13th World Conference on Earthquake Engineering
Vancouver, B.C., Canada
August 1-6, 2004
Paper No. 1004

CORRELATION BETWEEN DAMAGE DISTRIBUTION AND SOIL BEHAVIOUR ESTIMATED WITH AMBIENT VIBRATIONS

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SUMMARY

The January 1st, 1980 earthquake produced severe damages in the Angra do Heroísmo town, with a non-homogeneous spatial distribution. In order to understand the observed pattern a microtremor survey was carried out, using ambient vibrations, and the data were analysed following the Nakamura methodology. The obtained results are in good agreement with the surface geology and they show a good correlation with the observed damages. Taking advantage of two building surveys performed in 1980 and 2000, some building parameters were also analysed. With all these elements for 2111 buildings it was possible to perform several correlations, which enabled to identify some indicators that could be used to improve the damage estimation for future events.

INTRODUCTION

The Azores Islands are located near the junction (confluence) of the Euro-Asiatic, African and American plates and, because of this geographical location, they have a high seismicity characterized by the occurrence of big earthquakes, a lot of swarms and significant seismic-volcanic activity.

Since their discovery, in the XV Century, we can found several reports describing more then thirty destructive earthquakes and different volcanic eruptions in the Central and Oriental Groups.

The first of these important earthquakes, occurred on the 22nd of October 1522, in S. Miguel island, caused about five thousand deaths and a lot of destruction, in particular in Vila Franca do Campo, the capital of the island at that time.

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Another important earthquake took place in the Central Group, on the 9th July of 1757 and it was considered the most energetic event ever occurred in the Azores. It produced a big destruction in all the islands of the Central Group and caused the death of more than one fifth of the S. Jorge island's population.

During the last century, several earthquakes occurred in Terceira island. The last one took place on the 1st January of 1980. This event destroyed a lot of buildings in the islands of S. Jorge, Graciosa and Terceira and it caused a lot of damage in Angra do Heroismo, Terceira's capital. The maximum Mercalli modified intensity (MMI) was VIII (see figure 1).

Figure 1 – Mercalli modified intensities (MMI) felt in Terceira island during the 1980 earthquake (from IM).

This event caused more than fifty deaths, hundreds of injuries and thousands of homeless. The earthquake occurred at 16:42:39h (UTM) and was located about 50 km west from Angra do Heroismo (38,75° N; 27,25° W [ISC]). The magnitude was 6.9 Mw [NEIC] and the depth of the focus was about 10 km. In this earthquake more than 3000 buildings were totally or partially destroyed, most of them in Terceira island and, in particular in Angra do Heroismo.

The damage distribution in this town was not homogeneous [1] (see figure 2). This can be caused by two main reasons: (1) different behaviour of the several houses and buildings in the town; (2) different amplitudes of soil movement, do to several seismic behaviour of the most superficial layers.

The first hypothesis does not justify the observed damage distribution, and therefore the heterogeneity observed must be a consequence of site effects due to the upper geology and the topography.

The town is settled on two different kinds of geological formations: in the North and North West part of the town, the formations are stiff and composed by trachyts and trachy-andesites; in the South and South East part of the town, formations are composed by pyroclastic materials in layers of about 20 m thick. These two formations present different geotechnical properties and, consequently, different seismic

behaviour. On the other hand, the town shows an irregular topography with a depression in the central part near the sea, surrounded by hills in the North, East and West.
Trying to understand the different behaviour observed, a microtremor survey was carried on, by recording seismic noise in different points along the streets and, in some buildings. Taking advantage of building surveys performed in 1980 and 2000 [2,3] in the classified central part of the town (ZCAH), and using an empirical expression derived by Oliveira [4], it was possible to estimate the natural frequency of the different buildings considering their age and the number of stories. Several correlations between the different parameters were performed, which enabled the identification of the main parameters that influenced the observed damage distribution in 1980, providing some indicators that can improve the damage estimation in future events.

