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INFLUENCE OF WAVE AZIMUTH ON SITE EFFECTS

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ABSTRACT: Three-dimensional diffraction (3D) by two-dimensional (2D) surface structures are studied using the Indirect Boundary Element Method. Case studies of surface topographies and alluvial valleys are used separately to determine the influence of the direction of the incident waves on site effects.

The level of amplification and the time duration of seismic signals are shown to be not very different for 2D and 3D response of 2D structures, but the local amplification is highly dependent on the propagation direction of the incident waves. It is therefore not possible to predict the 3D response of the structure from the 2D one.

The amplification on a surface topography is shown to be typically a factor of between two and three, though observed *relative* amplifications between the top and the base of the topography can be significantly higher. High relative amplifications can therefore, at least in some cases, be attributed to de-amplifications at the reference station, rather than to high amplifications at the top of the topography.

It is finally observed that amplifications in real data are less azimuth dependent than the corresponding simulated ones, probably because the numerical simulations do not take into account the complexity of incoming seismic waves which arises from scattering and multi-pathing in the crust.

KEYWORDS: Site effects, 2.5D simulations, IBEM, alluvial valleys, surface topography, azimuth effects, surface waves.

1 INTRODUCTION

A great effort is at present invested into the development of methods for simulation of 3D site effects (e.g. Olsen *et al.*, 1995; Sánchez-Sesma and Luzón, 1995). The number of full 3D solutions remain few and not easily usable for interpretation of data, mainly due to limitations in computer memory and speed.

A particular 3D diffraction problem is the one where the structure is of 2D geometry. In practice, a structure which is significantly longer than wide (for example a very elongated alluvial valley) can locally be considered to be of 2D geometry because the local geometry plays the main role in the wave diffraction. Simple 2D simulations are not adequate to calculate the ground displacement across such structures because the incident waves are 3D in nature, e.g. can be incident upon the structure outside the 2D plane. When the waves are incident upon the structure outside the 2D plane, the wave diffraction is 3D with coupling of all wave-types. Such diffraction problems are often attributed the term "2.5D diffraction", which is partly misleading because the wave diffraction is 3D. However, we have adopted this abbreviation in places where the full expression would significantly complicate the text.

The calculation of 3D diffraction of plane waves by 2D structures is simpler than the calculation of diffraction by structures of 3D geometry, because the 2D structure can be represented by points solely in the 2D plane. Several solutions have been proposed (e.g. Khair et al., 1989; 1991; Pei et Papageorgiou, 1993). These methods have nevertheless been used mostly on purely theoretical problems. We here present results of another method, the Indirect Boundary Element Method (IBEM), which we extend to the case of 3D diffraction by 2D structures (which we denote as IBEM2.5D). The method is very precise and it is efficient in terms of computer-time. It is therefore possible to use it to systematically study the influence of different model parameters and to model data, for which a high number of simulations are necessary.

In this paper we present selected results obtained using IBEM2.5D for two types of sites, namely surface topographies and alluvial valleys. We focus on the following questions:

- How are site amplification and signal duration influenced by the arrival angle of the incident waves?
- Can high amplifications due to surface topographies be explained by the effect of a 3D wavefield?
- How do observed amplifications compare with theoretically predicted ones?

The organization of the paper is the following. We present the simulation method followed by the results of the numerical simulation and a discussion of how they compare to observed data. The presentation of the simulation results is split into two parts addressing the surface topographies and alluvial valleys.

2 IBEM

The theory and detailed discussion of the Indirect Boundary Element Method (IBEM) is presented by several authors, for example Sánchez-Sesma & Campillo (1991) and Sánchez-Sesma & Luzón (1995), so we here only discuss the main points that are necessary to evaluate the quality of the results presented in the following sections.

The Indirect Boundary Element Method (IBEM) is based on the representation theorem (Aki and Richards, 1980). The seismic waves (i.e. the displacement and the traction) at any location in a specific earth model are represented as the waves emitted by a fictive distribution of volume and surface forces in the model. In the case where the model is piecewise homogeneous, the seismic wavefield can be represented by a distribution of surface forces on the model interfaces.

