



Contribution of in situ geophysical methods for the definition of the São Sebastião crater model (Azores)

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ABSTRACT

The area located inside the São Sebastião volcanic crater, at the southeast end of Terceira Island (Azores), is characterized by an important amplification of ground motion with respect to the surrounding area, as clearly demonstrated by the spatial distribution of the damage that occurred during the Terceira earthquake (the strongest earthquake felt in the Island during the recent decades – 01/01/1980 – $M = 7.2$). Geological and geophysical studies have been conducted, to characterize the volcanic crater and understand the different site effects that occurred in the village of São Sebastião. The complexity of the subsurface geology, with intercalations of compact basalt and soft pyroclastic deposits, is associated to extreme vertical and lateral velocity contrasts, and poses a serious challenge to different geophysical characterization methods. The available qualitative model did not allow a complete understanding of the site effects. A new seismic campaign has been designed and acquired, and a single, geologically consistent geophysical model has been generated integrating the existing and new data. The new campaign included two cross-line P-wave seismic refraction profiles, four short SH-wave seismic reflection profiles, and seven multichannel surface wave acquisitions. The integration and joint interpretation of geophysical and geological data allowed mutual validation and confirmation of data processing steps. In particular, the use of refraction, reflection and surface wave techniques allowed facing the complexity of a geology that can pose different challenges to all the methods when used individually: velocity inversions, limited reflectivity, and lateral variations. It is shown how the integration of seismic data from different methods, in the framework of a geological model, allowed the geometrical and dynamic characterization of the site. Correlation with further borehole information, then allowed the definition of a subsoil model for the crater, providing information that allowed a better understanding of the earthquake site effects in the São Sebastião village. The new near-surface geological model includes a lava layer within the soft infill materials of the crater. This new model matches closely with the damage distribution map, and explains the spatial variation of building stock performance in the 1980 earthquake.

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1. Introduction

Often in an earthquake the spatial distribution of shaking is unequal, this means that at the same epicentral distance the shaking intensity at one site is higher than another (Aki, 1988, 1993; Anbazhagan and Sitharam, 2008; Bard, 1997; Kudo, 1995; Triantafyllidis et al., 2004). If this occurs, and if the ground motion amplification is significant, this site effect plays a major role in the seismic risk associated with damage and loss of lives. Some examples of earthquakes that occurred during the last decades with differentiation in seismic motion are Michoacan, Mexico in 1985 (Kobayashi et al., 1986), Loma Prieta, California, USA in 1989 (Hough et al., 1990), Kobe, Japan in 1995 (Kanaori and

Kawakami, 1996), Wenchuan, China in 2008 (Wen et al., 2010) and Tohoku, Japan in 2011 (Ghofrani et al., 2012).

The causes for this spatial variation of ground response are associated with the source-to-site distance factor (e.g., the wave type, angle of incidence) and the geological–geotechnical conditions at the site (e.g., the geometrical and dynamic characteristics of the surface layers).

From the examples mentioned before, the Mexico City region has some similarities to our case study, both sites are volcanic in origin and the geological–geotechnical conditions explain the differences in the ground shaking and consequently, the observed damage distribution. Interbedded lavas with softer deposits are found in the southern area of the Mexico City urban zone (Figueroa-Vega, 1984). However, no structure as the deep deposits of soft clays on the Lake zone, responsible for the huge site effect observed during the 1985 earthquake in Mexico City, was revealed in São Sebastião.

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Many researchers have worked in Mexico City, to develop theoretical and experimental methods that identify and characterize the local geological formations that are prone to generate site effects. For instance, Jongmans et al. (1996) used in situ measurements, such as refraction and seismic surface waves, complemented with laboratory measurements of P and S wave velocities to characterize the dynamic soil parameters, and Chavez-Garcia and Cuenca (1996) performed microtremor measurements to estimate the dominant period and maximum relative amplification; producing a detailed microzonation map of the region.

Seismic activity occurs in many areas of the volcanic islands of Azores. The village of São Sebastião (Terceira Island), is located inside a sediment/pyroclast filled volcanic crater, and in past earthquakes has shown an unexpected damage distribution in comparison with other areas surrounding the crater (Fig. 1b). In terms of damage distribution, it was possible to gather detailed information following the January 1st, 1980 event, with magnitude $M = 7.2$ (Hirn et al., 1980) and intensities between V and VIII (MM – Mercalli Modified Intensity Scale), substantiating also spatial variation of building stock performance within the crater area (Montesinos et al., 2003) and considering that the buildings' vulnerability is equal for the same period of construction. Since then other earthquakes, even some much smaller in magnitude, have shown the same phenomena. For instance, the $M_L = 2.5$ earthquake in 27/07/2006, with epicentre in southeast Terceira was

felt in São Sebastião with an intensity of III/IV (MM) (Instituto de Meteorologia I.P. and Universidade dos Açores, 2006). Also, a $M_L = 4.2$ earthquake in 27/01/2008 with epicentre in the S-SE region of the island lead to an intensity of IV/V (MM) in the village (Instituto de Meteorologia I.P., 2008) and the $M_L = 3.2$ earthquake in 12/03/2011 with epicentre in the eastern region resulted in an intensity II (MM) in São Sebastião (Instituto de Meteorologia I.P., 2011).