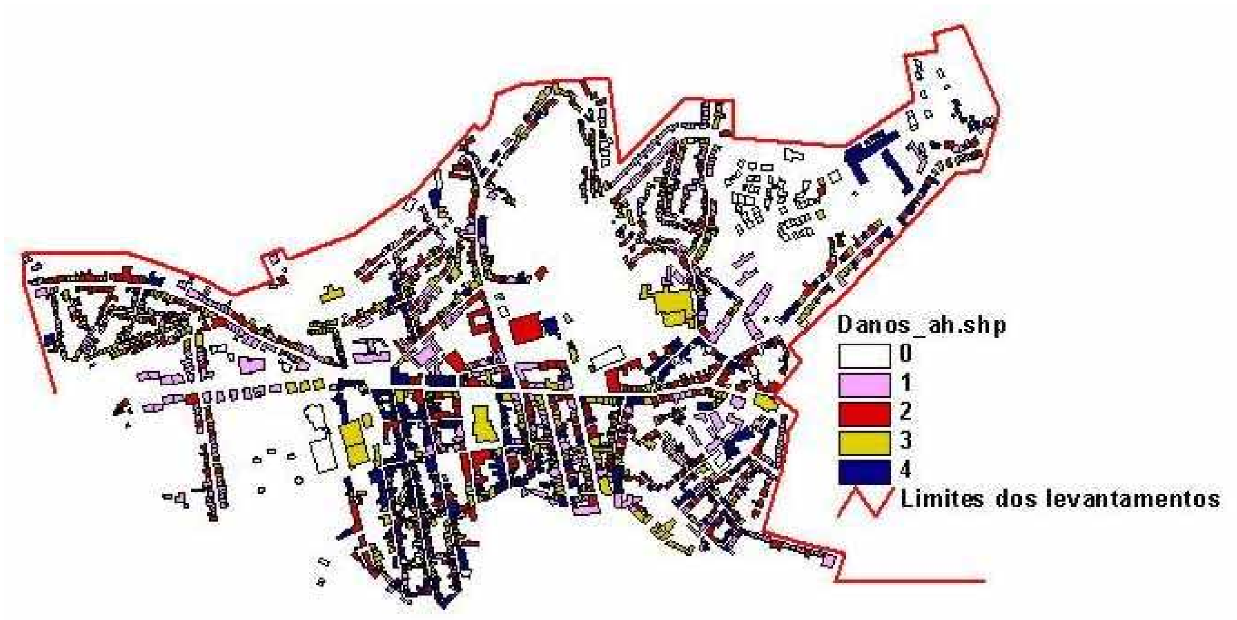

Figure 2 – Damage distribution in Angra do Heroísmo (ZCAH) (from [1]).

MICROTREMOR SURVEY

Detailed description of the microtremor survey was already presented in Teves-Costa and Senos [5]. We present here only a brief description for a better understanding of the data discussion.
Microtremor records were obtained in 230 points distributed along the streets that suffered more damages in the 1980 earthquake, according to a spatial grid with approximately 50 m wide. Four seismic stations were equipped with 3D Lennartz seismometers, with a natural frequency of 1 Hz. The duration of each record was 10 minutes. Most of the records were performed during the day and only a few were performed during the night, due to the intense traffic in some streets.
We used the methodology proposed by Nakamura [6,7], computing the H/V spectral ratio (the composition of the spectra of the horizontal components divided by the spectrum of the vertical component). Data processing was performed using the JSesame software developed under the Sesame project [8], which enable a quick visualization of the results, allowing the choice of several processing parameters (composition of the horizontal components, filtering, smoothing, window selection, etc.). For each record we select several windows of 20 seconds long, according to an algorithm developed in order

to choose the most "quiet" windows (figure 3). We compute the H/V ratio for each window, and the H/V ratio for the record is the mean of all the selected windows. After analysis of all the H/V ratios we selected for each record the peak frequency and its corresponding amplitude. According to Nakamura, this peak frequency corresponds to the natural frequency of the surface layers. So, they should be in good accordance with the surface geology. Figures 4 and 5 present, respectively, the distribution of the obtained peak frequency and the distribution of the surface geology. These two parameters are presented over the building distribution for the central part of the town. By visual inspection of figures 2, 3 and 4, it is possible to see the existence of a correlation between the peak frequency and the surface geology, as well as a correlation between the peak frequency and the damage distribution. Also it would be possible to observe that, in downtown, damages were more severe in the zones that present higher amplitudes for the peak frequency. All these correlations will be presented later, in the discussion paragraph.

