Bulletin of the Seismological Society of America, 90, 4, pp. 1101–1106, August 2000

On the Horizontal-to-Vertical Spectral Ratio in Sedimentary Basins

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Abstract The horizontal-to-vertical spectral ratio (HVSR) has been used by many researchers to characterize local conditions in terms of the dynamic response of the soil. One of its variants is that proposed by Nakamura (1989) in which records of microtremors are used. Usually, the analysis is aimed to obtain the predominant period of the site under study. In this work we explore what can be achieved by using this method. We study the response of different configurations under incident waves coming from an explosive source using the indirect boundary element method (IBEM). We investigate two cases: low- and high-velocity contrast, holding constant the physical properties inside the basin and changing only the properties of the bedrock. Then, we compute the seismic response using the horizontal sediment-to-bedrock spectral ratio (SBSR) at various locations on the free surface of the basins, and compare it with the one calculated by the HVSR at the same locations. The comparison shows that, in general, the predominant period computed with the HVSR is not the same as that obtained by the SBSR in all the locations. On the other hand, the HVSR approximation can reasonably well predict the fundamental local frequencies when the impedance contrast between the basin and the bedrock is low. However, HVSR cannot be used in sedimentary basins having a high impedance contrast with respect to the bedrock below.

Introduction

As it is well known, the local geological conditions can produce important changes in the ground motion during earthquakes. One way of estimating these local effects is by means of empirical methods that are based on the analysis and treatment of records (see Aki, 1988, for an extensive review). One popular technique is the one presented by Nakamura (1989), which uses microtremors to estimate the amplification for the horizontal motion of the surface layers during earthquakes. This approach has been used by a great number of seismologists and engineers in the last few years with the aim of characterizing the seismic hazard in a small scale and of providing detailed information for seismic microzonation in urban areas. In principle, this procedure has several advantages: only a seismic station with three components is needed, and it is not necessary to wait for the occurrence of an earthquake as microtremors provide the input motion. In some cases, the analysis with the horizontal-to-vertical spectral ratio (HVSR) provides a distribution of predominant periods of the zone under study (see, e.g., Konno and Ohmachi, 1998); that is, the periods with maximum amplification observed on the spectra of each site of the zone. Nevertheless, this technique is not at all reliable, and further work is necessary to calibrate the method to assess the limits of validity.

The purpose of this article is focused in this direction: we did some numerical experiments to determine how far we could go using this method in sedimentary basins. First, we show briefly Nakamura's technique and the underlying hypothesis. Subsequently, we present the response of sedimentary basins under incident waves coming from an explosive source using the indirect boundary element method (IBEM). After this, we compute the horizontal sediment-to-bedrock spectral ratio (SBSR) for various locations on the basins surface and compare it with the one calculated using the HVSR at the same locations.

Nakamura's Technique

Nakamura (1989) considered that spectral amplification of a surface layer could be obtained by evaluating the HVSR of the microtremors recorded at the site. This technique implies (Lermo and Chávez-García, 1994; Dravinski *et al.,* 1996) that microtremors are primarily composed of Rayleigh waves, produced by local sources, which propagate in a surface layer over a half-space; also, considering that the motion at the interface of the surface layer and half-space is not affected by the source effect, and that the horizontal and vertical motion at this interface are approximately equal, it is found that the site effect $S(f)$ can be computed by the spectral ratio of horizontal versus vertical components of the surface motion at the same place, that is,

$$S(f) = \frac{H_L(f)}{V_L(f)}.$$

In this way the predominant period as shown in Figure 1 can be obtained. On other hand, Konno and Ohmachi (1998) did a complete study and extended the problem to consider a multilayered system, as well. These authors reinforced the technique, which up to that moment had some theoretical gaps. On the other hand, Chávez-García *et al.* (1999) concluded that the "1D effects are robust and the HVSR technique allows correct amplitudes to be obtained, even if we still do not know why". The method is, therefore, reasonably good when the aim is to make a microzonation study in a place where the seismic response can be estimated by using a 1D model of soil conditions. Nevertheless, there are many places and cities located on sedimentary basins, where a set of plane layers can not be considered. On the contrary, it has been shown that recent earthquakes have been very destructive in cities located on zones where 2D and 3D effects produced by the geometry of the sedimentary basin have been present, and they gave a response completely different from the expected 1D seismic response of the site.

