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ESTIMATION OF LOCAL SITE EFFECTS DURING EARTHQUAKES: AN OVERVIEW

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ABSTRACT

A summary of methodologies to estimate local site effects of geology and topography on strong ground motion during earthquakes is presented. Some canonical solutions obtained by analytical methods for simple geometries are reviewed. Most common numerical methods used for complex geometries are briefly discussed. Experimental and hybrid methods are also described. A wide set of references is provided for the interested reader.

KEYWORDS: Site-Effects, Ground Motion, Analytical Solutions, Numerical Methods

INTRODUCTION

When observed with long scales, our planet has a relatively simple structure. In a first approximation, it is formed by spherical shells that surround the inner core up to the crust. A closer look (with scales of hundreds of kilometers) reveals that Earth has significant heterogeneities, both vertically and laterally. In fact, plate tectonics gives rise to most of the seismic activity. For smaller scales, the Earth is very heterogeneous, and its varying surface geology (topography, faults, alluvial basins, etc.) is at the origin of significant spatial variations of seismic ground motion.

It is now well known that local site characteristics may produce large ground motion amplifications during earthquakes. This issue can be investigated by means of the analysis of actual seismic records and the study of synthetic seismograms as well. In fact, our knowledge on local site effects has been historically improved, thanks to parallel advances in research of both branches. On one hand, seismic records give us a picture of "reality", on which theoretical and empirical speculations can be posed. On the other hand, by simplifying "reality", and representing it by models, we can split different contributions to a single effect; theory allows us to explain observations.

Early work by Reid (1910) pointing out the subject, when reporting on the San Francisco, California, earthquake of April 18, 1906, was followed by some pioneering investigations, including those by Sezawa (1927) on the scattering and diffraction of elastic waves by rigid cylinders embedded in an elastic space. By last century's middle years, effects of local soil and geological conditions were studied mainly in terms of peak accelerations or peak velocities (see, e.g., Kanai, 1949, 1951; Medvedev, 1955; Gutenberg, 1957; Duke, 1958). A decade later, Zhou (1965) introduced the idea of interpreting local site effects in terms of the changes of the shape of response spectra. During the 70's, a significant number of empirical studies, among others those conducted by Prof. M.D. Trifunac (e.g., Trifunac, 1971a, 1976a, 1976b, 1976c, 1978, 1979, 1980, 1987; Trifunac and Udwadia, 1974; Trifunac and Anderson, 1977; Trifunac and Brady, 1975a, 1975b, 1975c; Trifunac and Lee, 1978; Trifunac and Westermo, 1977; Wong and Trifunac, 1977), and theoretical ones (e.g., Trifunac, 1971b, 1973; Wong and Trifunac, 1974a) contributed to the overall understanding of local site effects. They also provided models and solutions which, even today, are used for validation of new methods to take into account this phenomenon.

The effects of topography on surface ground motion have been observed and studied from field experiments. Trifunac and Hudson (1971), Davis and West (1973), Wong et al. (1977), Griffiths and Bollinger (1979), and Tucker et al. (1984) among others, recorded significant amplifications. However, as remarked by Bard and Tucker (1985) and later by Geli et al. (1988), the amplifications observed in the field are systematically larger than the values predicted using theoretical models. They suggested that the models should incorporate layering, variations in wave velocities, and even irregular two- and three-dimensional configurations in order to better explain the observations. Bard and Tucker (1985) tested several such models and improved the predictions, but still showed amplifications smaller than the observed ones. Sánchez-Sesma and Campillo (1991) studied a set of relatively simple but extreme topographical profiles under various types of seismic waves, and proposed that the maximum amplification due to topographical effects is generally lower than about four. In a more recent study, Pedersen et al. (1994) found good agreement between experiments and models. They found that diffracted waves recorded at the reference station might explain the large amplitudes in the spectral ratios.

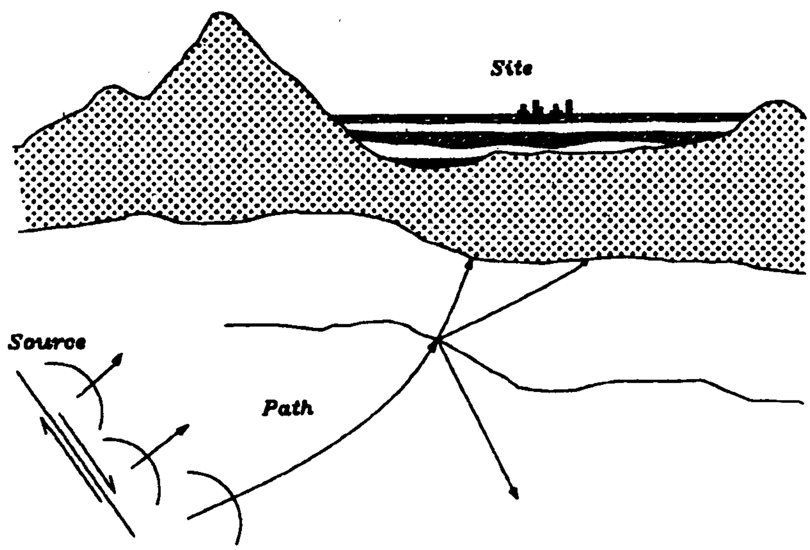


Fig. 1 Main factors in earthquake ground motion: source, path and site characteristics

Almost fifteen years ago, Aki (1988) considered that site effects could be adequately inferred if the input motions and the distributions of velocities, densities and attenuation of the materials are known. In fact, he presented several successful examples in which such conditions are met. He was foreseeing the spectacular advances in the computational power and the available numerical methods. Nowadays, the speed and processing capacity of computers is impressive. However, the majority of the procedures are expensive in terms of the required input. The most common situation is the poor knowledge of the geometry and the mechanical properties of the geological materials. Uncertainties are often large. The same is true when we talk about size and location of earthquake sources. For several applications, Aki pointed out that significant correlations exist between amplifications and geotechnical and geological characteristics. He also suggested that these relationships could be represented by meaningful microzonation maps. Now, thanks to modern Geographical Information Systems (GIS) technology, microzonation maps are a reality.

Trifunac (1989) and Trifunac and Lee (1989) have proposed a statistical approach that uses extensively recorded strong motion data, and some theoretical results to assess amplifications and response spectra ordinates at regional scale. Later, Trifunac (1990) proposed a simple equation to describe the frequency-dependent amplification of strong ground motion, which is based both on physical basis and on various regression analyses. Such an equation provides reasonable average estimates. Essentially, this is in agreement with Aki's proposal.

The quantitative prediction of strong ground motion at a given site involves dealing with the source of seismic waves, their paths to the site, and the effects of site conditions (see Figure 1). Moreover, uncertainty has to be explicitly taken into account. The great difficulty of the problem is well known. However, for many practical circumstances, the use of random vibration theory results (e.g., Udwadia and Trifunac, 1974; Vanmarcke, 1976) allows approximate descriptions of both ground motions and the corresponding response spectra, when simplified seismological models of source and path are explicitly considered (e.g., Boore, 1983; Rovelli et al., 1988). This simplified approach, which is essentially inspired by Trifunac's ideas, produces practical and reliable estimates of ground motion at a given location, when reasonable values of ground motion duration (e.g., Trifunac and Brady, 1975b) are available. Site effects can be taken into account if appropriate transfer functions are used (e.g., Reinoso et al., 1990). Of course, care is needed in selecting the characteristics of the incoming wave field.

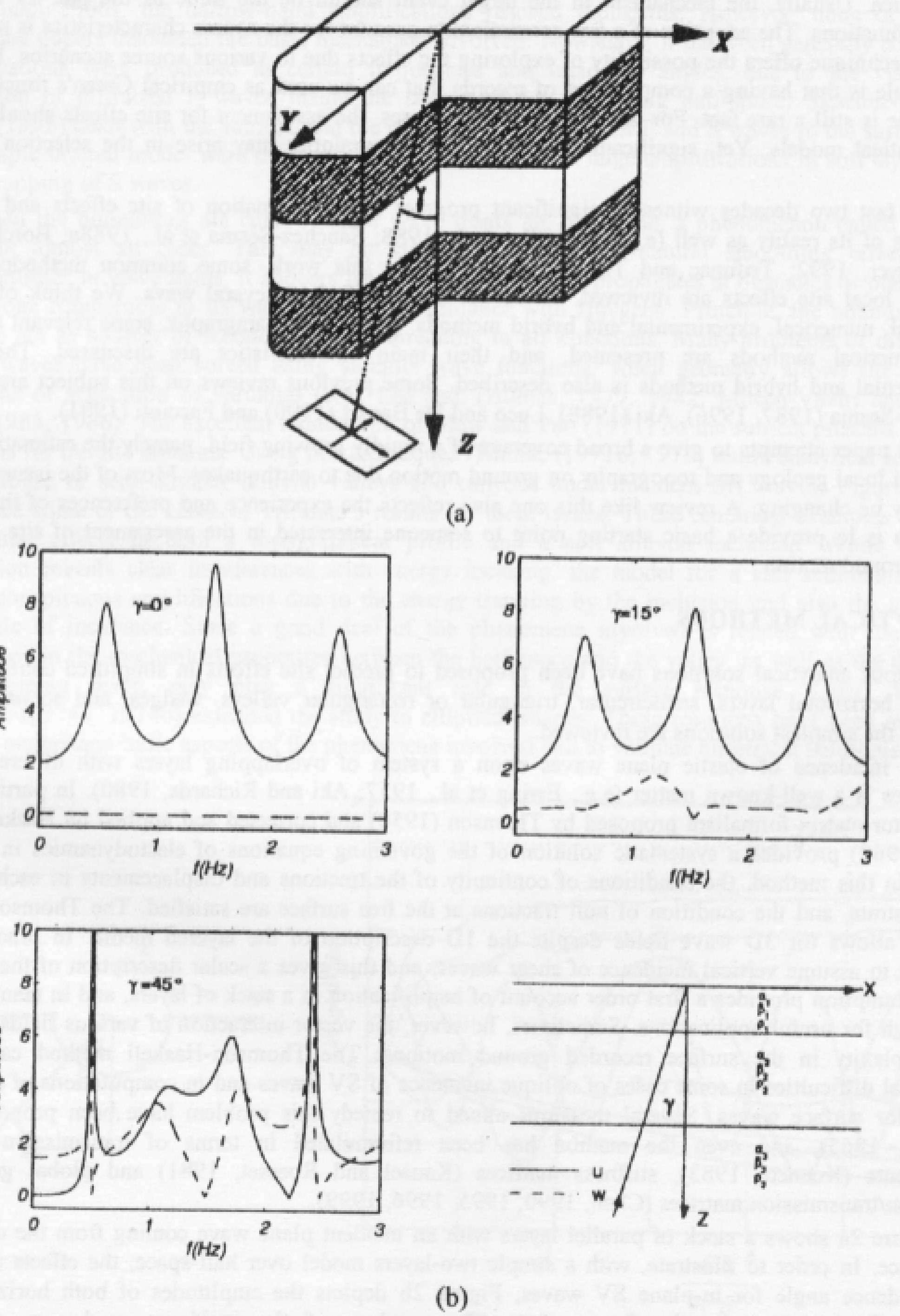


Fig. 2 (a) Plane layers model with incident plane waves, (b) Surface response versus frequency of horizontal (continuous) and vertical (dashed) displacements of a system of two layers over a half-space; material properties, with arbitrary but compatible units, are: 1.0, 1.5, 5.0 for P-wave velocities and 0.5, 0.7, 2.5 for shear velocity in layers 1, 2 and the half-space, respectively; density is 1.0 for all media; depth of layers are $h_1 = 1$ and $h_2 = 2$

A popular approach that accounts for source, path and site effects is the use of small earthquakes as empirical Green's functions (Hartzell, 1978; Irikura, 1983; Somerville et al., 1991; Hutchings, 1994; Ordaz et al., 1995). This method requires some records at the site from small earthquakes at the potential source area. Usually, the mechanism of the target event should be the same as the one for empirical Green's functions. The adoption of a few constraints to account for the source characteristics is necessary, but the technique offers the possibility of exploring the effects due to various source scenarios. However, the trouble is that having a complete set of records that can be used as empirical Green's functions at a given site is still a rare fact. For this reason, in most cases, the assessment for site effects should rely on mathematical models. Yet, significant difficulties and uncertainties may arise in the selection of input motion.

The last two decades witnessed significant progress in the evaluation of site effects and dramatic examples of its reality as well (e.g., Campillo et al., 1988; Sánchez-Sesma et al., 1988a; Borcherdt and Glassmoyer, 1992; Trifunac and Todorovska, 1998). In this work, some common methodologies to estimate local site effects are reviewed. These can be classified in several ways. We think of them as analytical, numerical, experimental and hybrid methods. In the next paragraphs, some relevant analytical and numerical methods are presented, and their main characteristics are discussed. The use of experimental and hybrid methods is also described. Some previous reviews on this subject are those of Sánchez-Sesma (1987, 1996), Aki (1988), Luco and De Barros (1990) and Faccioli (1991).

This paper attempts to give a broad coverage of a rapidly growing field, namely the estimation of the effects of local geology and topography on ground motion due to earthquakes. Most of the issues touched here may be changing. A review like this one also reflects the experience and preferences of the writers. The idea is to provide a basic starting point to someone interested in the assessment of site effects in strong ground motion.

ANALYTICAL METHODS

Various analytical solutions have been proposed to predict site effects in simplified configurations, such as horizontal layers, semicircular, triangular or rectangular valleys, wedges, and so on. In what follows, the simplest solutions are reviewed.

The incidence of elastic plane waves upon a system of overlapping layers with different elastic properties is a well-known matter (e.g., Ewing et al., 1957; Aki and Richards, 1980). In particular, the propagator-matrix formalism proposed by Thomson (1950) and corrected and applied by Haskell (1953, 1960, 1962) provides a systematic solution of the governing equations of elastodynamics in stratified media. In this method, the conditions of continuity of the tractions and displacements in each interface among strata, and the condition of null tractions at the free surface are satisfied. The Thomson-Haskell method allows for 3D wave fields despite the 1D description of the layered media. In practice, it is frequent to assume vertical incidence of shear waves, and this gives a scalar description of the problem. This assumption provides a first order account of amplification in a stack of layers, and in many cases, it is enough for useful applications. Sometimes, however, the vector interaction of various fields may lead to complexity in the surface recorded ground motions. The Thomson-Haskell method can present numerical difficulties in some cases of oblique incidence of SV waves and in computations of dispersion curves for surface waves. Several measures aimed to remedy this problem have been proposed (e.g., Dunkin, 1965), and even the method has been reformulated in terms of transmission-reflection coefficients (Kennett, 1983), stiffness matrices (Kausel and Roesset, 1981) and global generalized reflection/transmission matrices (Chen, 1990, 1995, 1996, 1999).

Figure 2a shows a stack of parallel layers with an incident plane wave coming from the underlying half-space. In order to illustrate, with a simple two-layers model over half-space, the effects of varying the incidence angle for in-plane SV waves, Figure 2b depicts the amplitudes of both horizontal and vertical displacements at the free surface. Three values of the incidence angle are considered ($\gamma = 0$, 15 and 45 degrees, respectively). Material properties are given in the figure caption. Horizontal amplitudes for 0 and 15 degrees are similar, but the latter incidence shows vertical components, suggesting the presence of converted P waves within the layers. For 45 degrees, when horizontal and vertical components of the incidence are equal, the pattern is notoriously different and very large peaks appear at certain frequencies in both horizontal and vertical components. In fact, the existence of such sharp peaks at certain frequencies for incoming plane SV waves at the critical incidence and larger angles in layered media has been pointed out by several authors (e.g., Burridge et al., 1980; Shearer and Orcutt, 1987; Kawase et al., 1987; Mateos et al., 1993; Papageorgiou and Kim, 1993), but it is still not widely known. Mateos et al. (1993) studied the 1D response of a stack of layers under incident SV waves. In their computations, the narrow-band amplifications reached thousands. However, none of the above mentioned papers discussed the basic mechanism involved. Nowadays, it has been generally accepted that amplifications were produced at certain frequencies and incidence angles, due to the very efficient generation of diffracted P waves inside the layer and the underlying half-space. Sánchez-Sesma and Luzón (1996) dealt with the subject, and the relative contributions of P and S waves to the surface motion of a simple layered model were obtained. They showed that the huge amplifications in soft layers are due to the trapping of S waves.

When the boundaries are curved and/or wave fronts are not plane, a phenomenon called diffraction arises in almost all cases. This may be viewed as a kind of natural smoothing effect to avoid discontinuities in wave fields. It appears when the incident wave propagates at obstacles or openings with dimensions comparable to its wavelength. In accordance with Huygens' Principle, the boundaries of the obstacle act as sources of secondary waves spreading in all directions. Many problems of diffraction of elastic waves have been solved using suitable wave functions, when geometry allows the use of the technique of separation of variables (e.g., Lee and Trifunac, 1979, 1982; Moeen-Vaziri and Trifunac, 1981, 1985, 1986). The excellent monograph of Mow and Pao (1971) on the subject presents many such solutions for infinite domains. Using this technique, Trifunac (1971b, 1973) found analytical solutions for the response of semi-circular alluvial valleys and canyons under incident SH waves. Figures 3 and 4 reproduce some of the classical Trifunac's results on these issues. These canonical examples exhibit the spectacular effects in both a topographical profile and a soft alluvial inclusion. While the former simulation reveals clear interferences with energy focusing, the model for a soft sedimentary deposit shows conspicuous amplifications due to the energy trapping by the inclusion and also the influence of the angle of incidence. Since a good deal of the phenomena involved is related with the geometry, differences in the mechanical properties between the half-space and the valley, as well as the direction of the incoming wave, may play a significant role in the surface response. Later, Wong and Trifunac (1974a, 1974b) extended the study to elliptical shapes. These solutions have been most useful, both to understand basic aspects of the phenomena involved and to validate numerical solutions.

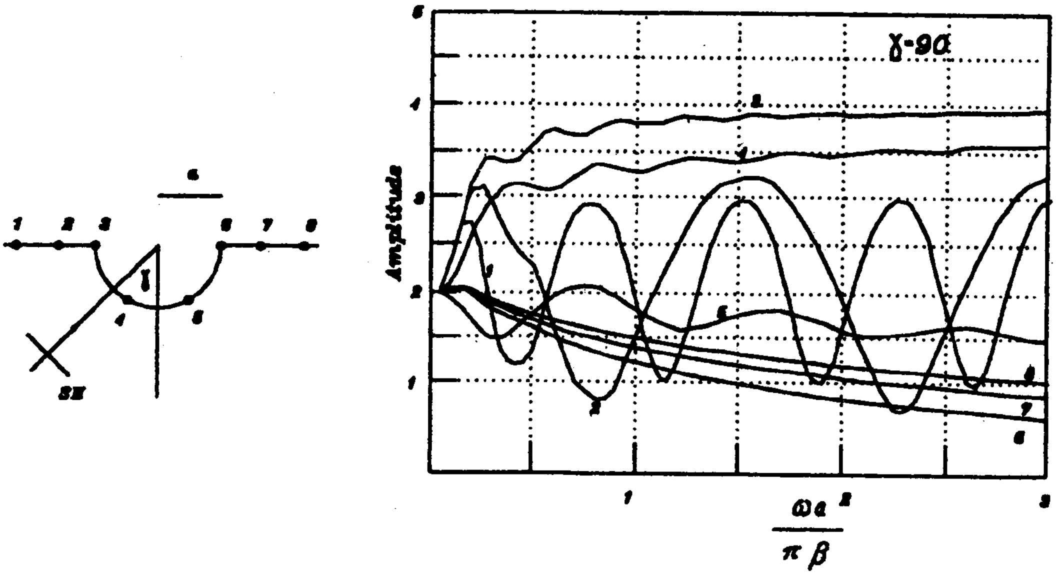


Fig. 3 Transfer functions for eight receptors located on the surface of a semi-circular topography for a 90 degrees incidence angle; here a = radius of the canyon, ω = circular frequency and β = shear wave velocity; largest amplifications occur at receptor No. 3 where the incident wave meets the canyon; note that receptors No. 5 to 8 are in the shadow zone, still motion is recorded (after Trifunac, 1973)

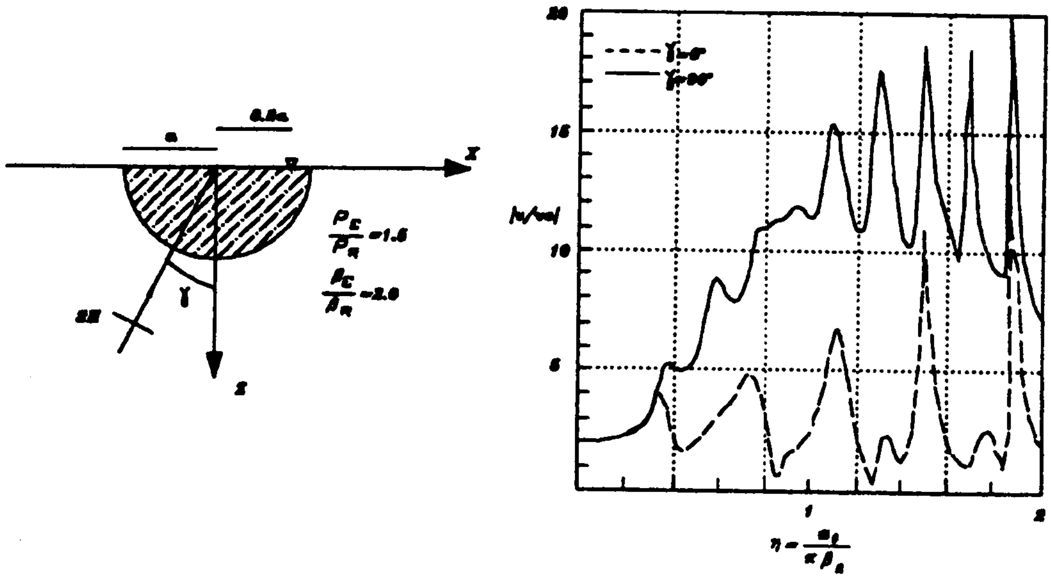


Fig. 4 Transfer function for a station located at $0.8a$ on the surface of a semi-circular alluvial valley under two different incidence angles of incoming SH waves; here a = radius of the valley, η = dimensionless frequency, ω = circular frequency, ρ = mass density and β = shear wave velocity; subscripts E and R stand for the half-space and the inclusion, respectively; $|v/v_0|$ is the absolute value of the ratio between the amplitude of the displacement at the station and that of the free-space solution (after Trifunac, 1971b)

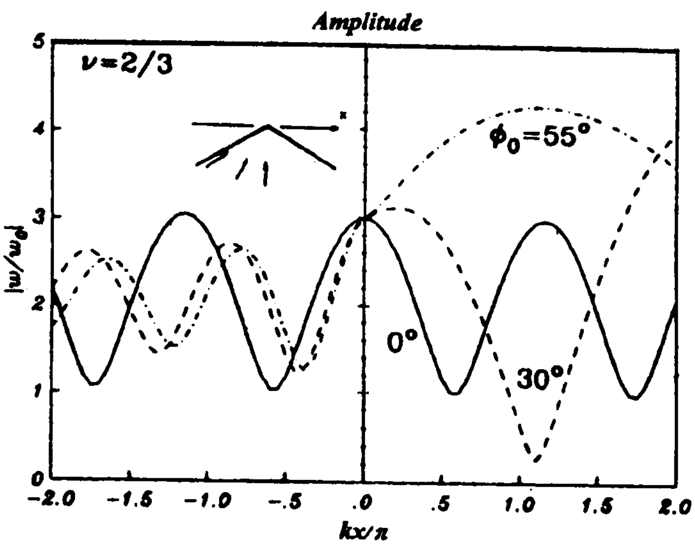


Fig. 5 Amplification in a wedge-like configuration under incidence of SH waves; here $|w/w_0|$ is the absolute value of the ratio between the amplitudes of the displacements along the wedge and those of the free-space solution; kx/π is the normalized coordinate in the horizontal direction with origin at the vertex; the amplification at the vertex remains the same for all incidences (after Sánchez-Sesma, 1985)

The exact solution for a wedge-like configuration under incidence of SH waves is due to Sánchez-Sesma (1985) who adapted MacDonald's (1902) solution in terms of series expansions of Bessel functions of fractional order and discovered a simple rule to predict the amplification at the vertex. He found that, for any incident angle, the amplitudes at the vertex of the wedge are $2/\nu$ times those at the free space, where $\nu\pi$ is the internal angle of the wedge (with $0 < \nu < 2$). Figure 5 illustrates this fact for a wedge where $\nu = 2/3$ under wave incidences of 0, 30 and 55 degrees, respectively. Although the amplification along the x-axis is different for the various incident angles displayed, and differences are notorious in the shadow zone, the amplification at the vertex remains constant with a value of $2/\nu = 3$ for all incidences. Faccioli (1991) pointed out that this solution can be used to assess amplifications in varying profiles.

In almost all analytical solutions, use should be made of the computer to evaluate the solution, i.e. the spectra and synthetics. There are some approaches that require some more computations, but still are named analytical. That is the case in the study of a 3D alluvial valley of hemispherical shape under incidence of elastic waves. Lee (1984) succeeded in obtaining power series expansions of the eigenfunction coefficients and the corresponding boundary conditions. He wrote down an infinite system of equations which, once truncated, can be solved. This approach is limited to the studied hemispherical shape and to low frequencies as well. For shallow circular geometries, several analytical solutions of this type have been obtained (e.g., Todorovska and Lee, 1990, 1991a, 1991b) for incident P and SV and Rayleigh waves.

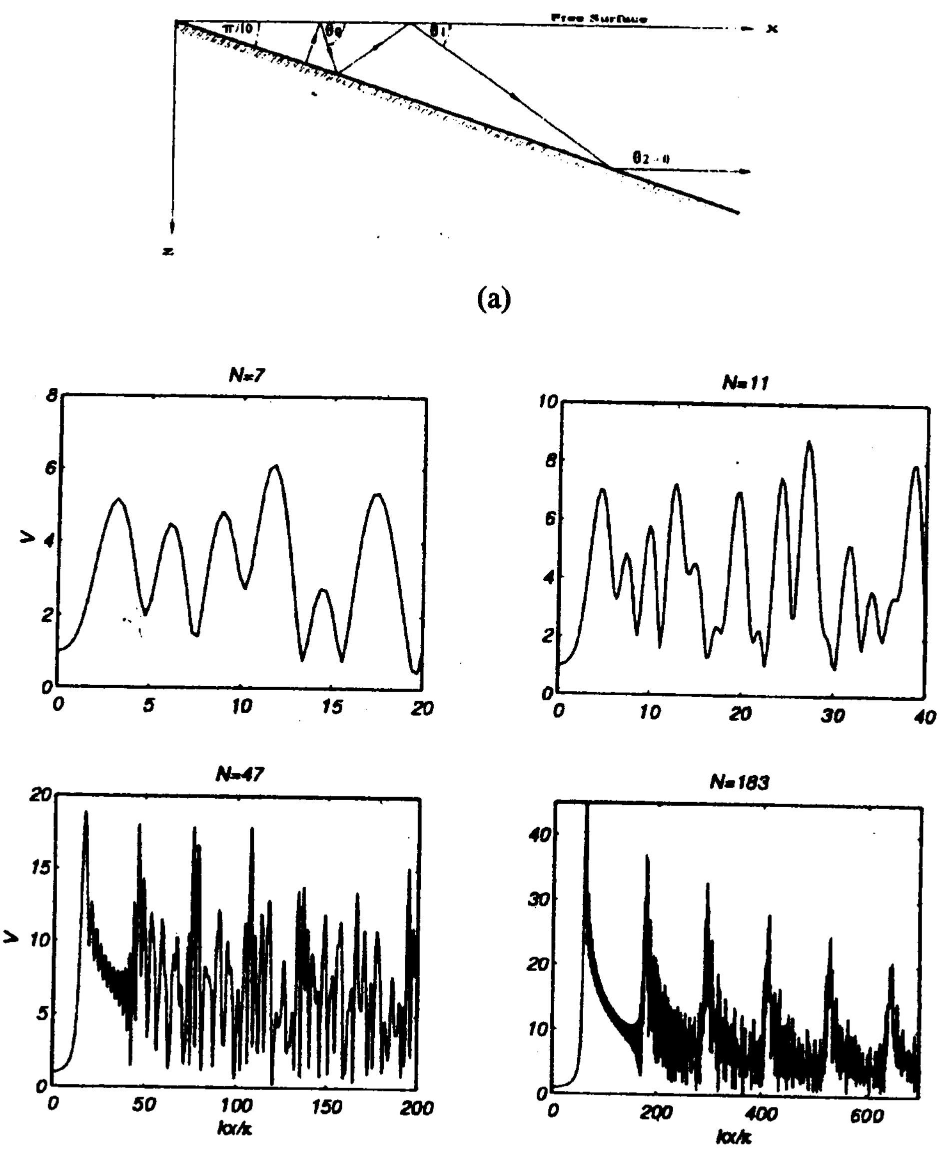


Fig. 6 (a) Dipping layer model and geometrical construction of the path of a wave inside the layer for N = 5, (b) Transfer functions for different dipping angles (N = 7, 11, 47 and 183)

The exact solution for the antiplane SH motion of a dipping layer overlaying a moving rigid base was found by only geometrical means (Sánchez-Sesma and Velázquez, 1987). For a family of dipping angles of the form $\pi / 2N$, where N is an odd integer, it came out that there is no diffraction, and the whole solution is attained by a very simple combination of plane waves. in Figure 6, reflected wave propagation is illustrated by ray tracing for $N = 5$. It can be seen that the last ray is horizontal and, therefore, satisfies by itself the free-surface boundary condition. Figure 6 displays the transfer functions for $N = 7$, 11, 47 and 183, respectively. The model has no attenuation and reveals complicated interferences of geometrical nature. For large values of N, results approach asymptotically to the 1D case. Notice that this solution is self-similar, as there is no scale involved. This model allowed a simple approximation, valid in high frequencies, for the response of a class of alluvial valleys of triangular shape (Sánchez-Sesma et al., 1988b). The same approach leads to the exact solution for the incidence of plane SH and SV waves upon some infinite mountain-like wedges, in which the complete field has been obtained again by only geometrical means (Sánchez-Sesma, 1990). Thus, only plane waves are needed to fulfill boundary conditions. Faccioli (1991) presents examples of the use of these simple solutions. A large simplified wedge model has been proposed recently to explain a relatively large broad-band amplification of southern locations in the Valley of Mexico, relative to northern ones (Montalvo-Arrieta et al., 2002).

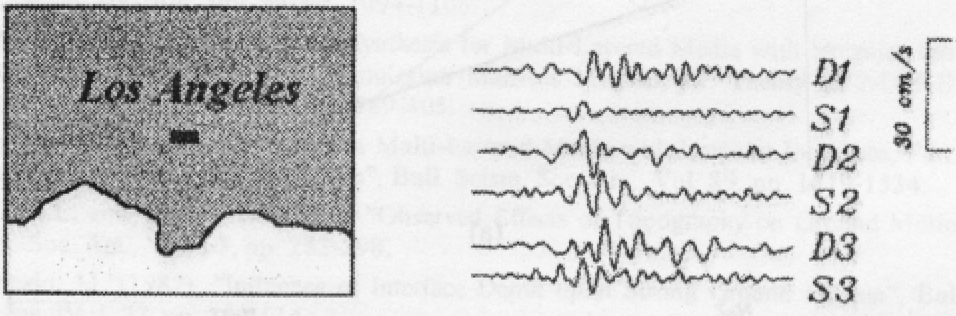


Fig. 7 Comparison between data and synthetic seismograms calculated by Olsen (2000) for a receiver located in the Los Angeles basin (shaded area delimited by the coast line); recorded data (D) and synthetic (S) in three orthogonal directions: 1, 2 and 3 are compared (redrawn from Olsen, 2000)

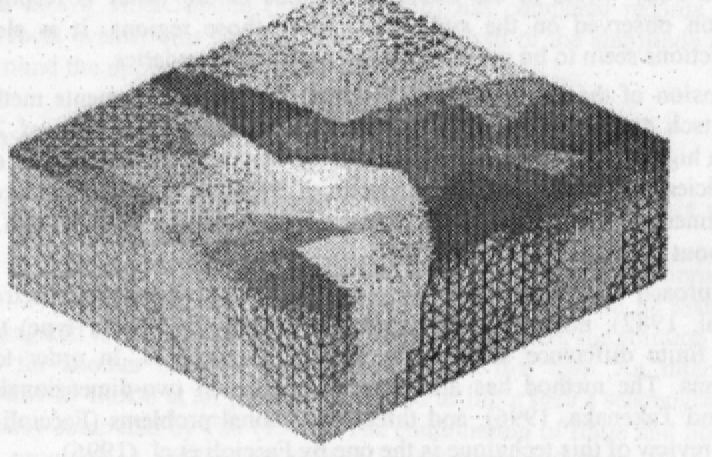
NUMERICAL METHODS

For arbitrary geometries and/or general heterogeneous media, analytical solutions are no longer valid. Therefore, numerical techniques had to be developed. They all are based on the wave equation, and many different models have been proposed to take account of several of the various aspects of site effects. We can classify such techniques into domain methods, boundary methods and asymptotic methods. In the first two approaches, discretization is required for the media and the boundaries, respectively. In a general sense, domain methods are more useful for complex structures, but are also more computationally demanding than boundary methods. On the other hand, asymptotic methods make use of Ray Theory and geometrical techniques.

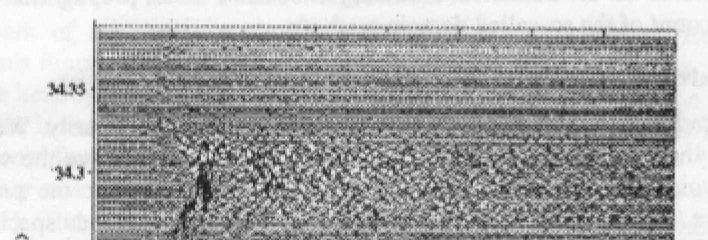
1. Domain Methods

Examples of domain methods used to study elastic wave propagation are the finite-difference (e.g., Boore, 1972; Virieux, 1984, 1986; Hill and Levander, 1984; Fäh, 1992; Yamanaka et al., 1989; Olsen and Schuster, 1991; Frankel and Vidale, 1992; Yomogida and Etgen, 1993; Frankel, 1993; Moczo et al., 1996; Schenková and Zahradnik, 1996; Graves, 1998; Wang et al., 2001; Hayashi et al., 2001) and finite-element methods (e.g., Lysmer and Drake, 1972; Smith, 1975; Toshinawa and Ohmachi, 1992; Li et al., 1992; Rial et al., 1992).

The most realistic simulations to date are those of finite differences. Use of this technique implies that the differential equations governing the movement are replaced by a group of recursive equations, expressed in form of finite differences that discretely approximate the partial derivatives. The medium is usually divided by means of a regular or structured grid, and the solution in each node of the grid is obtained in successive intervals of time. This method was first used in order to study wave propagation in elastic media by Alterman and Karal (1968). Since then, finite difference algorithms, models and meshing schemes have been growing in complexity, mainly due to the notorious improvement in available computational resources. Among the many good recent results obtained, we can mention the paper by Frankel (1993) on the response of the San Bernardino Valley or those of Olsen et al. (1995, 1997) for the Los Angeles basin to nearby earthquakes. In Figure 7, a comparison between data and synthetic seismograms, obtained by Olsen (2000), for a receptor located in the Los Angeles basin is provided. Notice the agreement in the second component between both, data and synthetic, as well as the good approximation in the other two components. Irregular grids have been explored recently, and they offer interesting possibilities (e.g., Wang et al., 2001; Hayashi et al., 2001).



(a)



(b)

Fig. 8 (a) Mesh for the San Fernando Basin simulation using finite elements; the 77 million elements mesh is partitioned into 256 subdomains; the coarser mesh is shown for 64 subdomains, (b) E-W surface velocity component along a N-S axis (redrawn from Bao et al., 1998)

On the other hand, in finite-element techniques, the medium is divided into 2D or 3D elements that do not have to be of equal size or of equal form. The displacement field anywhere inside the medium is related to that at certain points, called nodes, by means of shape functions. Nodal values are then obtained from a discrete system of equations that results from appropriate integrations of the field equations (see, e.g., Zienkiewicz and Taylor, 1989). The finite element technique provides a natural great meshing flexibility, and can deal with non-linear behavior of soils (e.g., Joyner and Chen, 1975; Joyner, 1975).

These methods (finite differences and finite elements methods) are inherently more computationally demanding than other domain methods. However, they are quite general and accurate, and fit handily into large-memory supercomputers and systems for parallel computation. This fit accounts for their current popularity. Figure 8a depicts the model for a rectangular parallelopiped, 54 km long by 33 km wide by 15 km deep, in the San Fernando Basin in Southern California, as used by Bao et al. (1996, 1998). The mesh consists of 77 million tetrahedra, is generated in 13 hours on one processor of a DEC 8400, and requires 7.7 Gb of memory. Figure 8b shows the E-W surface velocity component along N-S axis. Longer durations are associated with the deeper parts of the valley. It seems that the constructive interference of surface and trapped body waves in the shallower regions of the valley is responsible for the stronger motion amplification observed on the surface overlying those regions. It is also noteworthy that no spurious wave reflections seem to be generated at the artificial boundaries.

A natural extension of the finite elements method, the spectral elements method, has been recently applied by Komatitsch and Vilotte (1998) to simulate the seismic response of 2D and 3D geological structures. This is a high-order variational method for the spatial approximation of elastic-wave equations, which is highly efficient in terms of computer resources. Paolucci et al. (1999) have used this method to perform the 3D numerical simulation of the seismic response of a 250 m high hill, by using a last-generation PC in about 15 hours of computer time.

A different approach within domain methods, the so-called pseudo-spectral or Fourier method (Kosloff and Baysal, 1982), makes use of transforms (usually of Fourier type) to compute the spatial derivatives, and a finite difference scheme for the time derivatives, in order to solve various wave propagation problems. The method has allowed the analysis of two-dimensional (Ávila et al., 1993), 2.5-D (Furumura and Takenaka, 1996), and three-dimensional problems (Faccioli et al., 1997). A clear and comprehensive review of this technique is the one by Faccioli et al. (1996).

A compilation of works on the numerical modeling of seismic waves propagation (Kelly and Marfurt, 1990) gives a good account of the so-called domain methods.

2. Boundary Methods

In the last two decades, boundary methods have gained increasing popularity. With such algorithms, only the conditions at the boundaries and their discretization are used to solve the wave equation. This kind of techniques avoids the introduction of the fictitious boundaries for the problem that domain methods usually require. There are two main approaches: (1) boundary methods specifically based on the expansion of wave fields in terms of a complete family of functions, each one of them satisfying the differential equations that governs the problem, and (2) methods based on representation theorems that make use of Green's functions, where the wave field is expressed as an overlapping of plane waves, including the inhomogeneous ones, spreading in all the directions from the boundaries of the elastic space.

In a pioneering work, Aki and Larner (1970) introduced a numerical method, the so-called Discrete Wavenumber method, based on a discrete superposition of plane waves. Bouchon (1973) and, later, Bard (1982) and Geli et al. (1988), used the Aki-Larner technique to study the response of irregular topographies. With the same approach, Bard and Bouchon (1980a, 1980b) studied 2D alluvial valleys. Three-dimensional problems have been also dealt with the Aki-Larner method (e.g., Horike et al., 1990; Ohori et al., 1990; Jiang et al., 1993). The Discrete Wavenumber method, however, cannot deal with large slope features because of numerical difficulties to accurately simulate locally upgoing waves. Sánchez-Sesma et al. (1989a) showed that the Rayleigh *ansatz* (trial solution) is exact, but the problems are of numerical nature; they are associated to a very slow convergence of the representation.

Another type of boundary method has been used to deal with topographies, valleys and layered media. In its many variants, including in some cases three-dimensional problems and layered media, the technique is based upon the superposition of solutions for sources, with their singularities placed outside the region of interest. The singularities may be distributed close to the boundaries or may be of multipolar type, i.e. by using expansions of complete families of solutions. Boundary conditions are satisfied in a least-squares sense, and a system of linear equations for the sources' strengths is obtained.

In fact, Wong (1982) considered the problem as that of generalized inversion. In some applications, however, the location of sources requires particular care, and the trial and error process needed is difficult to apply. This is particularly true when many frequencies are to be computed (see, e.g., Sánchez-Sesma, 1978; Sánchez-Sesma and Rosenblueth, 1979; Sánchez-Sesma and Esquivel, 1979; Wong, 1979, 1982; Dravinski, 1982; Sánchez-Sesma, 1983; Sánchez-Sesma et al., 1984; Dravinski and Mossessian, 1987; Sánchez-Sesma et al., 1985, 1989b; Jiang and Kuribayashi, 1988; Moeen-Vaziri and Trifunac, 1988a, 1988b; Bravo et al., 1988; Eshraghi and Dravinski, 1989; Khair et al., 1989; Bouden et al., 1990; Mossessian and Dravinski, 1990).

Algorithms based on boundary integral equations approaches and their discretizations are known as Boundary Elements Methods (BEM). They have produced many successful solutions to various problems in dynamic elasticity. Recognized advantages over domain approaches are the dimensionality reduction, the relatively easy fulfillment of radiation conditions at infinity, and the high accuracy of results. Excellent surveys of the available literature on these methods in elastodynamics are those of Kobayashi (1987) and Manolis and Beskos (1988).

The most popular approaches are the so-called direct methods, because in their formulation, the unknowns are the sought values of displacements and tractions. These methods arise from the discretization of integral representation theorems. On the other hand, the Indirect Boundary Elements Method (IBEM) formulates the problem in terms of force or moment boundary densities, which can give a deep physical insight on the nature of diffracted waves. In fact, the indirect method has a longer history than the direct one, and is closely related to classical work on integral equations (see, e.g., Manolis and Beskos, 1988).

The combination of discrete wavenumber expansions for Green's functions (Bouchon and Aki, 1977; Bouchon, 1979) with boundary integral representations has been successful in various studies of elastic wave propagation. Bouchon (1985), Campillo and Bouchon (1985), Campillo (1987), Gaffet and Bouchon (1989), Bouchon et al. (1989), and Campillo et al. (1990) used source distributions on the boundaries, whereas Kawase (1988), Kawase and Aki (1989), and Kim and Papageorgiou (1993) used Somigliana representation theorem. These are discrete wavenumber versions of BEM, indirect and direct, respectively. Such combination is particularly attractive: the singularities of Green's functions are not present in each one of the terms of the discrete wavenumber expansion. The integration along the boundary effectively makes the singularities to vanish and improves convergence as well. However, such procedures require a considerable amount of computer resources. As the singularities of Green's functions are integrable (see, e.g., Brebbia, 1978; Banerjee and Butterfield, 1981; Kobayashi, 1987; Manolis and Beskos, 1988; Brebbia and Dominguez, 1992), the sources can be put at the boundary and their effects properly considered. In this way, the uncertainty about the location of sources is eliminated, and the linear system of equations that arises from the discretization can be directly solved. Therefore, the IBEM approach retains the physical insight of the sources method, with all the benefits of analytical integration of exact Green's functions. In the various applications reported here, diffracted fields are represented with the superposition of the radiation from boundary sources, using exact expressions of the 2D Green's functions in an unbounded elastic space. This method can be regarded as a numerical realization of Huygens' principle. The single layer integral representation of elastic wave fields allows computing tractions, once the boundary singularity is appropriately interpreted. Boundary conditions lead to a system of integral equations for boundary sources.

Nearly thirty years ago, Wong and Jennings (1975) used a direct formulation to study arbitrary canyon geometries. More recently, Zhang and Chopra (1991) studied the scattering of elastic waves by topographical irregularities. The response of 2D alluvial settings has been dealt with by Reinoso et al. (1994), whereas 3D problems have been studied by Shinozaki and Yoshida (1992), and Kawano et al. (1994).

The IBEM has been applied by Sánchez-Sesma and Campillo (1991, 1993) to study the diffraction of P, SV and Rayleigh waves by topographical irregularities on the surface of a half-space. The seismic response of 2D alluvial valleys was dealt with by Sánchez-Sesma et al. (1993a), whereas 3D site effects cases were studied by Sánchez-Sesma and Luzón (1995), Ortiz-Alemán et al. (1998), and Gil-Zepeda et al. (2001). The 3D response of 2D topographies, the so-called 2.5D problem, has also been considered by Luco et al. (1990) and Pedersen et al. (1994) by using the IBEM. This method has also been applied to study irregular layering under the incidence of elastic waves (Vai et al., 1999).

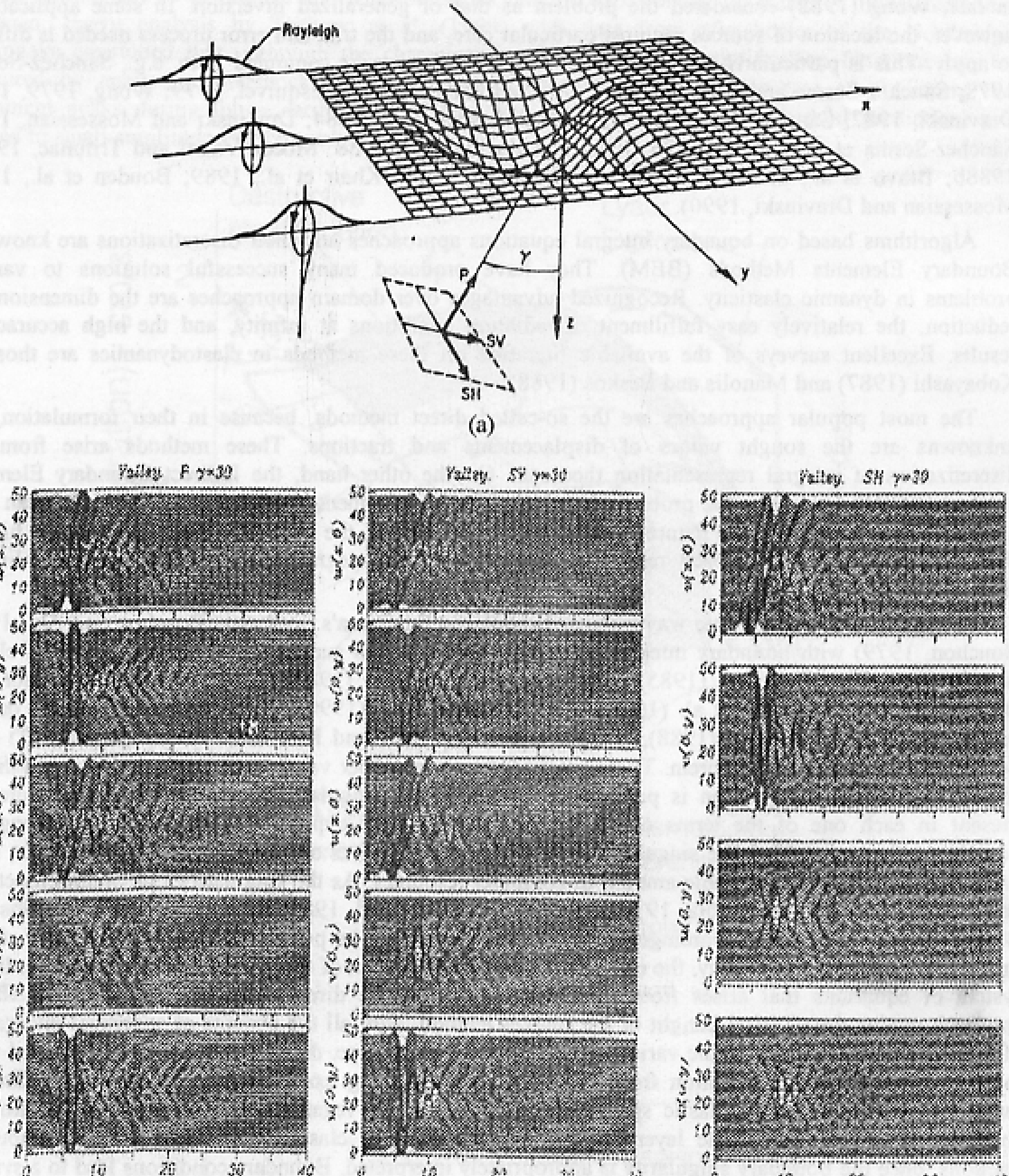


Fig. 9 (a) Perspective view of the basement of an irregular valley with P, SH, SV and Rayleigh wave incidence; azimuth $\phi = 0$; incidence angle γ with respect to the vertical for body forces, b) Synthetic seismograms for displacements u, v and w at 48 receivers, equally spaced along the x or y axes; the incident waveform is a Ricker wavelet with characteristic period of $t_p = 3$ s (redrawn from Sánchez-Sesma and Luzón, 1995)

Figure 9a shows a perspective of the basement of an irregular valley under incident P, SH, SV and Rayleigh waves. Material properties are $\beta_R = 1$ km/s, $\beta_E = 2$ km/s, $\nu_R = 0.35$, $\nu_E = 0.25$, and $\rho_R = 0.8\rho_E$, where subscripts R and E stand for the soft inclusion and the half-space, respectively.

The width of the valley is 8 km in the *y* direction, its depth is about 1 km, and a quality factor of 100 was assumed. Figure 9b depicts the synthetic seismograms obtained with the IBEM for the P, SV and SH cases, with an azimuth of 0 degrees and an incidence angle of 30 degrees with respect to the vertical. The results present very interesting patterns of interference of the refracted waves inside the basin, and in some cases, significant emission of waves is observed. Incident P and SV waves produce forward and backward scattering of Rayleigh waves by late emission, after refracted waves bounce back and forth in the sediment. Meanwhile, the SH incidence shows significant late emission of scattered SH pulses as a consequence of the shape of the valley, in which refracted waves of Love and Rayleigh types are generated continuously at the edge. One interesting finding for soft, shallow alluvial valleys is a mechanism of coupling of the 1D response and the locally generated surface waves. It is found that the lateral resonances are strongly coupled with the 1D response (Sánchez-Sesma et al., 1993b). The resonant frequencies may be predicted by using an asymptotic semi-classic approach (Rial, 1989).

3. Asymptotic Methods

When the high-frequency behavior is of interest, diffraction can be ignored and optics may be used. Ray theory is based upon the asymptotic behavior of wave solutions in high frequency, so that geometrical methods can be used (e.g., Cerveny, 1985; Lee and Langston, 1983; Sánchez-Sesma et al., 1988b).

The use of Ray methods presents problems associated with its geometrical nature that sometimes give rise to singularities or caustics. To approximately overcome them, a regularized form has been proposed, that uses Gaussian beams. Gaussian beams are solutions of an asymptotic form of wave equation that allows for some lateral variation, and thus, some "artificial" diffraction that smoothes out the discontinuities and eliminates singularities, is introduced (e.g., Nowack and Aki, 1984; Cerveny, 1985; Alvarez et al., 1991). The technique has been used by Yomogida and Aki (1985) to model long-period surface waves, in which the horizontal propagation and smoothing lateral effects were accounted for with Gaussian beams, whereas the vertical variation was considered using the normal modes. This approach assumes smooth variation along the propagation. An extension of these ideas has been proposed by Kato et al. (1993) and applied to model 3D large-scale sedimentary settings.

EXPERIMENTAL METHODS

Records of earthquakes are of great value to understand site effects and the response of structures. Sometimes, the site of interest has already suffered a destructive earthquake, and detailed macroseismic observations are available. However, the rare occurrence of intermediate and strong earthquakes makes the evaluation of site-specific transfer functions for the use in design directly from earthquake records difficult. Engineers and scientists have tried to overcome this lack of strong motion data by recording and analyzing weak motions (from microtremors, microseisms and aftershocks) or effects due to explosions, in order to estimate the site-specific transfer functions experimentally (see, e.g., Kanai, 1983, and Bard, 1999).

Microtemors provide a constant excitation, from which some properties of site response like predominant period, relative amplification, directional resonances, etc. can be characterized. Accounts of the technique and its application to some sites are the works by Dravinski et al. (1991), Morales et al. (1991), Lermo and Chávez-García (1994), Chávez-García et al. (1996), and Trifunac and Todorovska (2000b). Unfortunately, a problem arises because there may not be any similarity of spectra of recorded earthquakes and of measured microtremors at some sites. Udwadia and Trifunac (1973) pointed out that the differences might be attributed to the fact that recorded waves associated to strong and weak motion: (1) are of different types; and (2) have different propagation paths.

The technique proposed by Nakamura (1989) uses the horizontal to vertical (H/V) spectral ratio of weak motion records with very interesting findings. Although there is some discussion on the interpretation of their results (e.g., Lachet and Bard, 1994; Field and Jacob, 1995), Horike et al. (2001) have shown that the microtremor H/V ratios are either in agreement with or a little smaller than the earthquake ratios, and that sharp peaks in the microtremor H/V ratios can be chosen as the resonance frequency of a site, when the value of the peak is large (at least 4 to 5).

Aftershocks frequently occur following destructive earthquakes, and can provide valuable information on the reoccurrence of site effects (Trifunac and Todorovska, 2000a). Amplification of ground motion due to geological and soil conditions may be extrapolated by means of linear methods. However, recent analysis by Trifunac et al. (1999) with data from aftershocks of the Northridge earthquake concluded that, although the characteristics of site-specific amplification functions can be measured by analyzing aftershocks or small earthquake records, the success rate of predicting the prominent peaks during future earthquakes is less than 50%, and that the successful predictions are limited to small amplitude motions only.

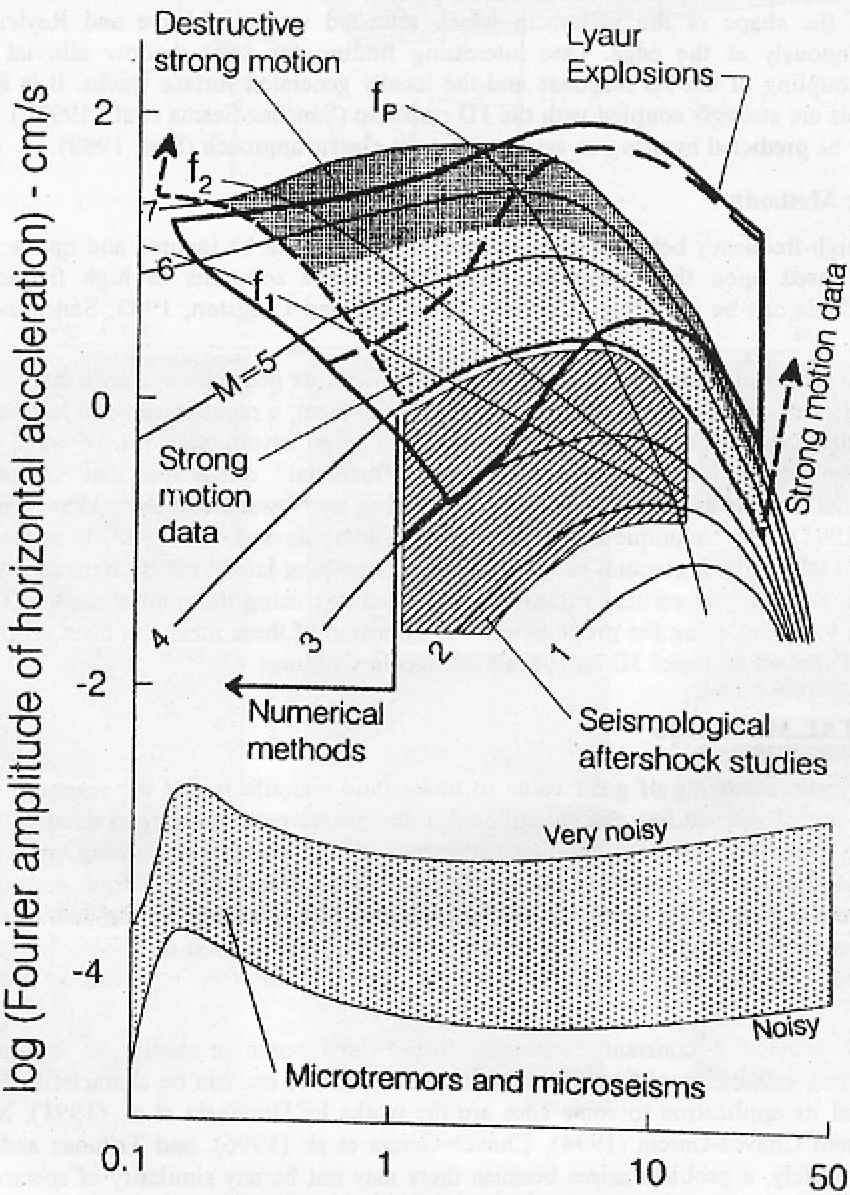


Fig. 10 Comparison of Fourier spectrum amplitudes of strong and weak motions; for the recorded strong motion, epicentral distance $R = 10$ km, focal depth $H = 5$ km and 0.5 probability of exceedance was taken for geological and soil "rock" sites; 10 calibration explosions at the Lyaur testing range were used (after Negmatullaev et al., 1999)

Recordings from distant nuclear explosions have been used to study local amplification of incident waves (e.g., Rogers et al., 1984). However, explosions have more rapid energy release than earthquakes and higher stress changes in a smaller source region. In a recent work, Negmatullaev et al. (1999) compared strong motion data of controlled explosions, detonated in arrays, with those of strong earthquake shaking and other published explosion data. They compared the Fourier amplitude spectra with estimates by recent empirical scaling laws for strong ground motion, in the near-field of earthquakes, and suggested that such explosions can offer powerful possibilities for testing of almost full-scale structures. This is shown in Figure 10 where the upper gray shaded area stands for the amplitude spectra of recorded strong ground acceleration from both, destructive and non-destructive earthquakes, the area enclosed by a heavy line is for spectra from calibration explosions, spectra of typical seismological aftershock studies are in the hatched region, and spectra of microtremor and microseism noise are in the lower gray zone. The continuous lines labeled 1-7 show smoothed Fourier spectra of ground acceleration based on empirical scaling laws; f_1 and f_2 are corner frequencies (Trifunac, 1993), and f_p is the magnitude-dependent frequency of the spectral maximum.

A class of studies that begins to widen the scope in the study of near-surface propagation of seismic waves, including their amplification, attenuation and scattering, relies on data gathered from deep borehole seismometer arrays. Abercrombie (1995a, 1995b) has compared records and spectra up and downhole for several local events, thus showing that almost a half of the amplitude attenuation for those earthquakes occurs around the upper 300 m.

HYBRID METHODS

The so-called "hybrid" methods use the combinations of different techniques or the adaptation of approaches originally devised to study other problems.

A good example of this kind of methods is the successful combination of normal modes and finite differences (Fäh et al., 1993a, 1993b). In this approach, realistic sources can be assumed, and the waves they produce, are propagated to the site using normal mode theory. Then, the solution obtained at this step is used as the input for another method, finite differences in this case. An interesting example was computed with the IBEM by Luzón et al. (1995). They used as input data a seismogram at the surface, but outside an alluvial valley computed by Fäh (1992). The combination of finite and boundary elements has been used for wave propagation studies by Beskos and Spyrakos (1984), Kobayashi et al. (1986), Mossessian and Dravinski (1987), and Bielak et al. (1991).

In the framework of the source method (an IBEM with least squares), Benites and Aki (1989) computed the Green's functions by using expansions in terms of Gaussian beams. This approach allowed them to study some heterogeneous media. A similar but more complex idea is the combination of surface waves with BEM, as it has been proposed by Hisada et al. (1993) to model 3D alluvial valleys. In this approach, the Green's functions are computed using normal mode theory for long distances and the discrete wave number near the source points. A much-simplified approach was proposed by Rodríguez-Zúñiga et al. (1995). They neglected the interaction of the three-dimensional basin with the sediments, assuming that the motion is given at the basin interface. In some cases, simplifying assumptions are in order, and fast procedures can be devised. Such is the case for triangularly-shaped alluvial valleys (Paolucci et al., 1992), in which the geometry allows for explicit computation of Green's functions for a related configuration.

A promising technique that combines Ricatti method and IBEM, is currently being developed by Haines and Benites (personal communication) after the proposal of Haines (1989). In this approach, the geologically complex medium is assumed to be embedded into a bedrock half-space, upon the incidence of seismic waves. The wave equation in the complex medium is expressed in terms of generalized curvilinear coordinates, choosing one of them as the preferred propagation direction, in analogy to the Cartesian coordinate z (or r) in the reflectivity method (Kennett, 1983; see also Aki and Richards, 1980). In the other reference direction, the wavefield is expanded into basis functions, commonly Fourier components. This form of the wave equation yields non-linear differential equations of the Ricatti type (Haines, 1989), relating traction and displacement fields for each wavenumber, coupled at every point along the propagation coordinate. The wavefield scattered outside the complex medium, into the bedrock, is represented by a boundary integral scheme with artificial wave point source distribution along the boundary separating inner and outer media (e.g., Sánchez-Sesma and Esquivel, 1979). The weights of wave contribution of each wavenumber and the strength of each point source are found by matching boundary conditions in the least-squares sense.

CONCLUDING REMARKS

This rapid passage over some common methodologies to estimate local site effects on strong ground motion excludes many relevant techniques. The coverage is far from exhaustive. By example, an obvious absence is the effect of non-linear behavior of soils, including liquefaction.

Various analytical solutions and methods developed to study site effects were described. The interested reader may find in this short review a guide to pursue independent study.

Finite differences and finite elements methods are well-established techniques which can be used if the geometry and mechanical properties are well known and represented. Absorbing boundary conditions may be sufficient to reduce the models to a reasonable size.

Boundary element methods seem to be powerful tools for simulating wave propagation in homogeneous media with lateral irregularities. If detailed data of media properties are not available, reasonable estimates of ground motion can be obtained with BEM using simplified models. Indirect BEM is being applied to 2D and 3D configurations.

The various techniques have advantages and limitations, and the desired precision and availability of data should dictate the choice of method for a given problem.

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