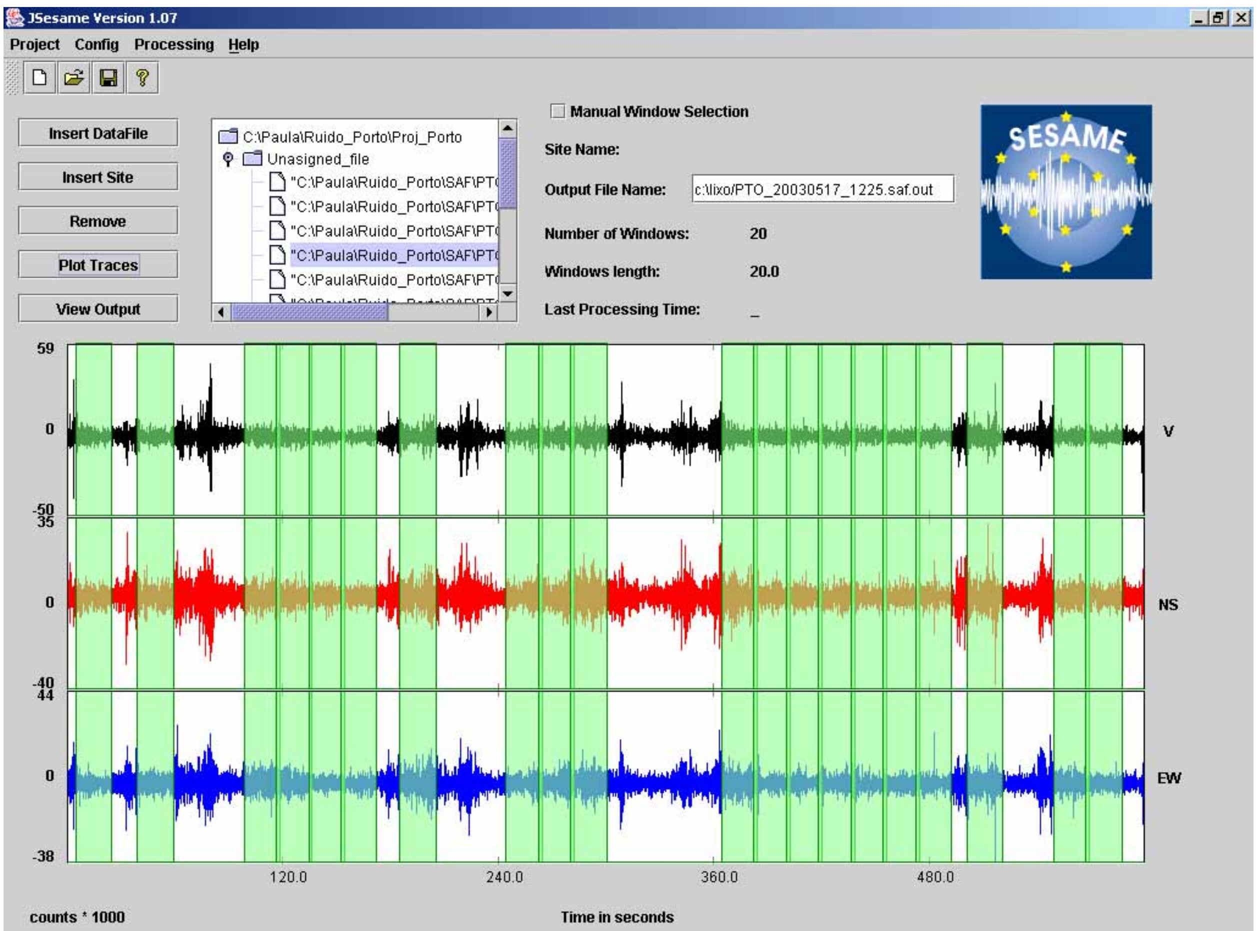

Figure 3 – Main screen of the JSesame software showing the 3 traces corresponding to the 3 ambient vibration components. The window selection algorithm selected the most "quiet" windows, rejecting the most perturbed part of the record (here due to intense traffic).