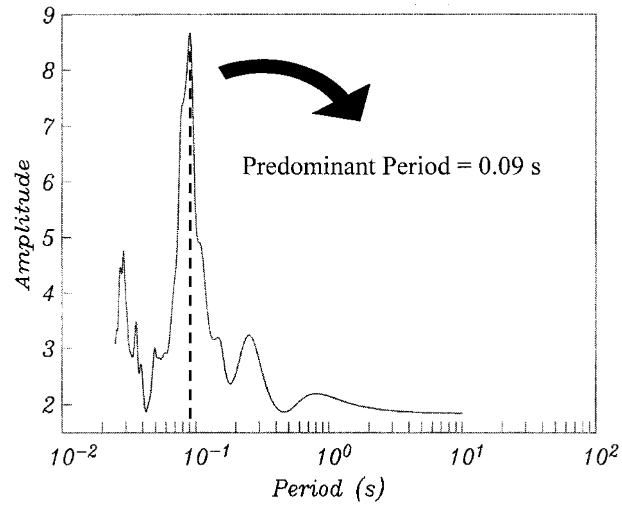

Figure 1. Example of horizontal-to-vertical spectral ratio (HVSR) and predominant period.

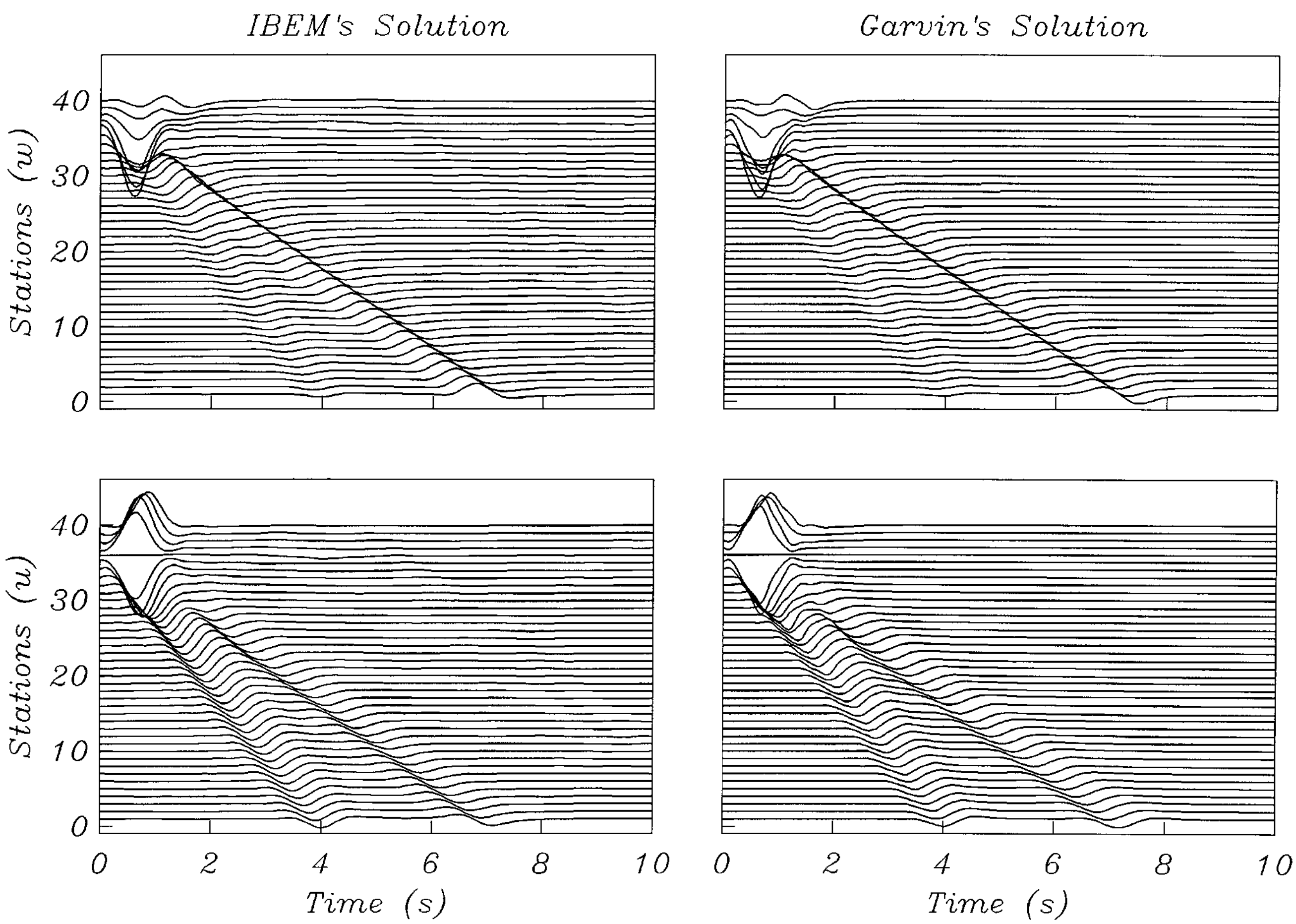

Figure 2. Comparison of the displacements due to an explosive source in a halfspace computed with the indirect boundary element method (IBEM) and that calculated with the solution given by Garvin (1956).

Seismic Microzonation in a Sedimentary Basin

In this section, with the aid of the IBEM we study the seismic response of a sedimentary basin and perform some numerical experiments to determine how far we could go using the HVSR at a site. The IBEM was used by Luzón *et al.* (1995) to deal with a 2D alluvial basin under incident plane waves, and by Luzón *et al.