During the last decades, efforts have been made to deeply understand the different site-effects that occurred in the village. Between 1997 and 2001, under the PPERCAS research project (Praxis Project for the Risk/Hazard Study of the Central Group of the Azorean Archipelago), geological (Nunes, 2000), geotechnical (Malheiro, 1998) and geophysical (Montesinos et al., 2003; Senos et al., 2000) studies were performed. The variety of parameters and the different spatial resolution of measurements have made the integration of results difficult, preventing the development of a geological–geotechnical model of the near-surface that is able to explain the spatial variation of ground motion.

In 2003, the research continued with several multichannel seismic surface wave acquisitions, with the aim of measuring the shear wave velocity (V_s) to characterize the different geological units of the crater area. The results identified spatial differences in the V_s profiles within the soft soil deposits that fill the crater, but considering the geological knowledge at that time, some of the results were considered doubtful (Lopes, 2005) and the site amplification question remained unanswered. The acquired surface wave data, showing at some sites strong multiple modes and large phase velocity contrasts, suggested the presence of a higher complexity in the shallow subsurface.

The need for a multidisciplinary approach for an integrated geological and geophysical model led to a new investigation in 2006 to evaluate the dynamic properties of the soil in the shallow subsurface of São Sebastião village and surrounding area. More seismic measurements, with different methods, along with a new geological surface inspection were designed, taking into account the lack of knowledge in some zones of the crater and the information already acquired with the previous surveys. A crucial element of the campaign is the use of methods with different sensitivities and resolutions, but also with different limitations, to face the different situations that were expected. The geophysical campaign consisted of seven additional multichannel surface wave acquisitions, two cross-line P-wave seismic refraction profiles and four short SH-wave seismic reflection profiles. In-hole seismic testing (e.g. cross-hole testing and/or vertical seismic profiling – VSP) would certainly have enabled better interpretation of all available data but, unfortunately, limited funds unabled using such valuable method. Notwithstanding, integrating previous and new geophysical data, new borehole information, and joint-interpreting them, allowed the filling of some gaps in the geological model of São Sebastião, which can now better explain the site effects observed at this site.

2. Local geology

The Azores archipelago is a volcanic group of islands in a complicated tectonic setting. The archipelago is located at the North America, Eurasia and Africa triple junction. The Mid Atlantic ridge (MAR – Fig. 1a) separates the North American plate from the others, while the Azores–Gibraltar fault zone is the boundary between the Eurasian and the African plates (EAFZ – Fig. 1a). The seismicity and volcanism of this area are due to its location on an active plate boundary (Fig. 1a).

The detailed volcanological map of São Sebastião and surrounding area was made by Nunes (2000). A simplified version of the map is presented in Fig. 2, and shows that the geological formations of the area are mainly basaltic in composition. According to Montesinos et al. (2003) the eastern and southeastern sectors have extensive scoria deposits, either as lapilli layered deposits or as scoria cones of different sizes and ages. Cruzes cone is one of the oldest of the area, and is responsible for the extrusion of porphyritic basaltic lavas that are buried under the “intermediate-age” lava flows. These authors state that it is

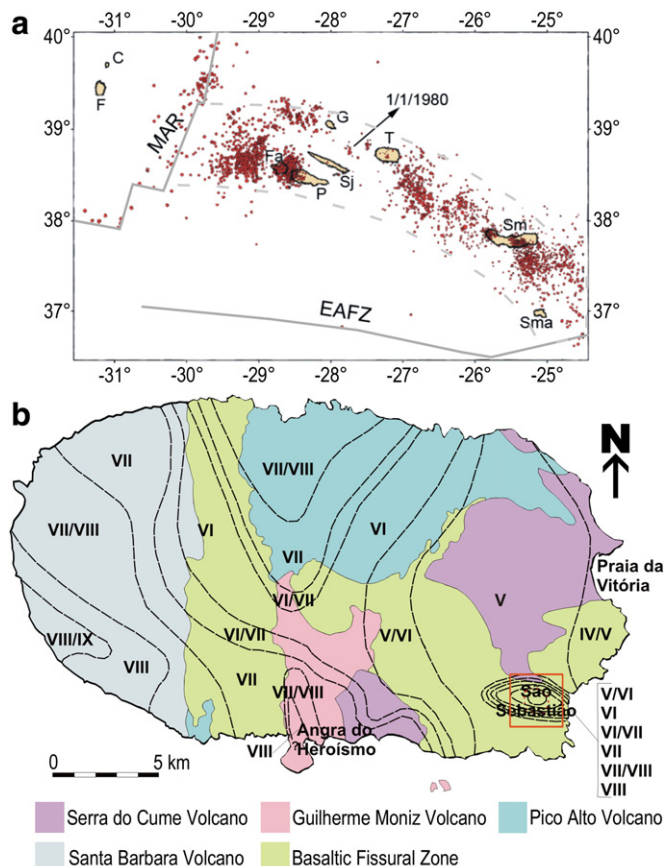


Fig. 1. Location of the study area: a) Seismicity in the Azores archipelago recorded between July 1998 and May 2001 with schematic tectonic setting of the area (modified from Dias et al., 2007), showing also the approximate location of the January 1st 1980 earthquake (MAR – Mid Atlantic Ridge, EAFZ – East Azores Fault Zone, Azores Islands: C – Corvo; F – Flores; G – Graciosa; T – Terceira; Sj – São Jorge; Fa – Faial; P – Pico; Sm – São Miguel; Sma – Santa Maria); b) Terceira Island map presenting the sketch of the main volcanic structures of the island and the isoseismal lines (MM) for the January 1st 1980 earthquake (modified from Montesinos et al., 2003). The red line square shows the location of São Sebastião area.

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