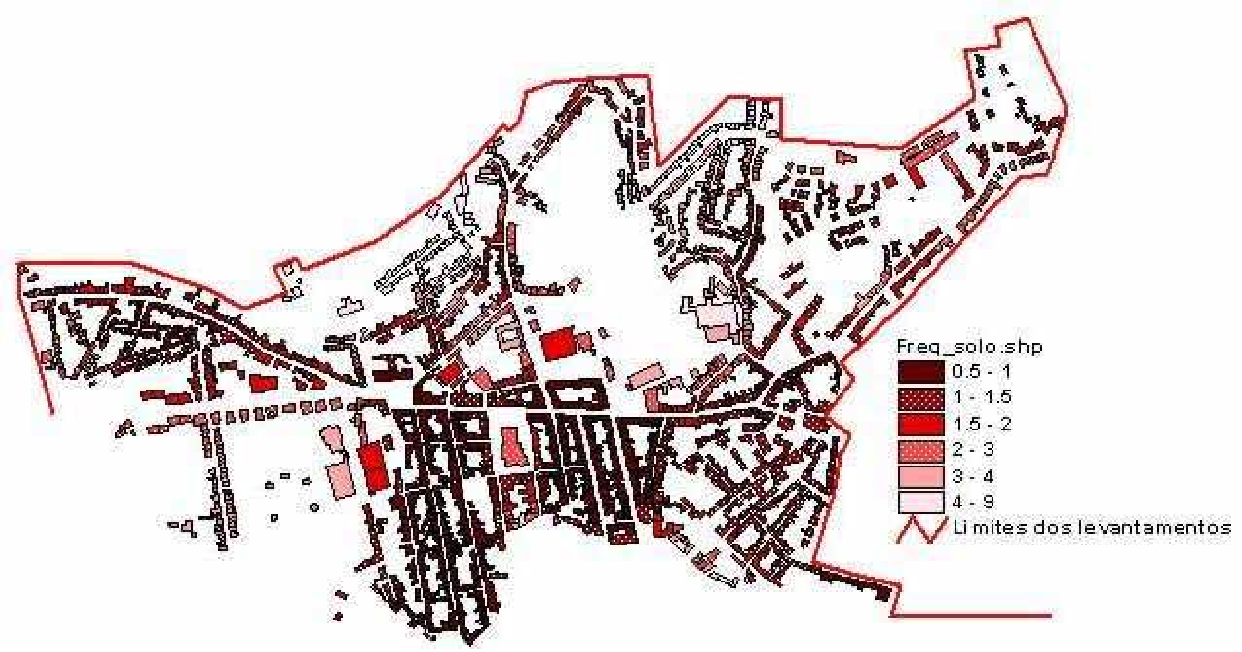

Figure 4 – Soil peak frequencies, determined by ambient vibrations analysis, marked upon the building stock survey. Each building is assigned to the soil peak frequency where it is settled.