* (1997) to study the diffraction of *P*, *S*, and Rayleigh waves by 3D surface topographies. Here we introduce an explosive source near the basin, using for its construction the analytical expressions of the Green functions (Sánchez-Sesma *et al.,* 1993) in the 2D elastic case. The displacement in the direction i (u_i) due to the source can be computed as the contribution of two dipolar vectors, that is,

$$u_i = M_0\left(\frac{\partial G_{i3}}{\partial \xi_3} + \frac{\partial G_{i1}}{\partial \xi_1}\right)$$

where M_0 is the moment of the source, ξ_i are the local coordinates, G_{ij} is the analytic Green function of the elastic space, and the subscripts 1 and 3 refer to the horizontal and vertical components, respectively.

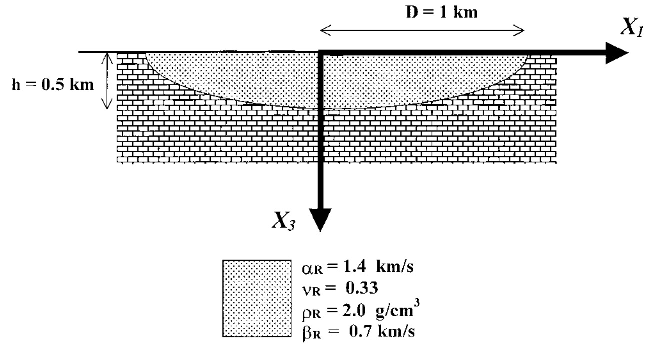

Figure 3. Semi-elliptical basin and physical properties used in this work.