We are interested in the total wavefield due to body waves and surface waves incident upon a laterally heterogeneous structure. The incident waves will induce discontinuities in displacement and traction across the interfaces of the structure. According to the wave equation, the displacements and tractions must be continuous across all interfaces, so the discontinuities due to the incident waves will be compensated for by diffracted waves. These diffracted waves are represented as the radiation from surface forces on the interfaces. IBEM is therefore a two-step method. The first step is to find the (unique) surface force distribution that yields a total wave field (incident plus diffracted waves) which satisfies all boundary conditions. The second step is to calculate the displacements at the surface, using this force distribution. All calculations are carried out in the frequency domain, so synthetic seismograms are obtained by multiplication with a source function followed by an inverse Fourier transform.

IBEM has the advantage that no approximations are applied in the theoretical development. The method has therefore in principle no limitations to a particular domain of wavelengths. This is particularly important in the case of site effects because here the wavelengths are comparable to the size of the structure, so neither low-frequency nor high-frequency approximations apply. IBEM also makes it possible to consider high changes in elastic parameters across interfaces. The contrasts in elastic parameters between for example an alluvial valley and the underlying bedrock can therefore be taken into account.

We use a version of IBEM adapted for simulating 3D diffraction of plane seismic waves by 2D structures. The 3D diffraction can be taken into account by the use of Green's functions that are adapted to this particular problem (Pedersen *et al.*, 1994a). The structure is infinitely long in the direction of the y-axis, with the x-axis perpendicular to the structure, and the z-axis vertical. The incident (plane) wave is characterised by its azimuth and incidence angles, where the azimuth is defined as the angle between the the x-axis and the propagation direction, and the incidence angle is defined as the angle between the propagation direction and the z-axis.

We have adapted this particular version of IBEM to study wave diffraction by surface topographies and by simple alluvial valleys (Pedersen *et al.*, 1994a, 1994b, 1995). The valleys do not have any internal layering, but they can be of any shape and include surface topography. We have used the two applications for theoretical studies of the influence of azimuth on site effects and to compare observed surface amplifications with the simulation methods. The results are presented in the following section.

3 RESULTS

3.1 Surface Topographies

Wave amplifications on surface topographies (hills and mountains) are reported to be very high in some cases. This is in disagreement with predictions made with numerical simulations. Numerical 2D simulations predict only modest amplifications (typically between one and three, depending on the shape of the topography) in a rather large frequency band for which the wavelengths are comparable to the size of the topography. We have therefore investigated whether obliquely incident waves induce higher amplifications than waves incident on the topography in the 2D plane, as a possible cause for the apparent discrepancy between observations and numerical simulations.

We present here the results of numerical simulations and the corresponding data for wave amplification and diffraction across the Mt. St. Eynard in the French Alps. The geometry and geological structure of the mountain is shown in Fig. 1. Hardrock outcrops on the north-western slope of the mountain, and a several hundred meter high cliff is present on the south-eastern side. Mt. St. Eynard is well suited for studying azimuth dependent site effects, because it is much longer than wide (and therefore approximately of 2D geometry), and hardly any loose sediments are present at the surface.

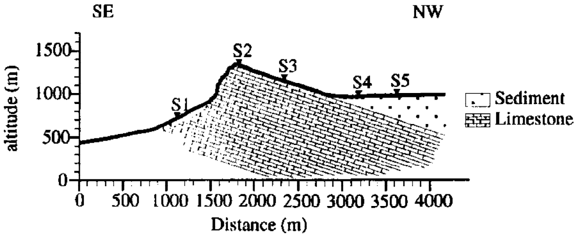

Fig. 1. Simplified geological cross-section of Mt. St. Eynard. Seismological stations are indicated by triangles.