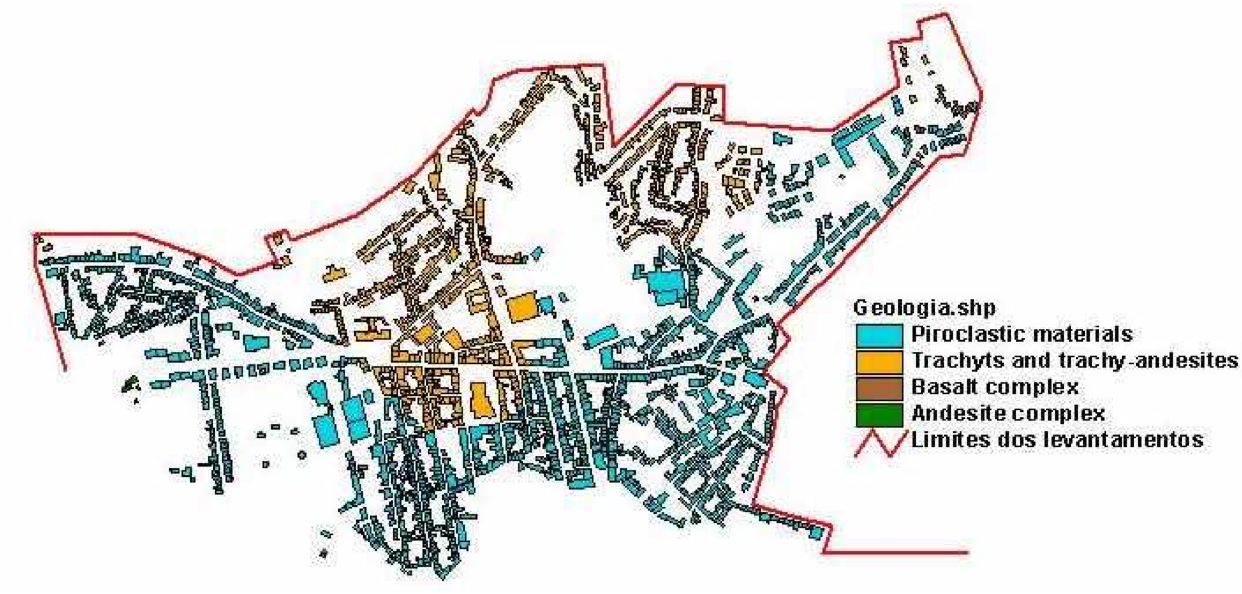

Figure 5 – Surface geology, marked upon the building stock survey. Each building is assigned to the geological formation where it is settled.

BUILDING STOCK CHARACTERIZATION

The building stock of Angra do Heroísmo, in the ZCAH, and at the time of the 1980 earthquake can be divided in two main categories:

(i) Buildings with mansory walls made of stones of local volcanic material arranged in a more or less order, 2 to 4 storey high. Interior partitions are timber walls or made of concrete blocks; pavements are made of wooden beams supporting timber floors; roof of heavy clay tiles supported by spatial wooden trusses; stairways are stone made until the second storey and wooden in the upper levels. These buildings, which present larger spaces in the first floor for commercial areas, use arches of good quality parallel to the façades to give support to the second floor beams. They were built since the XVII century until 1950-60.

(ii) Buildings of identical size as in (i) but containing some kind of connecting elements made of light reinforced concrete columns and beams, located at corners and intersections of interior walls with façades and reinforced concrete light slabs. This type of construction was introduced in the 1940, but for practical effects only in the decade 1950-1960 they were widely spread.

The building stock suffered several structural damages during the 1980 earthquake that, according to other studies about the behaviour of simple structures, could produce maximum accelerations of 150 to 250 cm/s^2. The damages were classified in 4 categories: (1) slight or no damage, (2) moderate damage, (3) severe damage and (4) collapse. Figure 2 presents the damage distribution according to a survey performed just after the earthquake (in this figure, buildings presenting damage of level 0 are buildings that did not exist at that time or that were not include in the survey). The most important damages occurred in the central southern part of the town where entire blocks suffered severe damages. In other blocks the damage distribution is more irregular, with the central buildings or the corner buildings exhibiting higher damages.

Based on ambient vibrations recorded in several buildings, in Angra do Heroísmo and other places presenting similar typologies, Oliveira [4] derived an empirical law of vibration periods (T), corresponding to the lowest modes, with the form $T=\alpha N$, where T is expressed in second, N is the number of stories and α is a parameter obtained by a least square fit (Table 1). Two values of α were obtained, the linear derived directly from the ambient vibrations measures and the non-linear, which already reflects a different behaviour for higher levels of the input soil motion.

