K., 1983. Semi-empirical estimation of strong ground motions during large earthquakes. Bull. Disas. Prev. Inst., Kyoto Univ., 33, 63-104.

Irikura, K., 1986. Prediction of strong acceleration motions using empirical Green's functions, Proc. 7th Jap. Earth. Eng. Symp., 151-156

Irikura, K. and K. Kamae, 1994. Estimation of strong ground motion in broad-frequency band based on a seismic source scaling model and an empirical Green's function technique, Annali di Geofisica, XXXVII-6, 1721-1743.

Kawase, H., F.J. Sánchez-Sesma and S Matsushima, 2011. Proc. 4th IASPEI/IAEE Int. Symp., University of California Santa Barbara.

Kobayashi, K., 1980. A method for presuming deep ground soil structures by means of longer period microtremors, Application of the H/V Spectral Ratios for Earthquake and Microtremor Ground Motions. Proc. of the 7th WCEE, Sept. 8-13, Istanbul, Turkey, 1, 237-240.

Kohrs-Sansorny C., F. Courboulex, M. Bour, and A. Deschamps, 2005. A Two-Stage Method for Ground-Motion Simulation Using Stochastic Summation of Small Earthquakes. *Bulletin of the Seismological Society of America*, Vol. 95, No. 4, pp. 1387–1400, doi: 10.1785/0120040211.

Konno, K. and T. Ohmachi, 1998. Ground-motion characteristics estimated from spectral ratio between horizontal and vertical components of microtremor. Bull. Seism. Soc. Am. 88-1, 228-241.

Kottke A. R. and E. M. Rathje, 2008. Technical Manual for Strata. PEER Report 2008/xx. Pacific Earthquake Engineering Research Center, College of Engineering, University of California, Berkeley.

KTA 2201.1, 2010 (draft revision). Auslegung von Kernkraftwerken gegen seismische Einwirkungen; Teil 1: Grundsätze. Sicherheitstechnische Regel des KTA.

KTA 2201.2, 1990. Auslegung von Kernkraftwerken gegen seismische Einwirkungen; Teil 2: Baugrund. Sicherheitstechnische Regel des KTA.

Kudo, K. 1995. Practical estimates of site response, State-of-the-Art report. In: Proceedings of the Fifth International Conference on Seismic Zonation, October 17-19, Nice, France, Ouest Editions Nantes, 3, 1878-1907.

Lacave C, P.-Y. Bard, M. Kham, M. G. Koller, 2008. 2D equivalent-linear site effect simulation: example applications to two deep valleys. *Bull. Earthquake Eng.* No. 6, pp.197–211. DOI 10.1007/s10518-007-9054-1.

Lachet C. and Bard P.-Y., 1994. Numerical and Theoretical Investigations on the Possibilities and Limitations of Nakamura's Technique, J. Phys. Earth, 42, pp. 377-397.

Lachet, C., D. Hatzfeld, P.-Y. Bard, N. Theodulidis, C. Papaioannou and A. Savvaidis, 1996. Site effects and microzonation in the city of Thessaloniki (Greece): comparison of different aproaches. Bull. Seism. Soc. Am. 86, 1692-1703.

Langston, C.A., 1979. Structure under Mount Rainier, Washington, inferred from teleseismic body waves, J. Geophys. Res., 84, 4749-4762.

Lemoine A., J. Douglas and F. Cotton, 2012. Testing the applicability of correlations between topographic slope and Vs,$_{30}$ for Europe. Submitted to Bull. Seism. Soc. Am.

Lermo, J. and F.J. Chavez-Garcia, 1993. Site effect evaluation using spectral ratios with only one station, Bull. Seism. Soc. Am. 83, 1574-1594.

Lermo, J. and F.J. Chavez-Garcia, 1994. Are microtremors useful in site response evaluation ? Bull. Seism. Soc. Am. 84, 1350-1364.

Leydecker, G., T. Schmitt, H. Busche et T. Schaefer, 2005. Ingenieurseismologische Parameter für Standorte von Zwischenlagern an deutschen Kernkraftwerken. D-A-CH-Tagung 2005 in Köln, DGEB-Publikation Nr. 13, 81-88.

Li X. S., Z. L. Wang and C. K. Shen, 1992. SUMDES - A Nonlinear Procedure for Response Analysis of Horizontally-layered Sites Subjected to Multi-directional Earthquake Loading. Department of Civil Engineering University of California, Davis.

Louie, J., 2001. Faster, Better: Shear-Wave Velocity to 100 Meters Depth from Refraction Microtremor Arrays, Bulletin of the Seismological Society of America, 91, 347-364.

Magistrale, H., S. Day, R.W. Clayton, and R. Graves, 2000. The SCEC Southern California Reference Three-Dimensional Seismic Velocity Model Version 2, Bull. Seism. Soc. Am., Vol. 90, pp. S65-S76.

McGuire, R.K., W.J. Silva, and C.J. Costantino, 2001. Technical Basis for Revision of Regulatory Guidance on Design Ground Motions: Hazard- and Risk-Consistent Ground Motion Spectra Guidelines, NUREG/CR-6728, U.S. Nuclear Regulatory Commission, Washington, DC.

McGuire, R.K., W.J. Silva, and C.J. Costantino, 2002. Technical Basis for Revision of Regulatory Guidance on Design Ground Motions: Development of Hazard- and Risk-Consistent Seismic Spectra for Two Sites, NUREG/CR-6769, U.S. Nuclear Regulatory Commission, Washington, DC.

Michlin, S. G., 1970. Variacionnyje metody v matematicceskoj fizike. Nauka, Moskva.

Moczo P., J. Kristek, M. Galis, P. Pazak and M. Balazovjech, 2007. The finite-difference and finite-element modeling of seismic wave propagation and earthquake motion. acta physica slovaca vol. 57 No. 2, 177 – 406.

Mueller C., 1985, Source pulse enhancement by deconvolution of an empirical Green's function, Geophys. Res. Lett., 12, 33-36.

Mulargia F. And S. Castellaro, 2009. Experimental Uncertainty on the Vs(z) Profile and Seismic Soil Classification. Seismological Research Letters, v. 80 no. 6 p. 985-988. doi: 10.1785/gssrl.80.6.985.

Nakamura Y., 1989. A Method for Dynamic Characteristics Estimations of Subsurface Using Microtremors on the ground Surface", QR RTRI, 30, pp. 25-33.

Nakamura, Y, 1996. Real-time information systems for seismic hazard mitigation UrEDAS, HERAS and PIC. Q.R. of R.T.R.I., 37-3, 112-127.

Nogoshi, M. and T. Igarashi, 1971. On the amplitude characteristics of microtremor (Part 2), Jour. seism. Soc. Japan, 24, 26-40 (in Japanese with English abstract).

NSC, 1981. Regulatory Guide for Aseismic Design of Nuclear Power Reactor Facilities.

NSC, 2006. URL:http://www.nsc.go.jp/english/taishin.pdf.

NZS 1170.5:2004, 2004. Structural Design Actions Part 5: Earthquake actions NZS 1170.5: 2004 – New Zealand.

Ohori, M., Nobata, A., and K. Wakamatsu, 2002. A Comparison of ESAC and FK Methods of Estimating Phase Velocity Using Arbitrarily Shaped Microtremor Arrays, Bull. Seism. Soc. Am., 92(6), 2323-2332.

Ohrnberger, M, 2005. Report on the FK/SPAC capabilities and limitations. SESAME Deliverable D19.06, 43 pp, http://sesame-fp5.obs.ujf-grenoble.fr/Delivrables/-Del-D19-Wp06.pdf.

Okada, H., 2003. The Microseismic Survey Method, Society of Exploration Geophysicists of Japan. Translated by Koya Suto, Geophysical Monographs Vol 12. Tulsa: Society of Exploration Geophysicists, 2003.

Park Y.J. and C.H. Hofmayer, 1994. Technical Guidelines for Aseismic Design of Nuclear Power Plants – Translation of JAEG 4601-1987, NUREG/CR-6241.

Parolai, S., 2012. Investigation of site response in urban areas by using earthquake data and seismic noise. In P. Bormann (Ed.), *New Manual of Seismological Observatory Practice 2 (NMSOP-2)* (pp. 1-38). Potsdam: Deutsches GeoForschungsZentrum GFZ. doi:10.2312/GFZ.NMSOP-2_ch14.

Parolai S., D. Bindi and P. Augliera, 2000. Application of the Generalized Inversion Technique (GIT) to a microzonation study: numerical simulations and comparison with different site-estimation techniques. Bull. Seism. Soc. Am., 90, no. 2, 286–297.

Pitilakis K., E. Riga and A. Anastasiadis, 2012. Design spectra and amplification factors for Eurocode 8. Submitted to Bulletin of Earthquake Engineering.

Prévost J.H., 2002. Dynaflow - A Nonlinear Transient Finite Element Analysis Program. Version 02, Release 10.A. *Tech. Report, Department of Civil and Environmental Engineering, Princeton University*, http://www.princeton.edu/~dynaflow/

PS 92, 1995. NF P 06-013, Règles de construction parasismique, Règles PS appliquables aux bâtiments, dites Règles PS 92, AFNOR.

Rathje E. M. and A. R. Kottke, 2008. Procedures for random vibration theory based seismic site response analyses. A White Paper Report Prepared for the Nuclear Regulatory Commission. Geotechnical Engineering Report GR08-09. Geotechnical Engineering Center, Department of Civil, Architectural, and Environmental Engineering, The University of Texas at Austin.

Riepl, J., P.-Y. Bard, D. Hatzfeld, C. Papaioannou and S. Nechtschein, 1998. Detailed evaluation of site response estimation methods across and along the sedimentary valley of Volvi (EURO-SEISTEST). Bull. Seism. Soc. Am. 88-2, 488-502.

Saenger E., N. Gold, and S, Shapiro, 2000. Modeling the propagation of elastic waves using a modified finite-difference grid, Wave Motion, Vol. 31, pp. 77-82.

Salichon J., C. Kohrs-Sansorny, E. Bertrand and F. Courboulex, 2010. A Mw 6.3 earthquake scenario in the city of Nice (southeast France): ground motion simulations. *J Seismol*, 14:523–541 DOI 10.1007/s10950-009-9180-0.

Schnabel B., Lysmer J. and Seed H.B., 1972. SHAKE – a Computer Program for Earthquake Response Analysis of Horizontally Layered Sites, Report EERC, pp. 72-12.

Sèbe, O. (2004). Déconvolution aveugle et sismologie : estimation de la source sismique et des effets de site. Thèse de Doctorat de l'Université Joseph Fourier, Grenoble 1. http://tel.archives-ouvertes.fr/tel-00010704/en/.

Seed, H.-B. et Idriss, I.-M., 1970. Soil moduli and damping for dynamic response analysis. Report N°. FERC 70-10, UCB.

SESAME, 2004. Guidelines for the implementation of the H/V spectral ratio technique on ambient vibrations: measurements, processing and interpretation. Sesame European research project. http://sesame-fp5.obs.ujf-grenoble.fr/ Delivrables/Del-D23-HV_User_Guidelines.pdf.

Shapiro N.M. and M. Campillo, 2004. Emergence of broadband Rayleigh waves from correlations of the ambient seismic noise, Geophys. Res. Letters, 31, L07614, doi:10.1029/2004GL019491.

Shiono, K., Y. Ohta and K. Kudo, 1979. Observation of 1 to 5 sec microtremors and their applications to earthquake engineering, Part VI: existence of Rayleigh wave components, Jour. seism. Soc. Japan, 32, 115-124 (in Japanese with English abstract).

Silva, W.J., 1997. Characteristics of vertical strong ground motions for applications to engineering design. Proc. Of the FHWAJNCEER Workshop on the Natl Representation of Seismic Ground Motion for New and Existing Highway Facilities, I.M. Friedland, M.S Power and R. L. Mayes eds., Technical Report NCEER-97-OO10.

Silva, W. and R.B. Darragh, 1995. Engineering characterization of strong ground motion recorded at rock sites. Technical report, Electric Power Research Institute, El Cerrito, California. EPRI Report TR-102262.

Smerzini C., R. Paolucci and M. Stupazzini, 2011. Comparison of 3D, 2D and 1D numerical approaches to predict long period earthquake ground motion in the Gubbio plain, Central Italy. Bull. Earthquake Eng. 9:2007-2029. DOI 10.1007/s10518-011-9289-8.

Steidl J.H., A.G. Tumarkin and R.J. Archuleta, 1996. What is a reference site? Bull. Seism. Soc. Am., Vol 86, No. 6, pp. 1733-1748.

SSHAC [Senior Seismic Hazard Analysis Committee, R.J. Budnitz, Chairman, G. Apostolakis, D.M. Boore, L.S. Cluff, K.J. Coppersmith, C.A. Cornell, and P.A. Morris], 1997. Recommendations for probabilistic seismic hazard analysis—Guidance on uncertainty and use of experts: Washington, D.C., U.S. Nuclear Regulatory Commission Report, NUREG/CR-6372.

Theodulidis, N., P.-Y. Bard, R.J Archuleta and M. Bouchon, 1996. Horizontal to vertical spectral ratio and geological conditions: the case of Garner Valley downhole array in Southern California, Bull. Seism. Soc. Am. 86, 306-319.

Toshinawa, T., J.J. Taber and J.J. Berrill, 1997. Distribution of ground motion intensity inferred from questionnaire survey, earthquake recordings, and microtremor measurements – a case study in Christchurch, New Zealand, during the 1994 Arthurs Pass earthquake. Bull. Seism. Soc. Am. 87-2, 356-369.

Towhata, I., and K. Ishihara, 1985. Modeling Soil Behavior Under Principal Axes Rotation, Fifth International Conference on Numerical Methods in Geomechanics, Nagoya, pp. 523-530.

Tumarkin A.G., R.J. Archuleta, 1994. Empirical ground motion prediction, Annali di Geofisica, XXXVII-6, 1691-1720.

Uniform Building Code 1997. Vol. 2, Structural Engineering Design Provisions, International Conference of Building Officials.

USNRC, 1996 (amended 2007). U.S. Code of Federal Regulations, Title 10, Energy, Part 100, Reactor Site Criteria, Part 100.23 - Geologic and seismic siting criteria, U.S. Nuclear Regulatory Commission, Washington, DC.

USNRC, 1997. Regulatory Guide 1.165, Identification and Characterization of Seismic Sources and Determination of Safe Shutdown Earthquake Ground Motion, U.S. Nuclear Regulatory Commission, Washington, DC.

USNRC, 2007. Regulatory Guide 1.208, A Performance-Based Approach to Define the Site-Specific Earthquake Ground Motion. U.S. Nuclear Regulatory Commission, Washington, DC.

Van Houtte C., S. Drouet and F. Cotton, 2011. Analysis of the Origins of κ (Kappa) to Compute Hard Rock to Rock Adjustment Factors for GMPEs. BSSA-D-10-00345.

Wald, D. J., and Allen, T. I., 2007. Topographic slope as a proxy for seismic site conditions and amplification, Bulletin of the Seismological Society of America, 97(5), 1379–1395, doi: 10.1785/0120060267.

Yamazaki, F. and M. A. Ansary, 1997. Horizontal-to-vertical spectrum ratio of earthquake ground motion for site characterization, Earthq. Engng. and Struct. Dyn., 26, 671-689.

Yoshimura C., J. Bielak, Y. Hisada and A. Fernández, 2003. Domain Reduction Method for Three-Dimensional Earthquake Modeling in Localized Regions, Part II: Verification and Applications. Bull. Seism. Soc. Am., vol. 93, no. 2, p. 825-841, doi: 10.1785/0120010252.

Zaré, M., P.-Y. Bard and M. Ghafory-Ashtiany, 1999. Site categorization for the Iranian strong motion network, Soil Dyn. and Earthq. Engng, 18, 101-123.

Project SIGMA

Review of:
Inventory of approaches to account for site effects: Methodologies and regulations

(Ref : SIGMA-2012-D3-39)

Alain Pecker
May 14, 2012

1. Scope of the work reviewed

The object of the report is to present methodologies that can be used to account for site effects and to review existing regulations, both in building codes and in the nuclear field, which give consideration to such effects. Methodologies include experimental field measurements, numerical simulations and semi empirical methods. This report is part of Work Package WP4, "Improving Seismic Hazard Models".

2. General comments

It is obvious that the identification of all possible methods and their critical assessment is a formidable task that nobody can pretend to cover in an exhaustive manner. Nevertheless, the report could be more useful if some specific techniques were described more in depth.

For all experimental techniques it would have been interested for a non-specialist, to avoid going through the numerous literature, to have more details on the authors' preferred or recommended one(s). More specific recommendations would have been appreciated.

For numerical models, it is suggested when referring to equivalent linear models not to use the word "nonlinear models". Equivalent linear models are indeed linear models. Along the same lines, characterization of nonlinear models with G/G_{max} curves is not sufficient; volume change characteristics under cyclic loading are also needed and essential; G/G_{max} curves are only sufficient for incompressible materials like saturated clays under undrained conditions.

3. Specific comments along the text

- In the introductory paragraph to the experimental methods, it is noted that dense arrays are essential to characterize the spatial variability of the ground motion. It is advocated that these data are needed to elaborate on the filtering of high frequencies by massive foundations. In order to prevent misunderstanding, it is advisable to make clear that filtering is not directly derived from measurements but, possibly, arises from soil-structure interaction, which needs to be assessed, is structure specific, and requires the spatial definition of the ground motion as input parameter.

- When describing the H/V technique it is indicated that Konno and Ohmachi obtained a good prediction of the measured H/V peak amplitudes with 1D linear simulations. More details would be appreciated because at the resonant frequency of the profile the peak amplitude depends on the damping ratio of the soil. It is well known that damping is one of the most difficult parameter to measure, or to estimate; it might be suspected that Konno and Ohmachi simply tuned the damping values to fit the data. The same comment applies to the result of figure 2 for which no details are given on the numerical calculations of the H/V peak amplitudes.

- In my opinion the use of 1D-RVT calculations (paragraph 2.2.1), in which randomization of the soil parameters is implemented, is not realistic. The calculation model is equivalent to assuming an infinite correlation distance in the horizontal direction; 2D numerical simulations (see for instance Assimaki et al, Journal of Earthquake Engineering, Vol. 7, Special issue 1, 2003) clearly demonstrates that realistic 2D randomization only impacts the high frequency content of the surface motion while 1D-RVT calculations show a strong effect even at low frequency. This can be physically understood since horizontal variations of the soil properties produce lenses of finite dimensions that can only be "sampled" by high frequency waves. Another evidence that results from 1D-RVT calculations overestimate the variability of the surface motion is provided in the paper by Pierre Labbé at the last AFPS national conference (2011) "Incertitude épistémique versus variabilité spatiale dans le calcul de la réponse sismique d'un profil de sol" (also to be published at the 15th World Conference on Earthquake Engineering in Lisbon "Epistemic Uncertainty versus Aleatory Variability in Seismic Response of Soil Profiles").

- In the paragraph on nonlinear calculations (§2.2.2) it is mentioned that calculations become numerically unstable for vertical accelerations in excess of 1g. This phenomenon is not, truly speaking, a numerical instability but arises in cohesionless materials that are unable to sustain tensile stresses; this is indeed a physical limitation of a continuum model in which soil particles would like to fly up. It is very likely that discrete element models would be more efficient for such situations.

- In the 2D equivalent linear calculations what is the definition of the equivalent shear strain used to compute the shear modulus and damping ratio: maximum shear strain, shear strain on a horizontal plane…?

- To be complete, in paragraph 3.1.3 describing Eurocode 8, the spectral shapes do not depend only on the soil classification but also on the ground motion type (I or II) characterized by its magnitude. One essential difference between IBC, or UBC, codes and Eurocode 8 is the existence of a constant spectral displacement branch in the latter code.

Review of Deliverable D3-39

Inventory of approaches to account for site effects: methodologies and regulations

Authors: C. Lacave, M. Koller

Reviewed by: R. Paolucci, Politecnico di Milano

This report is divided in two parts. In the first one, methods for estimating site effects are summarized, based on (i) experimental, (ii) numerical and (iii) empirical approaches. In the second part, a review of guidelines to account for site effects in some recent seismic codes and regulations is provided, with emphasis on the site classification issues and on the recommendations for design of nuclear power plants.

I have no specific remark on this compilation, which I found sufficiently clear and exhaustive for the purpose of an inventory of methods and code recommendations. The main concern that I have is about how this report is placed, and its main indications are harmonized, within the objectives of SIGMA project. In my opinion, there is probably a missing section of the work to complete the previous ones, where the introduction of site effects, and of the associated uncertainty related to the estimation of soil conditions and to the variety of experimental and numerical approaches, should be put in the proper perspective in the framework of seismic hazard assessment.

As a matter of fact, especially when dealing with site-specific probabilistic seismic hazard analyses, there are several approaches to account for site conditions and for the related uncertainties, having different levels of accuracy within a probabilistic framework. This topic is only marginally addressed in this report, when briefly introducing the different approaches in Table 4 of section 3, to produce soil motions consistent with uniform hazard rock spectra, according to US practice.

I suggest the authors to go into deeper detail on this topic, which is often overlooked by researchers, but which in my opinion is of key relevance for SIGMA project, where one of the main issues is the assessment of uncertainty of ground motion prediction at a specific site, either by probabilistic or by deterministic SHA approaches. Reference to the recent research contributions by Cramer (2003), Bazzurro and Cornell (2004), Perez et al. (2009) is recommended.

References

Bazzurro, P. and Cornell A. [2004] ‘‘Nonlinear soil-site effects in probabilistic seismic-hazard analysis,’’ Bulletin of the Seismological Society of America, 94(6), 2110–2123.

Cramer C. H. [2003] ‘‘Site seismic-hazard analysis that is completely probabilistic,’’ Bulletin of the Seismological Society of America 93(4), 1841–1846.

Perez, A., Jaimes, M.A. and Ordaz, M. [2009] “Spectral Attenuation Relations at Soft Sites Based on Existing Attenuation Relations for Rock Sites”, Journal of Earthquake Engineering, 13:2,236- 251.