Simulations of plane P waves incident upon this mountain for two different azimuths are shown in Figs. 2 and 3. The incidence angle is 25°. In Fig. 2, the azimuth is 0°, i.e. the waves are incident perpendicularly on the mountain. In Fig. 3, the azimuth is 90°. The simulations are carried out in a frequency interval between 0 and 12 Hz, and the synthetic seismograms are obtained using a Ricker wavelet with central frequency of 2.5 Hz. The simulation for the 90° azimuth confirms that 3D diffraction phenomena are significant. The incident waves have wave motion only in the y-z plane, but the scattered waves are of comparable amplitude on all components. The diffraction pattern is very similar in Figs. 2 and 3: the incident waves are amplified by a factor of two to three at the top of the mountain, and creeping waves are emitted from a region near the top. These creeping waves are very stable and they are of significant amplitude even far from the mountain. Though the diffraction mechanisms seem to be the same in the two cases, it is not possible to simply predict the 3D response from the 2D one. The general level of amplification

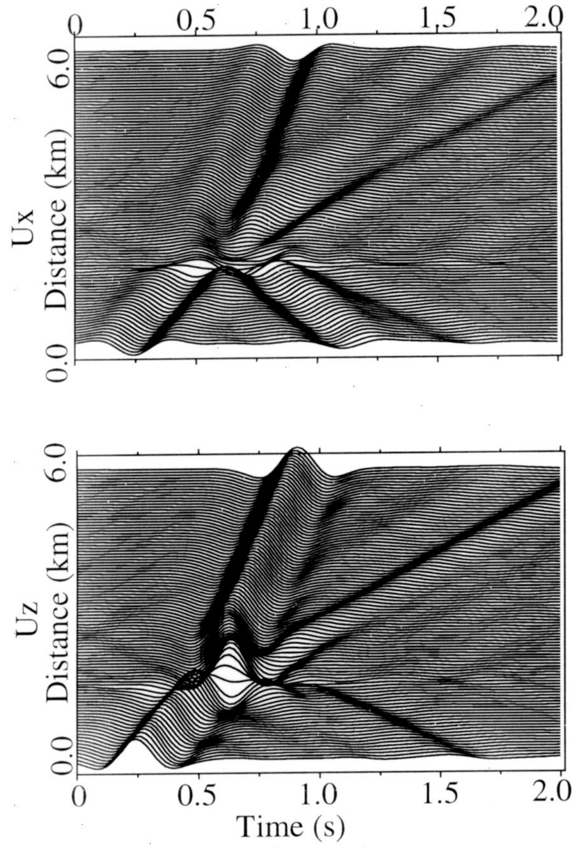

Fig. 2. Synthetic seismograms across Mt. St. Eynard for an incident P wave with azimuth 0° and incidence 40°.

and the duration of the signal are similar for the two azimuths.

Analysis of the spectra at different locations also shows that significant de-amplification takes place in some frequency intervals, especially at the base of the mountain. Consequently, amplifications measured using a reference station located at the base of the mountain can be strongly biased because the seismic waves at the reference station are de-amplified in some frequency intervals.

Field work was carried out across Mt. St. Eynard to investigate whether observed amplifications could be modelled by numerical simulations as the ones presented above. Five three-component seismographs were installed across the mountain at the locations indicated in Fig. 1. Stations two and three were located on hard-rock, while stations one, four, and five were located on thin sedimentary cover of poorly consolidated sediments.