Table 1 – Values of the α parameter

Typology	Linear	Non-linear
Constructed before 1950-60	0.06	0.09
Constructed between 1960-1980	0.05	0.08

DATA CORRELATION AND RESULTS

All the data were included in a GIS composed by several layers, each of them corresponding to one parameter. The main layer is the building localization and, for each building the number of stories, the age of construction, the suffered damage, the soil frequency and the geology where it is settled, are assigned. This data is complete for 2111 buildings and several correlations between the parameters were performed. The main results of the different correlations are:

(i) Age of construction: for the buildings constructed before 1960 the damage were distributed in a nearly uniform way for the different levels of damage, while for the buildings constructed after 1960 the damages are more concentrated in level 1 (figure 6);

(ii) Number of stories: buildings with one storey presents a higher percentage in the level 1 damage category; buildings with two stories (the most frequent) and 3 stories, the distribution of damage for all the damage levels are quiet uniform, exhibiting however a high number of collapses (figure 7);

(iii) Building frequency: all the buildings present high natural frequencies, between 4 and 10 Hz. The damages are uniformly distributed for all the damage levels for the buildings with natural frequencies up to 5 Hz; for buildings with higher natural frequencies, the light damages (level 1) became more frequent (figure 8);

(iv) Surface geology: damages are uniformly distributed for all the damage levels in the zones settled on the pyroclastic materials; buildings settled on the rock formations (trachyts and trachy-andesites), present mainly light damages (figure 9);

(v) Soil peak frequency: for frequencies below 1 Hz, the percentage of collapses is very high; for frequencies between 1 Hz and 1.5 Hz, the distribution of the damages in the different levels are more uniform; for frequencies of 3 Hz or higher, the lighter damages seem to be more frequent (figure 10).

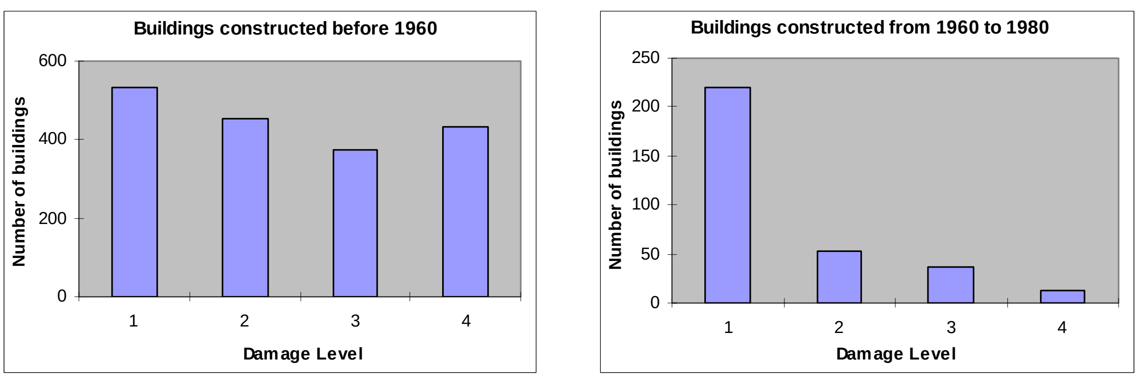

Figure 6- Damage distribution for the buildings constructed before 1960 (left graph) and for the buildings constructed between 1960 and 1980 (right graph).

