SITE-EFFECT ASSESSMENT OF SÃO SEBASTIÃO VOLCANIC CRATER, TERCEIRA ISLAND, AZORES

AVALIAÇÃO DOS EFEITOS DE SÍTIO NA CRATERA VULCÂNICA DE SÃO SEBASTIÃO, ILHA TERCEIRA, AÇORES

Chitas, Pedro, ICIST/DECivil/IST, Lisbon, Portugal, pchitas@civil.ist.utl.pt
Santos, Jaime, ICIST/DECivil/IST, Lisbon, Portugal, jaime@civil.ist.utl.pt
Sousa Oliveira, Carlos, ICIST/DECivil/IST, Lisbon, Portugal, csoliv@civil.ist.utl.pt

ABSTRACT

There is historical evidence that São Sebastião volcanic crater, at Terceira Island, Azores, exhibits stronger ground motion during seismic events than its surrounding areas. During the two seismic crises of 1997 and 1998 it was possible to obtain several records at three different places inside the volcanic crater: Escola, Junta and Misericórdia. Comparison between seismic records allowed a primary identification and analysis of site effects inside the crater (Santos et al. 2007). In the present work, two of the most usual site-effect assessment techniques were used, namely, the spectral ratio between the records at the crater and a given reference site (reference-site spectral ratio, or RSR) and spectral ratios for different components of the same accelerometric station (horizontal-to-vertical spectral ratio).

RESUMO

A cratera vulcânica de São Sebastião, situada na Ilha Terceira do Arquipélago dos Açores, evidencia uma forte amplificação do movimento sísmico relativamente às áreas vizinhas. Durante as crises sísmicas de 1997 e 1998 foi possível obter registos na cratera de São Sebastião, recorrendo-se a estações acelerométricas digitais colocadas na Escola, na Junta de Freguesia e na Misericórdia. A comparação entre registos permitiu a identificação e primeira análise dos efeitos de sítio no interior da cratera (Santos et al. 2007). No presente artigo, recorreu-se às técnicas de maior uso no estudo de efeitos de sítio, determinando-se razões espectrais, relativas tanto a diferentes componentes do movimento para uma só estação (razão espectral H/V), como à mesma componente para diferentes estações (razão espectral relativa a estação de referência).

1. INTRODUCTION

The Azores Archipelago is located in the middle of the Atlantic Ocean at the North America, Eurasia and Africa triple junction; its central group is placed at the so-called Azores microplate, which consists of a broad sheared region due to differential motion between the different plates. This fact is the main reason of the well known high seismicity and volcanism of the archipelago.

This paper focuses on São Sebastião volcanic crater, located in the south-eastern side of Terceira Island in the central group of the archipelago (Figure 1). Inside the crater lies a village of the same name.
The central group has felt in the historical times the effects of several seismic events, usually low to moderated events or swarms, but occasionally some with magnitude near 7 (Nunes et al. 2004). The last large earthquake, named the Terceira earthquake, occurred on January 1st 1980 with magnitude M=7,2 and showed that the seismic response of the São Sebastião volcanic crater, is characterized by an amplification of ground movements inside the crater with respect to the surrounding area (Figure 2).

In terms of damage distribution at São Sebastião, for the January 1st 1980 event, there was evidence of spatial variation of building stock performance. The number of buildings that were very damaged or were in ruins after the event were essentially located in the northern part of the village (Figure 3).

Several efforts to characterize the geological setting of the volcanic crater have been made. A more detailed description of the setting and the geophysical campaign was presented by Santos et al. (2007).

During two seismic crises in 1997 and 1998, three digital accelerometric stations were placed at the village of São Sebastião, namely at “Escola”, “Junta” and “Misericórdia”. Their location was chosen to reflect the differences of seismic behavior shown by the damage distribution (Figure 3). Several accelerometric records were obtained, and a first analysis of the strongest records has been made by Santos et al. (2007). For these records, there was clear evidence of differences in the ground motion recorded at São Sebastião comparing with records at Praia da Vitória, and differences in the records of Escola comparing to the other two stations, whether in terms of Peak Ground acceleration (PGA), Arias Intensity (AI) and of frequency content. The present work focuses on a much more significant number of records in order to validate the
2. EXPERIMENTAL SITE-EFFECT ASSESSMENT TECHNIQUES

2.1. Reference-site Spectral Ratio (RSR)

The Reference-site Spectral Ratio, or Standard Spectral Ratio, was first introduced by Borcherdt (1970). Conceptually, this technique is quite simple: if one has a rock outcrop site at the vicinity of the site to assess, as the former should not be influenced by site effects, if one calculates the ratio between the Fourier amplitude spectrum of latter and the Fourier amplitude spectrum of the former (the so-called reference site), one should obtain approximately the transfer function of the site.

This technique presents as advantage, along with its formal simplicity, the fact that it doesn’t require heavy signal processing (in fact, only Fourier transforms are needed). If the premises of this technique are met, i.e., if one has a reference station where there are no site effects, this technique should give the best estimation of site effects at a given station.

However, this method presents a major setback: sometimes it may be extremely difficult to find a reference site. Steidl et al. (1996) state that, in some geological settings, this happens indeed. According to the same authors, another issue that makes this technique prone to error is the fact that even some rock sites may have site effects, as happens, for an instance, when topography intervenes in the site response (this is especially important, typically, in valleys).

2.2. Horizontal-to-Vertical Spectral Ratio (H/V)

The first author to use the H/V technique having as purpose the estimation of the amplification factor at a given site was Nakamura (1989). The technique was first developed using microtremors. Lermo and Chávez-García (1993) expanded the horizontal-to-vertical spectral
ratio using earthquake records, obtained both by seismometers and accelerometers. These authors have determined the spectral ratio for the S-wave part of ground motion. The adoption of the S-wave windows of ground motion was justified by these authors with two lines of argument. First, analyzing data from Mexico City, concerning the 1985 Mexico Earthquake; there was evidence that, even for sites of great horizontal amplification, the vertical component of displacement had the same character and similar amplitudes, i.e., the vertical component of ground motion essentially contains features only concerning source and propagation effects. Second, using Aki-Larner’s method, for a simple stratigraphic model for SCT station at Mexico City, several incidence angles of ground motion were considered. For every case, the horizontal-to-vertical spectral ratio clearly identified the transfer function peaks, although the amplification values were not correct. There was also evidence that the amplification ratio determined by the technique was strongly dependent on the incidence angle.

The use of horizontal-to-vertical spectral ratio has as enormous advantage the fact that it doesn’t require a reference site. This is especially important in low-to-moderate seismicity zones, where network arrays are not available. The fact that it demands only one station makes this technique attractive in an economical point of view.

When ground motion records are used, the horizontal-to-vertical spectral ratio permits the identification not only of the fundamental mode, but also of other vibration modes. An important advantage of the use of horizontal-to-vertical spectral ratio using ground motion records is that one is able to determine the presence of topographic effects, for simple topographic settings (Chávez-García et al., 1996, 1999).

3. GROUND-MOTION RECORDS USED IN SITE-EFFECT ASSESSMENT

Table 1 contains the date, magnitude and recording stations for all the records taken into account for site-effect assessment. All the events were numbered, in order to ease identification of the obtained results.

As one should note, in spite of existing three different stations at the crater, only six seismic events were recorded by more than one station.

An important issue concerning these records was long-period noise, as the events’ magnitude was almost always lower than 5.0. Hence, signal processing techniques were needed. The adopted procedure closely follows the standard procedure of USGS (2006).

This array of records was used in the present work essential in the H/V ratio technique. Event #5 was used in RSR technique, as there was another site (Praia da Vitória) with a much lesser amplification and similar epicentral distance.

<table>
<thead>
<tr>
<th>Date (UTC)</th>
<th>Magnitude</th>
<th>Recording stations</th>
<th>Event Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>1997/07/15 21:00</td>
<td>4,5</td>
<td>E., J., M.</td>
<td>1</td>
</tr>
<tr>
<td>1997/08/27 18:50</td>
<td>4,9</td>
<td>E., J., M.</td>
<td>2</td>
</tr>
<tr>
<td>1997/07/07 20:07</td>
<td>4,5</td>
<td>E., J., M.</td>
<td>3</td>
</tr>
<tr>
<td>1997/10/03 08:58</td>
<td>3,7</td>
<td>E., J., M.</td>
<td>4</td>
</tr>
<tr>
<td>1998/07/09 05:19</td>
<td>5,7</td>
<td>E.</td>
<td>5</td>
</tr>
</tbody>
</table>

Table 1- Date, magnitude and recording stations (E.=Escola; J.=Junta, M.=Misericórdia) of used events.
4. Reference-Site Spectral Ratio (RSR)

Figure 4 shows the obtained spectral ratios with the transfer functions assumed for the Escola station.

In terms of RSR, the first vibration mode is clearly identified for a frequency around 1.2 Hz. For the N-S component, there is a great amplification associated to the second mode, for the bandwidth of 2.0 Hz - 2.5 Hz. There is also a great amplification for frequencies around 5.0 Hz, which is present in both components.

![RSR - Event #5 - N-S component](image1)

![RSR - Event #5 - E-W component](image2)

Figure 4 – RSR obtained at Escola for event #5 and for each of the horizontal components
Despite the lack of more numerous comparisons, this technique is in general agreement with the results obtained by Santos et al. (2007). It confirms the presence of a special feature for the second vibration mode, especially for the N-S component.

5. **HORIZONTAL-TO-VERTICAL SPECTRAL RATIO (H/V)**

For all the characterized events inside the crater of São Sebastião, one calculated the spectral ratio between the horizontal amplitudes and the vertical amplitude. This technique was made for 20 second S-wave time windows.

The SESAME project (2004) recommends the two criteria to check the reliability of the H/V curve. In the first place, the adopted window length should be greater than ten times the determined fundamental frequency. If so, the number of cycles, considering all the time windows, should exceed 200.

These criteria were completely fulfilled for the Escola station, as there were 23 records. However, for the Junta and the Misericórdia, that was not true, as the number of windows was not enough to fulfill the criteria. For the Junta station, if the fundamental frequency were to be 1.2Hz, as given by RSR, the number of cycles contained would be 192, a value pretty close to the criterion. Hence, despite not fulfilling the number of cycles criterion, the H/V curve was calculated for the Junta station.

The H/V curve was obtained following closely the guidelines of SESAME project (2004). First, a 5% co-sine tapering window was applied to the S-wave part of the acceleration time series (for the three components). Next, the FFT algorithm was applied to the three components of each selected time window. After the application of the FFT, the spectral ratios were calculated for

![H/V Curve including dispersion - N-S](image1)

![H/V Curve including dispersion - E-W](image2)

![H/V curve - Escola](image3)

Figure 5 – H/V curves obtained at Escola: N-S component, E-W component and combined H/V curve
the two horizontal components for each window. Considering all the windows, the geometric mean for the two horizontal components was determined (Equation 1). The standard deviation of the geometric distribution was also determined.

$$\frac{\sum \log (H/V_i)}{N}$$

$$H/V = 10 \frac{\sum \log (H/V_i)}{N} \quad (1)$$

After checking if there were differences in the two components, these were combined using a quadratic mean (Equation 2):

$$\left(H/V\right)_{comb} = \sqrt{\left(H/V\right)_{NS}^2 + \left(H/V\right)_{EW}^2} \quad \frac{2}{2} \quad (2)$$

The H/V curves obtained using this procedure for Escola are shown in Figure 5. The obtained H/V curve identifies clearly two amplification peaks, one for a frequency around 1.0Hz and other around 2.3Hz. Both components exhibit these peaks. The peaks are sharper and with greater value for the N-S component. Even if the use of S-wave windows allows one to determine vibration modes higher than the first one, the spectral ratio obtained for the second mode is similar to the first one. One of the possible causes to this fact may be a complex subsurface topography, or the presence of two large impedance contrasts (SESAME 2004, Bard 2006). The previous observations concerning the second mode are not valid for Junta, as one may see in Figure 6. The fundamental frequency determined for Junta is similar to the one obtained at Escola but higher modes cannot be identified.
6. CONCLUDING REMARKS AND FUTURE DEVELOPMENTS

The use of the experimental site-effect assessment techniques at São Sebastião volcanic crater allowed the authors to confirm the remarks made by Santos et al. (2007). Amplification at Escola is much greater than in Praia da Vitória and in Junta. Comparing Escola and Junta, this is mainly due to amplification for the bandwidth of 2.0Hz-2.5Hz. This feature was detected by both H/V and RSR techniques. This effect is more clear for the N-S component.

The use of these techniques helps in the definition of the geophysical and geotechnical campaign executed during the summer of 2007. The results of the latter campaign will be used to obtain a two-dimensional finite-element model of the crater for further research studies.

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