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HYBRID METHODS FOR SIMULATING SITE EFFECTS

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ABSTRACT

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 propagation path and the site response is needed. This can be accomplished with hybrid techniques which combine "analytical methods" such as modal summation, the reflectivity method, or the discrete wavenumber method with "numerical techniques" such as the finite difference method or the finite element method. An overview of the advantages of hybrid techniques is given, and the importance of the treatment of a realistic incident wavefield is discussed. Some examples for Mexico City show that synthetic signals obtained with hybrid techniques can explain the major characteristics (relative amplitudes, spectral amplification, frequency content, duration, waveforms) of observed ground motion.

KEYWORDS

hybrid methods; wave-propagation modelling; seismic strong ground motion; seismic micro-zonation; site effects.

INTRODUCTION

Some of the promising methods for the estimation of shaking potential involve strong-motion simulations. Strong-motion simulations can provide synthetic signals for areas where recordings are absent, and can thus give estimates of the dependence of strong ground motion on different parameters: the characteristics of the seismic source, the path, and local soil conditions. Time histories can be generated whose wave composition, duration, and frequency content reflect these characteristics. These computational methods have one important advantage over instrumental methods: there is no need to wait for an earthquake to obtain the recordings. In many seismic zones, strong earthquakes occur rarely, or the recorded events do not have sufficient magnitude to allow estimates of expected, strong ground motion. There are mainly weak motion records available, which in their frequency content can scarcely represent a strong event. An additional problem is the density of instruments in a strong motion array; only a few cities have sufficiently dense networks that cover most types of local soil conditions. All computational methods that are proposed in the literature for calculating site effects, can be used to estimate shaking potential. However, it is necessary to justify the validity of the selected method, relative to whether the structure of the site under consideration falls within the domain of the method. Far away from lateral heterogeneities such as edges of sedimentary basins or irregular subsurface topography, a local structure can be approximated by a horizontally-layered structural model. This allows the application of techniques such as for example the reflectivity method (Fuchs, 1968; Fuchs and Müller, 1971), the discrete wavenumber method (Bouchon, 1981), or the mode summation method (Thomson, 1950; Haskell, 1953, 1960, 1962; Knopoff, 1964; Panza, 1985). One-dimensional techniques are widely used for zonation studies since they are computationally cheap and can give an estimate of ground motion for layered structural models. An example is the computer program SHAKE (Schnabel *et al.*, 1972). They fail, however, to predict ground motion at sites close to lateral heterogeneities such as edges of sedimentary basins, where focusing of waves, excitation of local surface waves, and two-, or three-dimensional resonance effects can become important. This requires more general techniques--those which can handle the more complex lateral heterogeneities. On a routine basis, most of these last techniques have thus far only been applied to two-dimensional structural models because of the computer-resource requirements of the three-dimensional case.

Techniques that are not limited to one-dimensional structural are for example the Rayleigh-Ansatz method (Aki and Larner, 1970; Bouchon, 1973; Bard and Bouchon, 1980a; 1980b) which is also known as the Aki-Larner technique, the boundary integral equation methods (e.g. Wong and Jennings, 1975; Sánchez-Sesma and Esquivel, 1979; Bouchon 1985), 2D modal summation (Levshin, 1985; Vaccari *et al.*, 1989), the boundary element method and the discrete-wavenumber boundary-element method (e.g. Kawase, 1988). Such techniques have been widely used to study wave propagation in sedimentary basins (e.g. Bard and Bouchon, 1980a, 1980b, 1985; Bard and Gariel, 1986). Many of these methods can be used for zonation studies, but they are generally restricted to simple geometries of the sedimentary basin.

Computational techniques that are based on an approximate mathematical method for solving the formal representation of the problem are the finite difference method (Alterman and Karal, 1968; Boore, 1970), the pseudo-spectral method (Gazdag, 1981; Kosloff and Baysal, 1982), and the finite element method (Lysmer and Drake, 1972). These approaches are very powerful in terms of flexibility of modelling: they allow treatment of wave propagation in very complex structures. Their limitations are the computer CPU time and memory that they require. Computer memory limitations necessitate the introduction of artificial boundaries, which restrict spatial extent of the structural model. This is one of the most severe problems with these methods. Further, and again due to computer memory limitations, often the source cannot be included in the structural model. This occurs when the epicenter is too far from the site of interest. In such cases, the incoming wavefield is often approximated by a plane polarized body-wave.