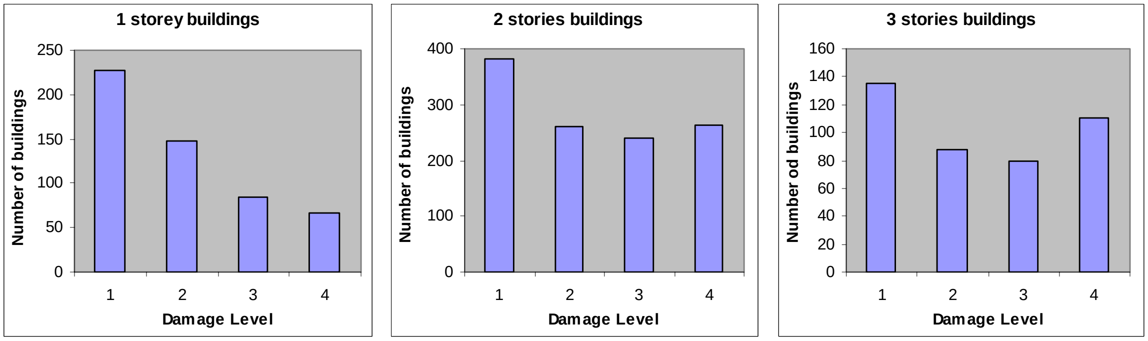

Figure 7- Damage distribution for the buildings with one storey (left graph), 2 stories (central graph) and 3 stories (right graph).

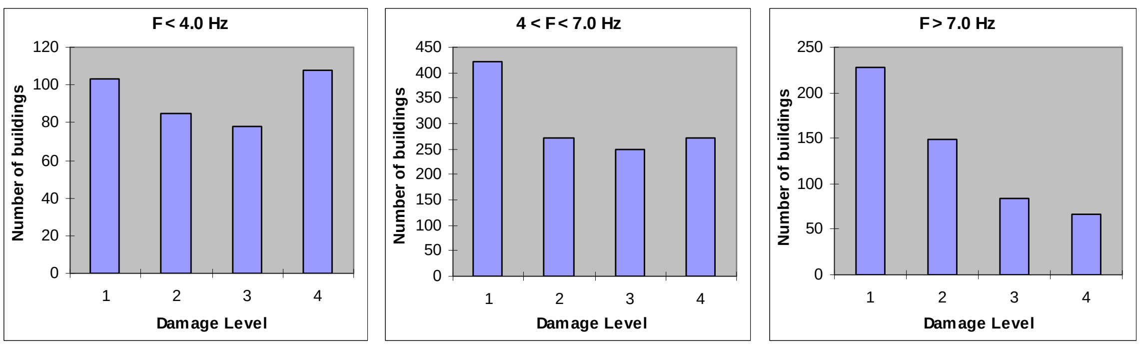

Figure 8: Damage distribution for buildings with different natural frequencies.

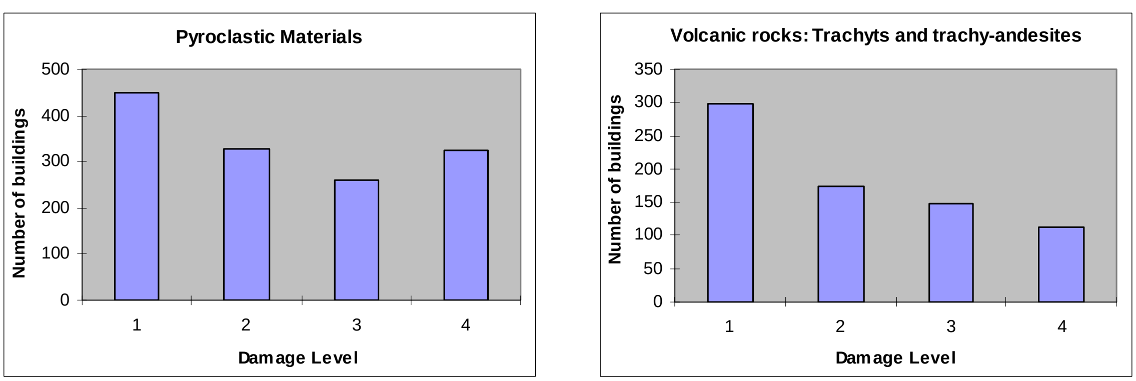

Figure 9: Damage distribution on buildings settled over pyroclastic materials (left graph) and over volcanic rocks (right graph).