To test the inclusion of the source in our problem we considered a semielliptical alluvial basin with maximum

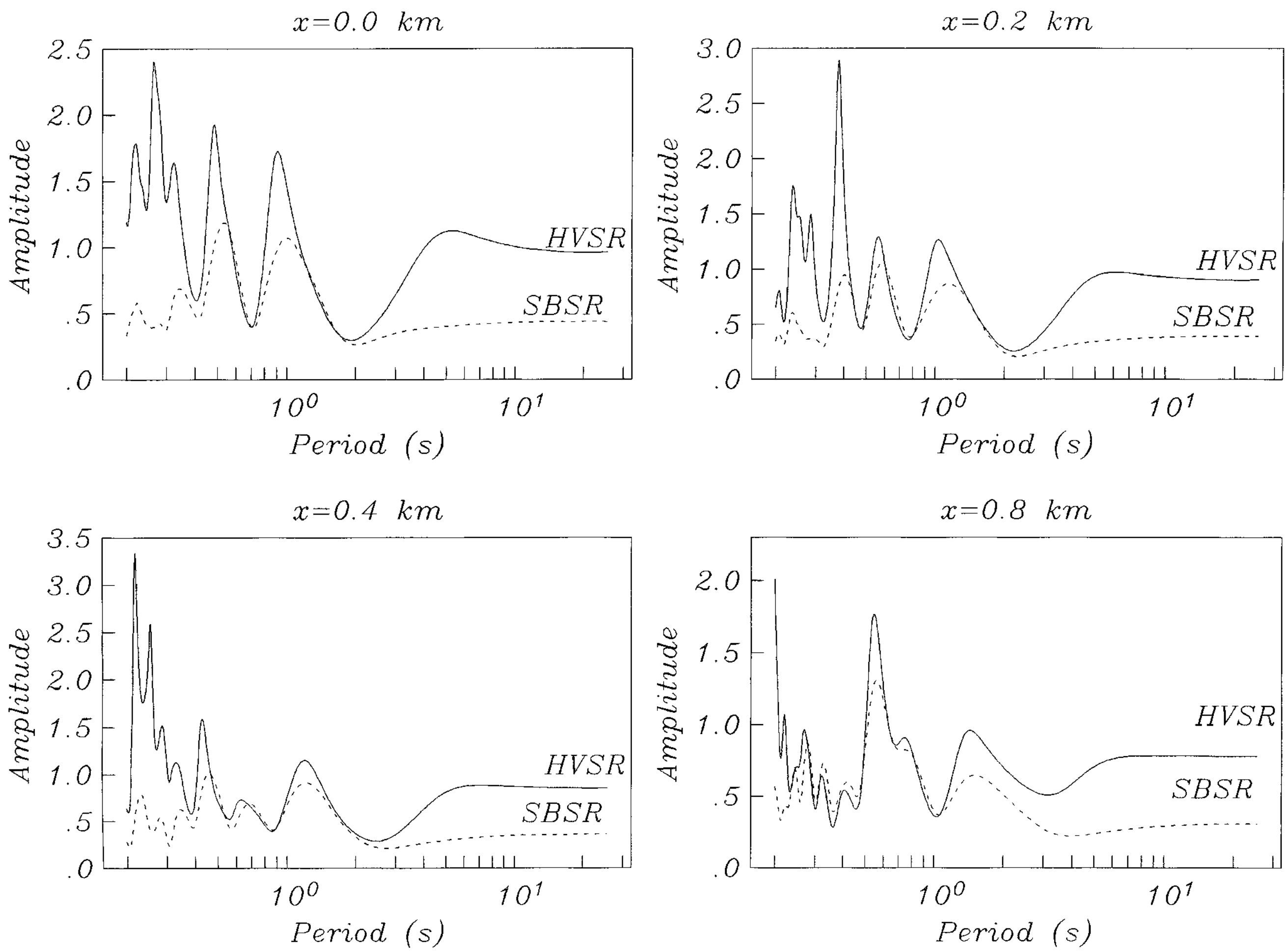

Figure 4. Comparison among the horizontal-to-vertical spectral ratio (HVSR), of the displacement amplitudes produced by an explosive source, in various surface locations x_1, and the horizontal sediment-to-bedrock spectral ratio (SBSR). Low-impedance contrast case.

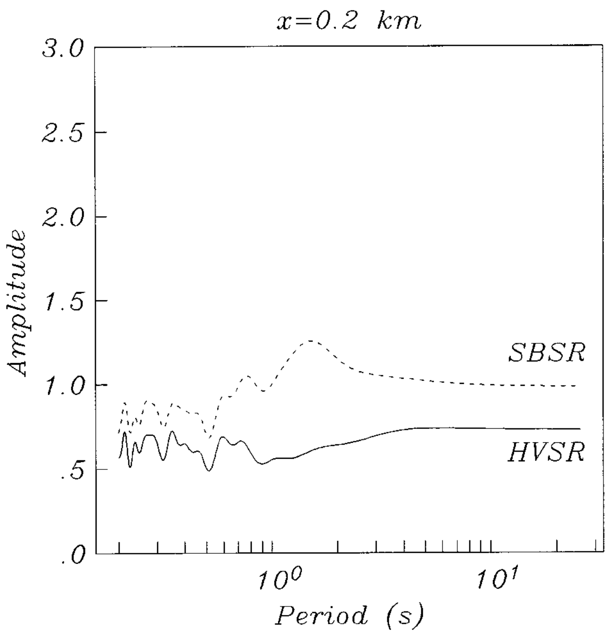

Figure 5. Comparison between the horizontal-to-vertical spectral ratio (HVSR), of the displacement amplitudes produced by incident Rayleigh waves, in $x_1 = 0.2$ km, and the horizontal sediment-to-bedrock spectral ratio (SBSR). Low-impedance contrast case.

depth of 0.5 km over a halfspace, in such a way that both media have the same physical properties: $\rho = 1.0$ g/cm^3, $\beta = 0.57$ km/sec, $\alpha = 1$ km/sec, and no attenuation exists in the space. We have located the explosive source at the position $x_1 = 1.5$ km and $x_3 = 150$ m, and have considered 40 receivers at the free surface from $x_1 = -2$ km up to $x_1 = 1.9$ km (the separation between each station is 100 m). We computed the displacements, in the frequency domain, for 128 frequencies from 1/25.6 Hz to 5 Hz, and calculated the synthetic seismograms produced in each station using the Fast Fourier Transform algorithm. We took into account a triangular pulse of one second as the source function. The displacements (horizontal u, and vertical w) in the time domain are represented in Figure 2, which can be compared with the results obtained by the Cagniard method used by Garvin (1956). By this comparison we can assess whether the inclusion of the source in our problem has been done correctly.

In the following we consider the semielliptical basin that is shown in Figure 3 for our next computations, and an explosive-source that is located at the position: $(x_1, x_3) = (-1.5$ km, 0.15 km$)$. We investigate two cases: low- and high-velocity contrast, fixing the physical properties inside the basin and changing only the properties of the half-space. The basin has an S-wave velocity $\beta_R = 0.7$ km/sec, a Poisson ratio $\nu_R = 0.33$, a mass density $\rho_R = 2.0$ g/cm^3, and a shape ratio h/D $= 0.5$. We consider again, 40 equidistant receivers at the free surface from $x_1 = -2$ km up to $x_1 = 1.9$ km, and compute the displacements, in the frequency domain, for 128 frequencies from 1/25.6 Hz up to 5 Hz. After this, we calculate the SBSR at various locations on the basin surface, (taking into account that the reference station is located at the corner of the basin in $x_1 = -1.0$ km) and compare them with those calculated using the HVSR at the same places.

Low-Impedance Contrast Case

For this case we use the following physical properties for the half-space: $\beta_E = 1$ km/sec, $\nu_E = 0.25$, and $\rho_E = 2.0$ g/cm^3. In Figure 4 we can see the comparison between both computations in various surface locations ($x_1 = 0.0$ km, $x_1 = 0.2$ km, $x_1 = 0.4$ km, and $x_1 = 0.8$ km) in the period domain, where we have used a Parzen smoothing of 0.35 Hz. This comparison shows that the predominant period computed with the HVSR is not the same as that one obtained with the SBSR for all the positions, and it can be seen, in particular, that on the receiver located at $x_1 = 0.2$ km, the maximum amplification corresponds to the period around 0.4 sec with HVSR, whereas the maximum one with SBSR is near 0.6 sec. In general, as the soil studied is nearer the corners of the sedimentary basin, the discrepancies between the two representations are smaller for the short periods; this fact was previously pointed out by Dravinski *et al.* (1996). Nevertheless, it can be observed that almost the same resonant periods are obtained in each location using both methods, although with different amplitudes in each technique, and with HVSR generally overestimating the mean amplification level.

Similar results were obtained using different sedimentary basins with trapezoidal, triangular, and semicircular geometries. Also, we made other computations assuming only incident Rayleigh waves; as an example, in Figure 5 the comparison of the SBSR and the HVSR is presented for the case of the semielliptical basin and incident Rayleigh waves for the receiver located in $x_1 = 0.2$ km. We again observe that different predominant periods are obtained in each technique, and that almost all the resonant short periods are the same in both methods. On the other hand, the largest period observed around 1.5 sec is not obtained by the HVSR approximation.

High-Impedance Contrast Case

For this other study we use the following physical properties for the half-space: $\beta_E = 3.5$ km/sec, $\nu_E = 0.25$, and $\rho_E = 3.3$ g/cm^3. In Figure 6 we depict the same comparison as in Figure 4 but for the actual case. We can see (1) that the spectral amplifications computed with the SBSR and with the HVSR are quite different, and (2) that these resonant periods are not the same as those obtained in the low-impedance contrast basin, with some special exceptions, such as the resonant period around 1 sec that appears at surface position $x_1 = 0.0$ km. In this problem, with a high-

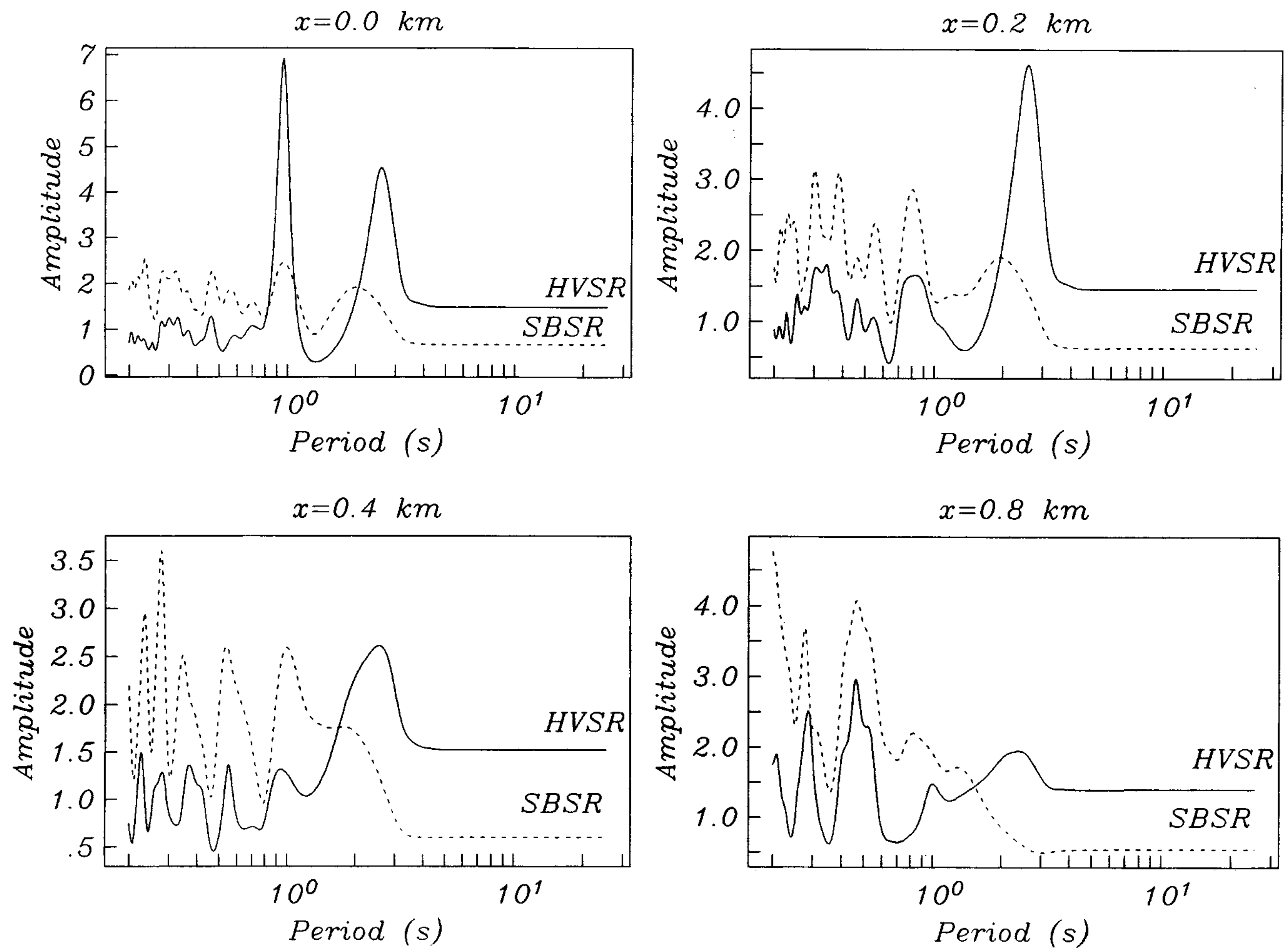

Figure 6. Same as Figure 4 but for high-impedance contrast case.

impedance contrast, surface waves are very efficiently generated and reflected at the edges of the basin, as was observed by Bard and Bouchon (1980a,b). These global resonances are characteristic of the behavior of this type of sedimentary structure. On the other hand, in this case study, even the larger period obtained with HVSR in each site is not the same as that computed with the SBSR. This stands in contrast to the low-impedance contrast case where the larger resonant period, that is the fundamental frequency of the site, was reasonably well reproduced by the HVSR.

Conclusions

In this article we have studied the seismic response of a sedimentary basin and carried out some numerical experiments to discover how far we could go using the HVSR for a given site. We have compared the response of the basin calculating the SBSR at various locations on the basin surface and that calculated by the HVSR at the same places. We have considered two different half-spaces with the same sedimentary basin with a shape ratio of 0.5, providing us interesting results for both low-and high-impedance contrast cases. We concluded that, for these type of structures:

- HVSR can not predict accurately the amplification levels of each period; therefore, it can not provide the predominant period of a site.
- HVSR can, reasonably well, predict the fundamental local frequency when there is a low-impedance contrast between the sedimentary basin and the bedrock.
- HVSR can not be used, at least, in sedimentary basins having high-impedance contrast with respect to bedrock and with shape ratios like the one studied here. In such basins, a complex pattern of global resonances is produced by the generation and reflection of surfaces waves at the edges of the basin that can not be reproduced well by the HVSR approximation.

From these results we conclude that if one wants to make a seismic microzonation study in a sedimentary basin using the HVSR technique, it is necessary not only to analyze the physical properties of the sediments, but to also analyze the properties of the bedrock.

Acknowledgments

Thanks are given to J. Martín and Lee K. Steck for the critical reading of the manuscript and many useful suggestions. This article was greatly improved by the helpful suggestions proposed by F. J. Sánchez-Sesma from the Instituto de Ingeniería (UNAM). This work was partially supported by DGESIC, Spain, under Grant HF1999-0129, by CICYT, Spain, under Grant AMB99-1015-C02-02, and by the Junta de Andalucía, Spain.

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Manuscript received 15 October 1999.