The computation of synthetic seismograms for media with localized heterogeneous areas can be performed best using hybrid techniques which combine "analytical methods" such as modal summation, the reflectivity method, or the discrete wavenumber method with "numerical techniques" such as the finite difference method or the finite element method. Such hybrid methods have been developed, for example by Shtivelman (1984; 1985), Vidale (1987), Van den Berg (1984), Kummer *et al.* (1987), Suetsugu (1989), Emmerich (1989), Regan and Harkrider (1989), Fäh *et al.* (1993a, 1994), and Zahradnik and Moczo (1995). In a hybrid approach (see Fig. 1), only a small part of the medium under study is laterally heterogeneous, and therefore, the finite difference and finite element methods alone are very inefficient due to their need for large CPU time and computer memory. In hybrid computational schemes the finite difference method or finite element method is applied only in the laterally heterogeneous part of the medium, whereas the laterally homogeneous part is treated with methods such as modal summation, the reflectivity method, the discrete-wavenumber method, or ray methods. Therefore, such computations are very efficient.

For the estimation of ground motion at a specific site, the two techniques are applied in that part of the structural model where they work most efficiently: the "numerical method" in the laterally heterogeneous part of the structural model, and the "analytical method" is applied to simulate wave propagation from source position close to the site of interest. The advantage of hybrid techniques is the fact that they allow to take into consideration source, path, and local soil effects. This allows us to calculate the local wavefield from a seismic event, both for small (a few kilometers) and large (a few hundreds of kilometers) epicentral distances.

The path from source position to the lateral heterogeneity can often be approximated by a structure composed of a sequence of flat, homogeneous layers. This allows the simulation of a realistic incident wavefield. The numerical methods permit the modelling of complicated and rapidly varying velocity structures in the final part of the propagation path. Such strong lateral heterogeneity is a characteristic of sedimentary basins, which in general consist of very complicated subsurface topography and velocity distribution.

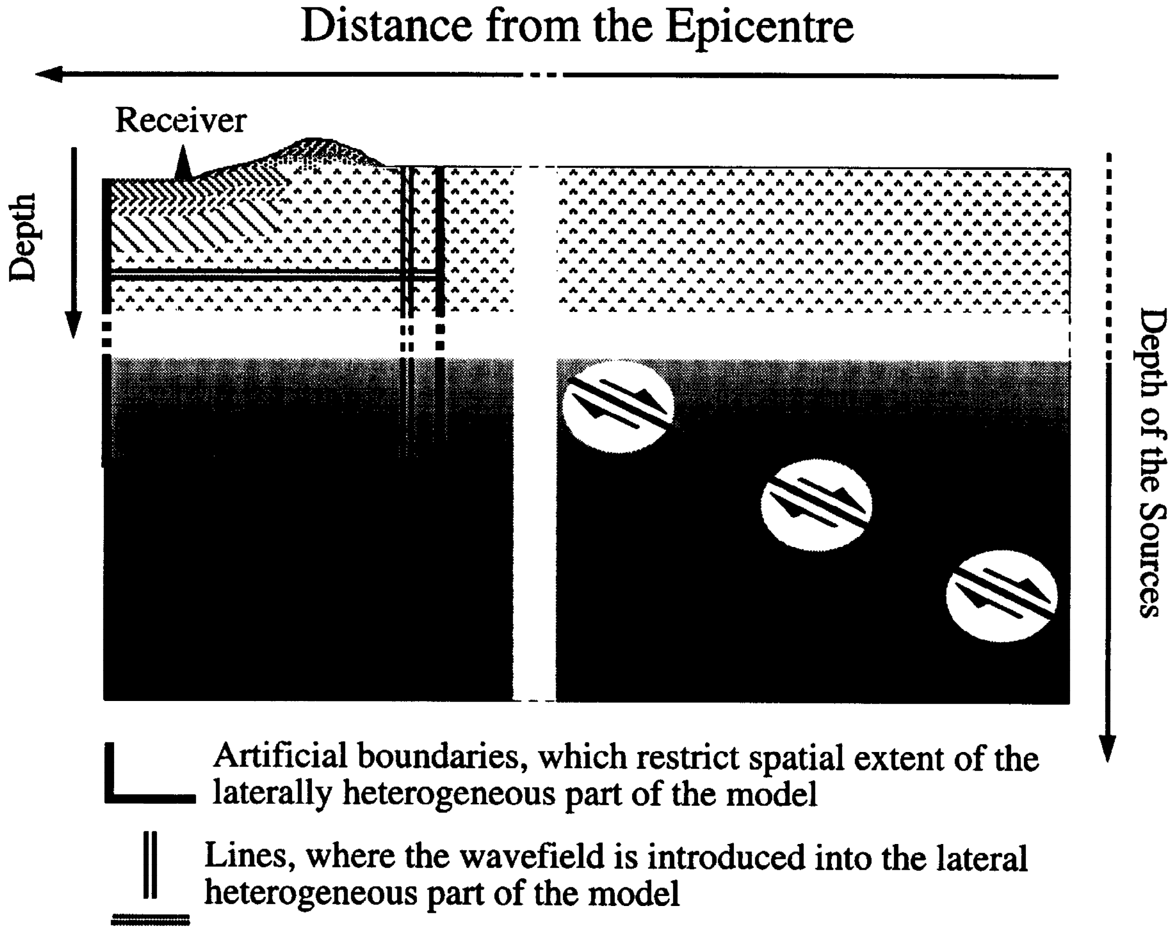

Fig. 1. Possible geometry used for the numerical modelling of ground motion with hybrid techniques. In the right part of the figure the spatial representation of an extended source is schematized.

THE IMPORTANCE OF A REALISTIC INCIDENT WAVEFIELD

Hybrid techniques can treat source, path and local soil effects. At the site of interest, this allows the simulation of a realistic incident wavefield. Fäh and Suhadolc (1994) have studied the strong-ground-motion response along a profile located within the city of Benevento (Italy) due to different incident wavefields. They compared the results obtained with one- and two-dimensional structural models for vertical incidence of plane polarized body waves. These results have then been compared with those obtained with a hybrid approach applied to two-dimensional structural models. An example is given in Fig. 2. There are important differences in the response obtained with the hybrid approach with respect to the response obtained with vertical incidence of plane polarized body-waves for one- and two-dimensional structural models. For the same site, these differences consist in strong variations in amplitudes and in shape of the spectral amplification. The comparison between the different techniques indicates that for a seismic source which is not located beneath the site of interest, vertical incidence of waves significantly overestimates the local hazard in a laterally homogeneous structure. The differences are due to the different incidence angles of a realistic wavefield.

For a laterally heterogeneous area, one-dimensional modelling fails to correctly 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 does not allow to correctly estimate the frequency bands at which amplification occur. Therefore, different input ground motion (hybrid technique with respect to vertical incidence of plane polarized body waves) leads to significant differences in the zonation results. For areas where only poor information of the crustal structure exists, Luzón *et al.* (1995) proposed a method to estimate a realistic incident wavefield from an observed strong motion record. This estimate can be obtained with a polarization analysis of the observed ground motion.

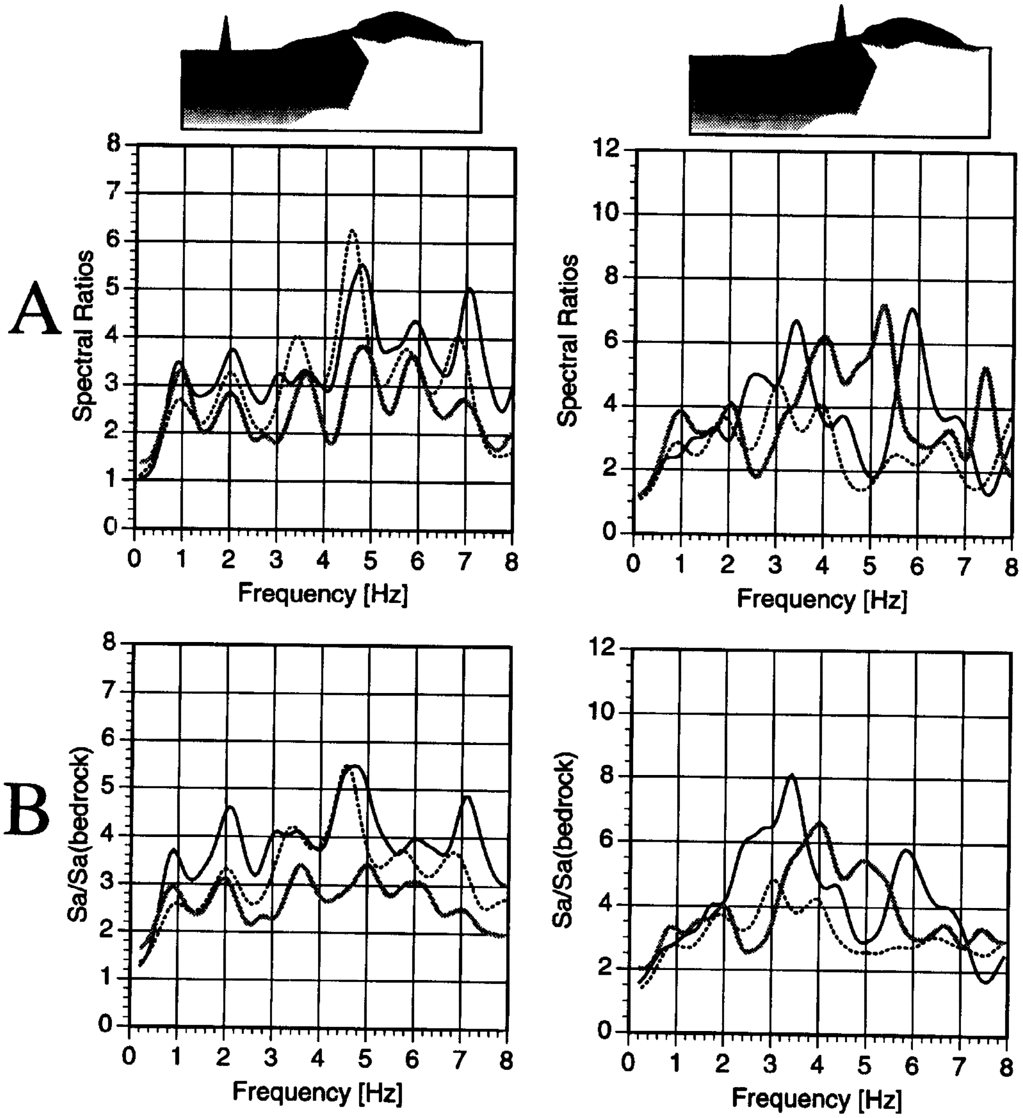

Fig. 2. A) Smoothed spectral ratios and B) smoothed relative spectral amplification (0% damping) obtained for two different receiver positions, one in a laterally homogeneous part of the structure (left part of the figure) and the other at the slope of the hill zone, in a laterally heterogeneous part of the structure (right part of the figure). The thick gray solid line is the result obtained with the hybrid technique, including the source, path and local site effects. The black solid line is the result for vertical incidence of plane polarized body-waves in the two-dimensional structure, and the dashed line for the vertical incidence of plane polarized body-waves in the one-dimensional local model which is representative for the structure at the receiver (modified from Fäh and Suhadolc (1994)).

COMPARISON BETWEEN NUMERICAL RESULTS AND OBSERVATIONS

Numerical simulation should always be compared with observed ground motion to establish validity of the numerical results. Fäh *et al.* (1993a, 1994) have given examples in which strong ground motion records can be explained by means of numerical simulations. The synthetic signals explain the major characteristics (relative amplitudes, spectral amplification, frequency content, duration) of the considered seismograms, and also the space distribution of the available macroseismic data (Fäh *et al.*, 1993b), even when quite simple source models are used. The theoretical computations show that waveforms and frequency content of seismograms are sensitive to small changes in the subsurface topography of the sedimentary basin, the velocity and quality factor of the sediments. The absence of dynamic irregularities in the rupture process in the simulations, in general, causes an underestimate of the absolute acceleration (Fäh and Panza, 1994). Despite these difficulties, observed waveforms can be quite well reproduced with synthetic signals. A comparison between seismograms recorded during the 1985 Michoacan earthquake in Mexico City and synthetics obtained with a hybrid method are shown in Fig. 3 (from Fäh and Panza, 1994). The computed radial component of motion (in Fig. 3B) is very similar to the observed horizontal ground motion (Fig. 3A). The underestimate in amplitude of the synthetic signals, and the remaining difference between synthetics and observations, is due to the simple source model in the modelling, the absence of dynamic irregularities in the rupture process, and the fact that only one two-dimensional cross-section of the sedimentary basin is considered.

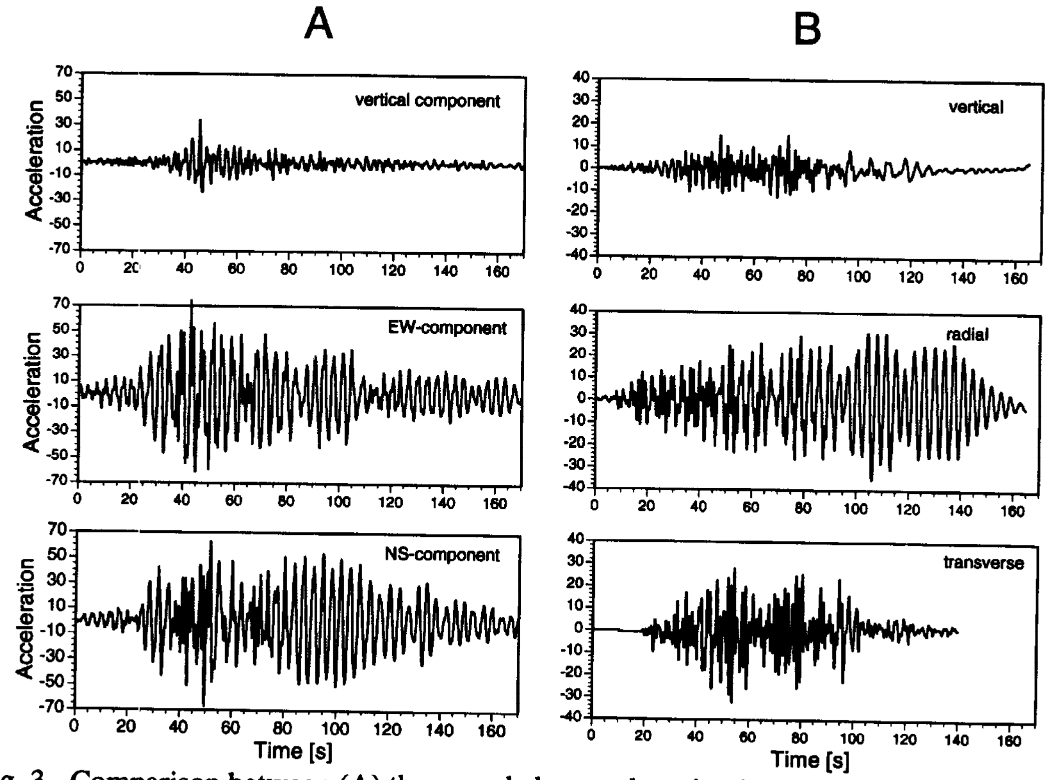

Fig. 3. Comparison between (A) the recorded ground motion in Mexico City at station CDAO for the 1985 Michoacan earthquake and (B) synthetic signals obtained for a receiver in a two-dimensional structural model representative for Mexico City (from Fäh and Panza, 1994). All signals are low-pass filtered with a 5-pole butterworth filter having its corner frequency at 1 Hz. The acceleration is given in units of cm s^{-2}. A) Observed horizontal and vertical components of acceleration at station CDAO. Both horizontal components of motion are characterized by SH-waves as well as P-SV waves. B) Synthetic acceleration due to three point sources, all located at a depth of 10 km and the same distance. The three point sources have different weights and time shifts (1.0, 1.0, 0.2 and 0 s, 26 s, 47 s) as it was proposed by Houston and Kanamori (1986) for the Michoacan earthquake. The synthetic signals are scaled assuming the seismic moment rate spectrum proposed by Singh *et al.* (1990).

Spectral amplification at the site of interest computed with respect to a reference site on bedrock gives a good representation for micro-zoning purpose, especially from the engineering point of view. An example of the theoretical spectral amplification based on numerical simulations with a hybrid technique, appropriate for a site similar to the one of station CDAO in Mexico City, is shown in Fig. 4a and 4c (from Fäh and Panza, 1994). The theoretical spectral amplification is very similar to the observations made at the station CDAO in connection with the April 25, 1989 earthquake (Fig. 4b, 4d). The two peaks in the spectral amplification can be attributed to the deep sediments (peak at about 0.8 Hz) and the surficial clay layer (peak at about 0.25 Hz) (Fäh *et al.*, 1994).