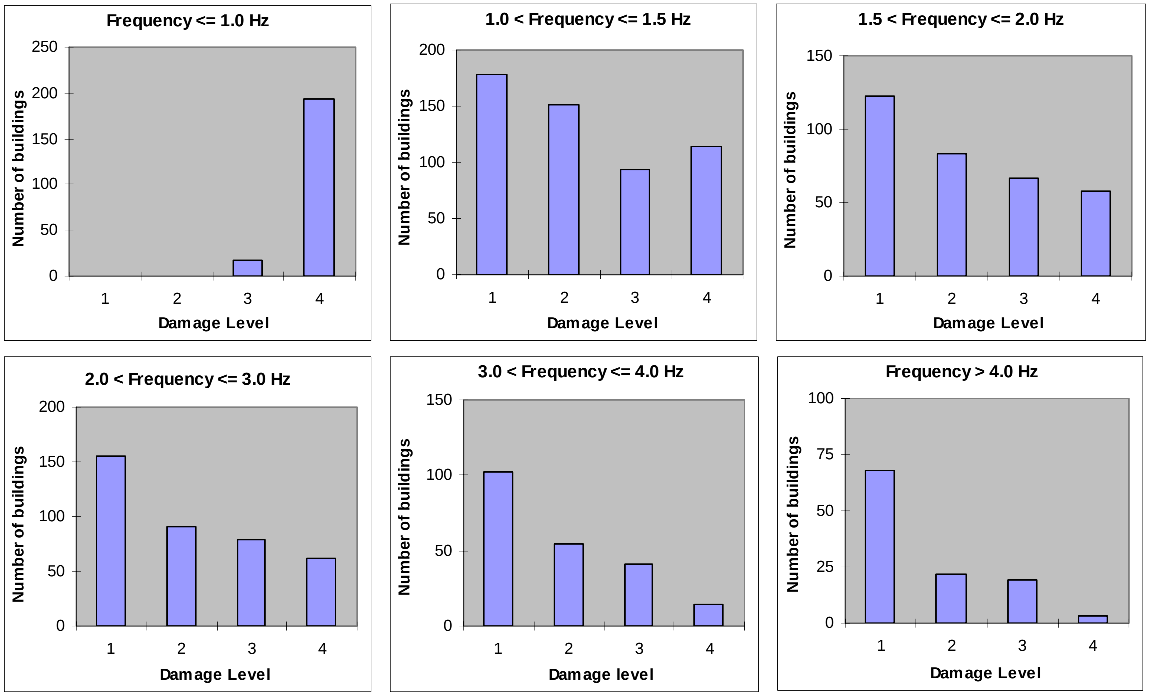

Figure 10 – Damage distribution for buildings settled in soils with different peak frequencies.

CONCLUSIONS

The different seismic behaviour of the geological formations covering the Angra do Heroísmo town was observed by the identification of the peak frequencies obtained from ambient vibrations recorded in several sites along the town. The geological formation composed by pyroclastic materials presents a peak frequency between 1 and 2 Hz, while the rock formation presents peak frequencies between 3 and 7 Hz. Besides, the amplitudes of these peaks show a light correlation with the damage distribution observed in the 1980 earthquake.

The correlations between the observed damages and the several parameters that characterized the building stock (age of construction, number of stories and natural frequency) clearly show the influence of these parameters for the building seismic behaviour.

In the near future the authors intend to study the influence of the topography and to use the acquired knowledge to estimate seismic scenarios for future earthquakes.

ACKNOWLEDGEMENTS

The authors would like to thank all the persons involved in the field survey, from the Institute of Meteorology (Azores delegation), the University of Lisbon (FCUL) and the Technical University of Lisbon (IST). A special thank is due to José Correia Guedes for the technical support in some field experiments, as well as for making available some elements concerning the surface geology and the building characteristics. This work was partially financed by the SESAME European project (EVG1– CT – 2000 – 00026) and the MASHA Portuguese project (POCTI/CTA/39158/2001).

REFERENCES

1. Lucas, A., C.S. Oliveira and J.H.C. Guedes, 1992. “Quantification of the damages observed in the building stock and the reconstruction process”. In: Oliveira, C.S., Lucas, A.R.A. and Guedes, J.H.C. (Ed.): Monograph: *10 After the January 1st, 1980, Azores Earthquake*, SRHOP, LNEC, p. 667-742 (*in Portuguese*).
2. Lucas, A., J.H.C. Guedes and C.S. