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Estimates of site effects in Oaxaca, Mexico using horizontal to vertical spectral ratios

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RESUMEN
Comparamos estimaciones de la respuesta sísmica de sitio en Oaxaca, México determinadas mediante el uso de métodos espectrales que no dependen de un sitio específico de referencia. En particular, usamos cocientes espectrales entre las componentes horizontal y vertical de las ondas S (e.g. Lermo y Chávez-García, 1993) para estimar la respuesta sísmica de sitios localizados en suelo duro y sobre sedimentos. Comparamos los resultados obtenidos con las funciones de sitio determinadas por Castro y otros (1995) usando una inversión generalizada. Aunque ninguno de los dos métodos depende de un sitio de referencia común, ambos métodos generan funciones de sitio similares en forma. Para sitios localizados en roca dura, los factores de amplificación obtenidos son además consistentes. Sin embargo, existe una discrepancia de escala para el sitio localizado sobre sedimentos, la cual puede deberse en parte a la condición de sitio impuesta en el esquema de inversión.

PALABRAS CLAVE: Efectos de sitio, razón espectral, Oaxaca, México.

ABSTRACT
We compare estimates of the site response in Oaxaca, Mexico determined using non reference-site spectral methods. In particular, the spectral ratio between horizontal and vertical components of the S-wave arrivals (e.g. Lermo and Chávez-García, 1993) is used to estimate the site response of hard-rock and sediment sites. The results are compared with site functions determined by Castro *et al.* (1995) using a generalized inversion. Although the methods used are independent of a reference site, both provide similar site functions; and consistent amplification factors for the hard-rock sites. However, there is a scale discrepancy for the site on sediments which can be explained in part by the site constraint imposed in the inversion scheme.

KEY WORDS: Site effects, spectral ratios, Oaxaca, Mexico.

INTRODUCTION

One problem that often arises for the evaluation of the site response, and in particular for the determination of the seismic amplification, due to low-velocity surface layers is the selection of a reference site, which should be amplification-free. The most commonly used method to estimate ground motion amplification is the spectral ratio technique, which uses as a reference site a station located on hard rock for regions where such sites exist. It is implicitly assumed that the reference site does not feature important amplifications. However, Tucker *et al.*, (1984), Castro *et al.*,(1990), Humphrey and Anderson, (1992), and others, show that hard-rock sites may also generate considerable amplifications due to topographic irregularities near the station and other factors.

To evaluate the ground motion amplification due to sedimentary deposits, for instance, the ideal reference site is at the base of the sediments. Borehole studies permit a comparison of the response of surface layers to underlying bedrock (Seale and Archuleta, 1989), but the resulting transfer function may not be extrapolated to other points of the basin. An alternative method is to use a non reference-site technique as proposed by Nakamura (1989) to identify the natural period of resonance (at which maximum relative amplitudes occur) as extended by Lermo and Chávez-García (1993) to estimate sediment-induced amplification of S-wave arrivals.

In this paper we compare site response estimates obtained using horizontal to vertical spectral ratios with site functions obtained by Castro *et al.* (1995) using a generalized inversion and records from a temporary network of digital stations installed near the coast of Oaxaca, Mexico, on hard-rock and sediment sites.

METHOD

The method by Nakamura (1989), used originally for microtremors, is based on the assumption that the vertical component of ground motion is insensitive to sediment-induced amplification and retains the same input information as the horizontal component of the tremor. This technique has been successfully used to determine the natural period of resonance of sedimentary deposits (Nakamura, 1989; Lermo and Chávez-García, 1992; Field and Jacob, 1993; among others). Following the same idea, Lermo and Chávez-García (1993) used horizontal-to-vertical spectral ratios from S-wave arrivals to evaluate site effects in three cities of Mexico. The extension of Nakamura's assumption to S waves is partly based on the similar wave-form character of the vertical component of displacement observed by Campillo *et al.* (1989) for different site conditions in Mexico City, and on 1-D numerical modeling by Lermo and Chávez-García (1993).

In this paper, we use Nakamura's assumption to estimate S-wave site responses using a data set of 85 spectral records of 16 earthquakes from the subduction zone of Oaxaca, Mexico recorded on a temporary array of 6 digital stations (Munguía *et al.* 1978). Stations ES, SJ and CT were installed along the coast of Oaxaca between Puerto Escondido and Puerto Angel at low elevation sites. The other stations were located inland at higher elevations, CD at 800 m, SG at 550 m and SP at 3300 m. For the stations installed at high altitudes, the site response may be influenced by topographic effects. Station SJ was located near the coast on thin sediments of unknown thickness.

The Fourier transform of the S-wave signal was computed using both vertical and horizontal components. The records were base-line corrected and time windows were selected starting with the first S-wave arrival and ending when the phase energy reached 90% of the total. The beginning and the end of the time windows were tapered with a 5% cosine taper. The instrument response was subtracted from the computed spectral amplitudes and the resulting spectra were smoothed with a one-third octave band filter. The horizontal-to-vertical spectral ratios were obtained using both components (North and West) for 14 spectral amplitudes at frequencies between 1 and 20 Hz.

Figure 1 shows the average spectral ratio calculated for each station (solid line) and the standard deviation (bars). The site geology of the recording stations is also indicated in the figure. All sites but SJ were located on hard rock, yet all of them show some amplification.

In a previous study, Castro *et al.*(1995) evaluated the site response of these sites using a different method. They first corrected the S-wave spectral records for the effect of attenuation using a 1/r geometrical spreading factor (r being the hypocentral distance) and a $Q_S = 56\ f^{1.01}$ (Castro and Munguía, 1993); then they assumed the remaining effects on the spectral amplitudes to be modeled as the product of the source $S_i(f)$ of earthquake i and the site response $Z_j(f)$ of station j:

$$R_{ij}(f) = S_i(f) Z_j(f) \quad . \qquad (1)$$

In order to eliminate the linear dependence between source and site functions, they imposed the following constraint on the inversion:

$$\sum_{j=1}^{N} \mathrm{Log}\ Z_j(f) = 0 \quad . \qquad (2)$$

This condition applies to stations with relatively small amplifications (hard-rock sites) and is equivalent to using the average site response over the network as a reference site.

Figure 1 also shows the site functions obtained by Castro *et al.* (1995) for the same sites.

DISCUSSION AND CONCLUSIONS

Comparing the spectral shape of the site response obtained using both methods (Figure 1), the similarity of the results for the hard-rock sites ES, CD, SP and SG is evident. The spectral shape of the site function obtained from spectral ratios differs somewhat from that obtained solving Equation (1), but the deviation of the amplitudes is within the error bars for most frequencies. We conclude that for hard-rock sites both methods yield site functions with similar spectral trends. Further, the results obtained by Castro *et al.* (1995) and those obtained here (Figure 1) show that hard-rock sites do not necessarily have constant site functions. This has also been observed by Tucker *et al.* (1984) and Humphrey and Anderson (1992) in other regions. Frequency dependence of site response at hard-rock sites may be an effect of wave propagation through a laterally heterogeneous medium and possible frequency dependent attenuation effects near the surface. Thus, the site function at station SP, reported by Castro *et al.* (1995), shows a strong frequency-dependent deamplification which could be explained by t* being frequency dependent near the surface.

For the site located on sediments, the trends shown in Figure 1 are also arguably similar, since both functions show amplification at low frequencies that may be related with thin sediments. However, there is an important scale discrepancy between the predicted amplification factors. The strong amplification reported for SJ relative to the other stations has also been observed directly on velocity records by comparing seismograms from events of similar magnitudes at comparable distances (Figure 2 of Castro *et al.*, 1995). Nevertheless, Nakamura's method predicts a low amplification for this site.

As discussed above, our reference frame for estimating sediment-induced amplifications was the average response of the hard-rock sites for the inversion scheme, which according to Equation (2) equals unity. On the other hand, for the horizontal-to-vertical spectral ratio the reference is the response of the basement, which is not necessarily equal to unity if it has an irregular shape. Hence, the amplification factor estimated from the inversion may differ from that obtained from spectral ratios.

In order to discuss possible explanations of the scale discrepancies observed in Figure 1, we calculate an average site function using the functions obtained with Nakamura's method for the hard-rock sites. This average is compared with the site functions calculated using horizontal to vertical spectral ratios (Figure 2). It has values close to unity but varies with frequency, suggesting that the spectral ratios contain information about the topography of the hard-rock sites used to calculate the average. For station SJ, the average at low frequencies is only a factor of 2 below the site response calculated by spectral ratios: this would not account entirely for the difference observed in Figure 1. The inconsistency between amplification factors suggests that the method proposed by Nakamura should be used with caution to estimate amplification factors.

In conclusion, the scale discrepancy of the amplification factor estimated for SJ may be due partly to the different reference frame used. However, other factors may also affect the estimates of the amplification levels.

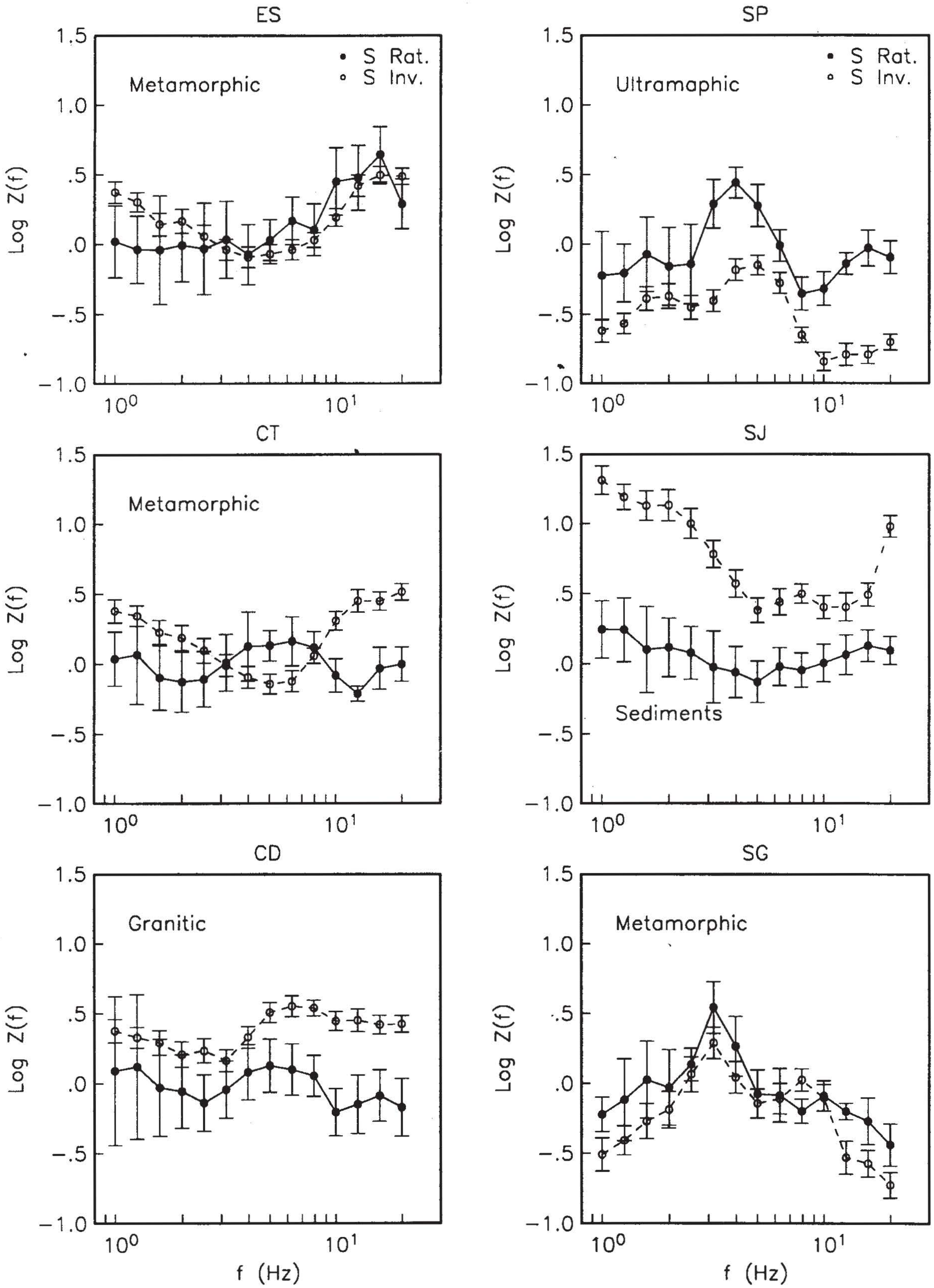

Fig. 1. S-wave site response obtained using horizontal to vertical spectral ratios (solid line) and the site functions obtained by Castro *et al.* (1995) using a generalized inversion (dashed line).

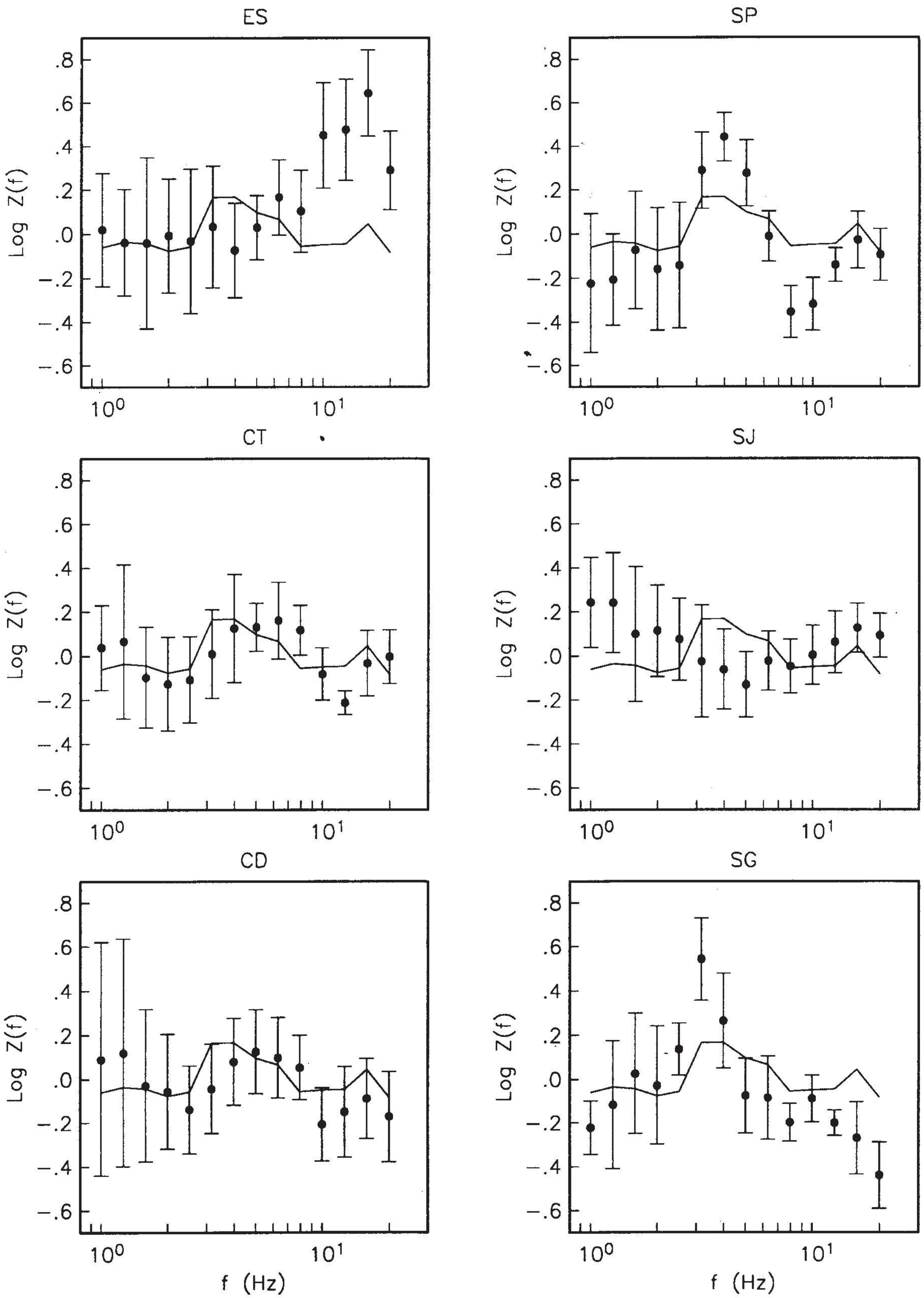

Fig. 2. Site functions obtained using Nakamura's method (dots), and average calculated using all stations except SJ (solid line).

On the whole, the results presented in this paper support the observations of Lermo and Chávez-García (1993) with regard to the use of horizontal to vertical spectral ratios of S-waves. This method can be used to identify the period at which the spectral maximum generated by S-wave arrivals occurs. Since the spectral ratios reproduce the response of hard-rock sites, this method may be useful for evaluating the effect of topography on ground motions.

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