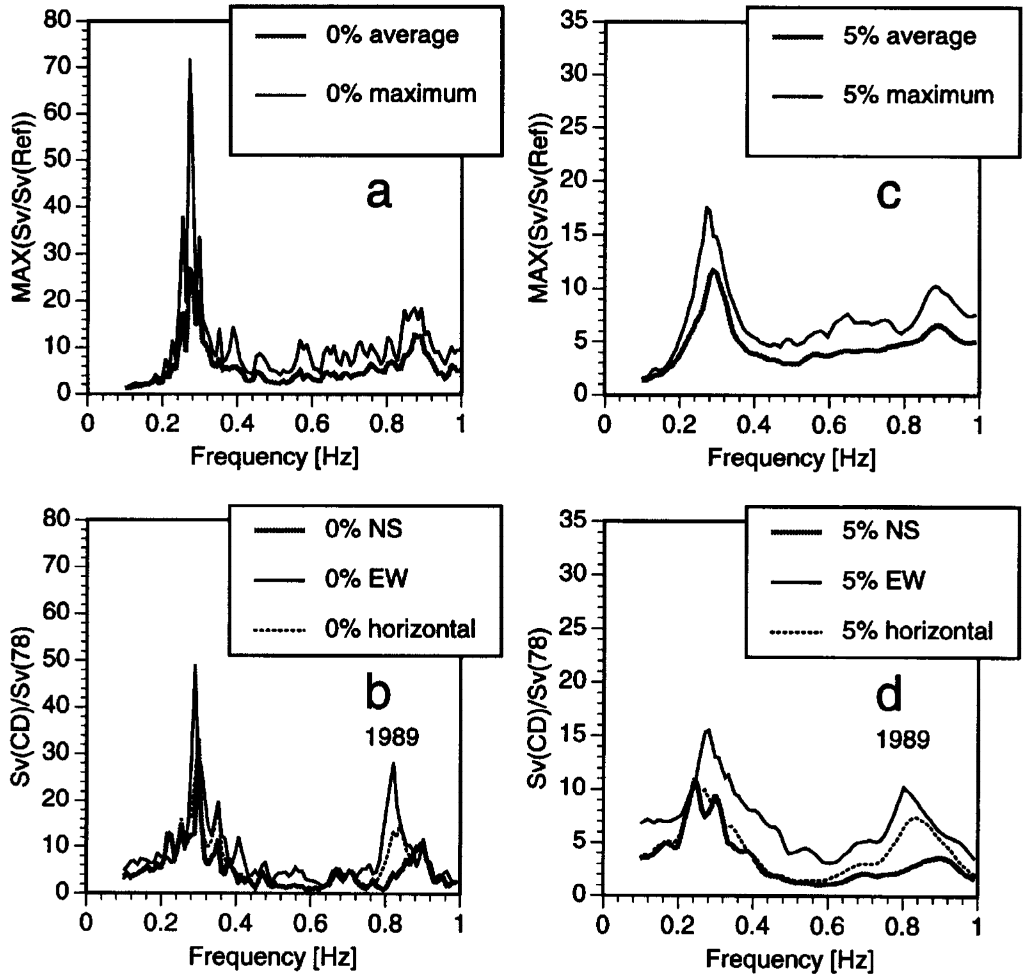

Fig. 4. Average and maximum relative spectral velocities for zero damping (a), and 5% damping (c), computed with synthetic signals obtained for receivers in a two-dimensional structural model representative for station CDAO (CD) located in Mexico City. They are compared with the observed relative spectral velocities Sv(CD)/Sv(78) for the 1989 earthquake, for zero damping (b), and 5% damping (d), determined from the station CDAO using station 78 on bedrock as reference (modified from Fäh and Panza, 1994).

CONCLUSIONS

In the future, it will be possible to study large-scale 3D problems with numerical simulations. This will resolve technical problems such as inconsistencies between 3D source radiation and 2D numerical simulations (Zahradnik and Moczo, 1995), and problems to correctly model geometrical spreading in two-dimensional numerical simulations. Possible applications of hybrid methods in earthquake seismology and engineering are wherever source, path and local soil effects have to be treated together. Hybrid techniques make it possible to study local effects even at large distances (hundreds of kilometers) from the source, to include the seismic source, and the entire propagation path. Such techniques can assist in the interpretation and prediction of ground motion at a given site. They can be applied in (micro-)zonation studies, and provide realistic estimates of ground motion for complex structural models, as long as the structure at the site of interest is reasonably well known.

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