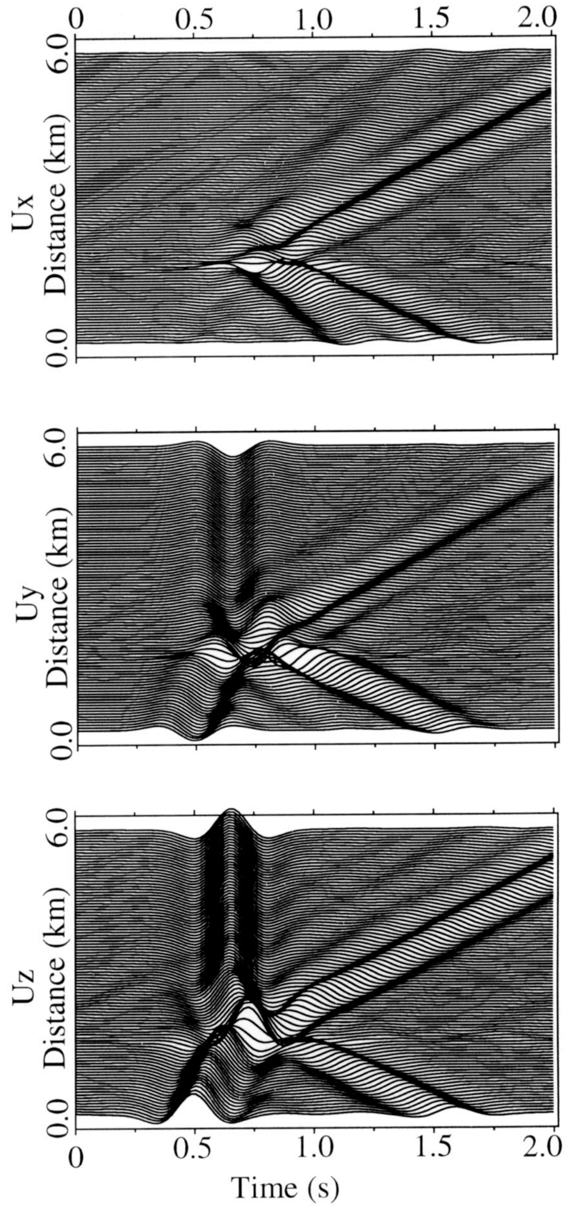

Fig. 3. Synthetic seismograms across Mt. St. Eynard for an incident P wave with azimuth 90° and incidence 40°.

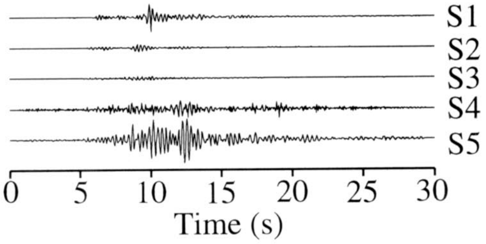

Fig. 4. Observed vertical motion for a regional event.

For all observed events, the thin sedimentary cover caused much higher amplifications than the surface topography. This is illustrated in Fig. 4, where raw data are shown for a regional seismic event. The amplitude at station two (on the mountain top) is approximately two to three times that at station three (located on the slope of the mountain). This is well within the range predicted by the numerical simulations.

In fact, the numerical simulations show an even higher spectral ratio (station2/station3) than the observed data, because de-amplification effects seem to be more significant in numerical simulations than in data. This discrepancy can be explained by considering the incident wavefield. The numerical simulations consider a single polarised incident wave. The diffracted waves interfere destructively in some frequency intervals at some locations inducing locally an almost complete extinction of surface motion at particular frequencies. The observed incident waves are in reality much more complex, mostly due to the diffraction in the crust, so the incident waves cover a whole range of azimuths, incidence angles and wave types. Complete extinction of the wavefield at any location due to destructive interference is therefore much less likely to occur. This also explains another general trend in observed data; the azimuth dependence on relative amplification between stations two and three is smaller in reality than predicted by the numerical simulations, even though it seems to have some systematic influence for the regional events. Unfortunately, no definite conclusion can be drawn on the azimuth dependence on amplification in the observed data because the data-set is too small to calculate reliable averages for most intervals of azimuths.

3.2 Alluvial Valleys.

Amplification in alluvial basins is now recognised as mainly due to the superposition of 1D resonance effects combined with lateral resonance effects due to the generation of surface waves near the edges of the basin. The propagating surface waves also significantly increase the duration of the motion, because they propagate slowly and they can bounce back and forth in the basin due to reflection at the edges. The amplification pattern is very complex due to the interference of these different waves.

Amplification by alluvial basins has been mainly studied for the pure 2D case, even though full 3D solutions are presently being developed (e.g. Sánchez-Sesma and Luzón, 1995; Olsen *et al.*, 1995). For alluvial valleys of approximately 2D geometry, the question is whether obliquely incident waves produce significantly different amplifications and durations than waves incident perpendicularly on the valley.

Figure 5 presents a model of an alluvial valley in the French Alps, the Ubaye valley, for which we present simulation results. The model is simplified compared to the well documented (Jongmans and Campillo, 1993) structure of the Ubaye valley, because internal layering is not taken into account as we focus on the low-frequency part of the data from the valley. The Ubaye valley is interesting for this study, because azimuth effects on wave amplification have been reported (Jongmans and Campillo, 1993).

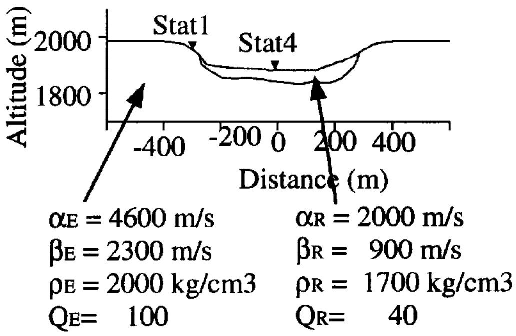

Fig. 5. Model of the Ubaye Valley in the French Alps.

Synthetic seismograms for SV waves incident on the structure with an azimuth of 90° and an incidence angle of 40° are shown in Fig. 6. As in the case of surface topographies, the 3D effects induce diffracted waves on all components of motion. Comparison with SV waves incident on the structure with 0° azimuth shows that the general level of amplification and the duration of motion is the same in the 2D and 2.5D cases. The surface waves that are created on the edges of the valley propagate with the same apparent velocity at the surface in both the 2D and 2.5D cases. In fact, the incident waves are refracted into the valley due to the velocity contrast, so the Green's functions of in-plane and out-of-plane motion are almost de-coupled (Pedersen *et al.*, 1995). The surface waves propagate almost perpendicularly to the structure, but their individual amplitudes

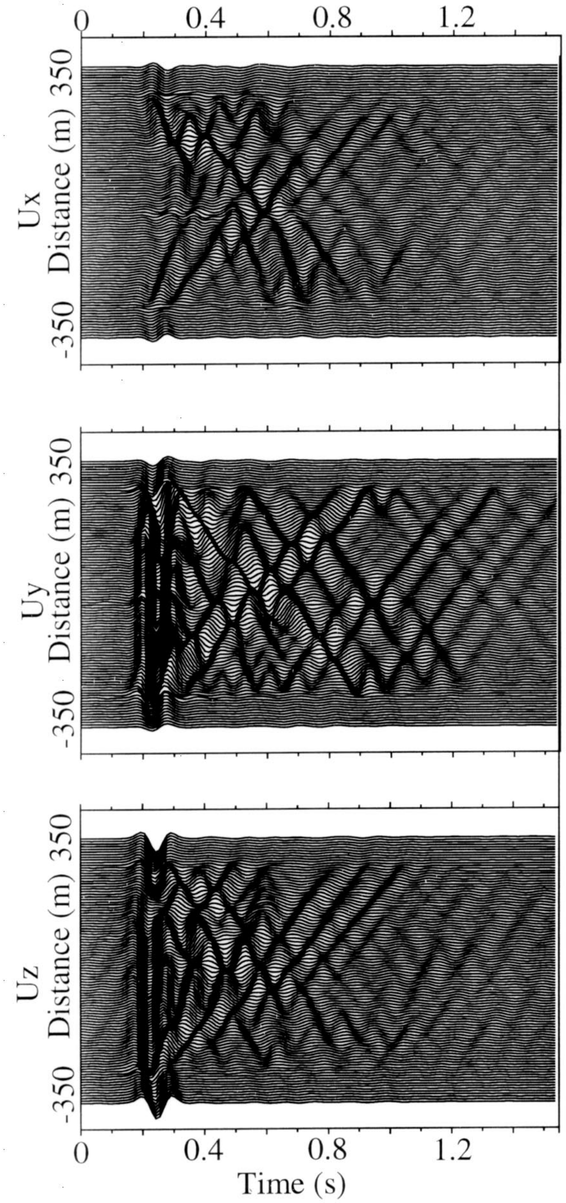

Fig. 6. Synthetic seismograms across the Ubaye Valley for an incident SV wave with 90° azimuth and 40° incidence angle.

are dependent on the incident wave's azimuth and incidence angles. As a consequence, the valley response, i.e. the interference between different seismic waves, is dependent on the azimuth of the incident waves.

The azimuth dependence on the local amplification is illustrated by Fig. 7 which presents the horizontal displacement amplitude (relative to the amplitude of the incoming waves) as a function of location and frequency. The incident waves are of type SV, and they have an incidence angle compared to vertical of 40°. In the absence of the valley, the horizontal amplitude at the surface would be 0.52, and the total amplitude 1.55 times the amplitude of the incident waves. In Fig. 7, the locations of high amplitude are shown as dark areas. Seven different azimuths between 0° and 180° at 30° intervals are considered.

Figure 7 illustrates that the azimuth influences the amplification pattern in the valley. When the SV waves are incident almost perpendicularly on the valley (azimuths 0°, 30°, 150°, and 180°), the locations of high amplitude are distributed in large areas and quite asymmetrically across the valley. Most of the energy is located on the side of the valley from which the waves are incident. When the waves are incident upon the valley close to parallel with the axis of the valley (azimuths 60°, 90°, and 120°), many small areas of high amplitude appear, so the amplification pattern is very complex. Note that the valley studied here is very narrow so a much wider valley of the same general geometry would show the very complex amplification pattern at much lower frequencies. The existence of a complex interference pattern was recognized by Sánchez-Sesma *et al.* (1993), who attributed it to the interference of horizontally propagating surface waves generated at the edges. They also recognized that the emission of surface waves is not located precisely on the edge of the valley, but for each frequency takes place approximately where conditions of 1D resonance are fulfilled. The effective width of the valley is therefore frequency dependent.

For all azimuths, the amplifications start at a frequency of approximately five to seven Hertz. This constant low-frequency response is probably due to the almost uniform valley thickness on the cross-section, so the local 1D response is almost constant. The 1D fundamental resonance frequency can be estimated to approximately five Hertz.

A comparison of observed spectral ratios between a seismic station located in the center of the valley and one on a hardrock site immediately outside the valley (Jongmans and Campillo, 1993; Pedersen *et al.*, 1995) shows that the level of azimuth dependence can be qualitatively explained by simulations. To obtain a reasonable fit to observed data, it is necessary to superpose

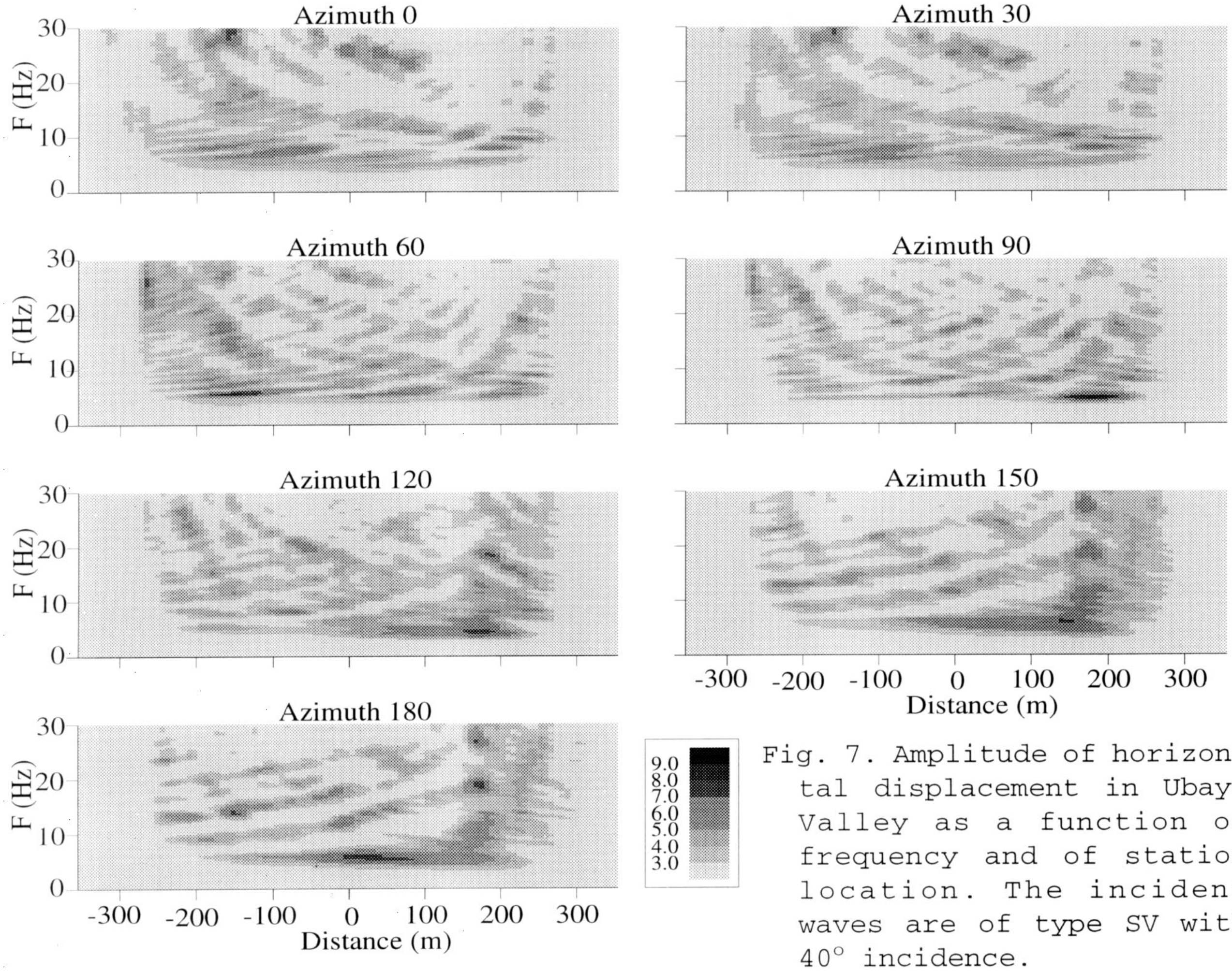

Fig. 7. Amplitude of horizontal displacement in Ubaye Valley as a function of frequency and of station location. The incident waves are of type SV with 40° incidence.

the theoretical SV and SH responses for several incidence angles (keeping the azimuth constant, according the locations of the recorded earthquakes). As in the case of surface topography, single-polarised waves are not adequate to correctly simulate the local amplification.

4 CONCLUSIONS

The Indirect Boundary Element Method extended to the case of 3D diffraction by 2D structures proves to be a useful tool for the understanding of diffraction phenomena across 2D topographies and alluvial valleys. The 3D diffraction is significant when waves are incident upon the structure outside the 2D plane, and coupling of all wave-types takes place.

The average level of amplification and the time duration of the seismic motion on topographies or across alluvial valleys do not seem to be azimuth dependent. However, the level of local amplification is highly azimuth dependent because the local amplification is a consequence of interference between different diffracted waves for which the time of creation and the amplitude depends on the azimuth.

The amplification on a surface topography seems to be relatively modest (typically a factor of two to three) for all azimuths. Off-azimuth effects does therefore not give an explanation for the difference between some observed amplifications and those predicted by theory. Observed amplifications can easily be over-estimated because the "reference station" is highly influenced by the surface topography, and de-amplifications can be significant on the slopes and at the base of a surface topography. The topography itself can not induce very high amplifications, so in cases where very high amplifications occur, other causes such as cracks or surface cover must be invoked.

The main difficulty in interpreting data by numerical simulation methods such as IBEM is the difficulty of taking into account a realistic incident wavefield. This is not linked to the simulation methods, but rather to our poor knowledge of the details in the incident waves (type, azimuth and incidence angles) because different waves arrive simultaneously and have approximately the same frequency content.

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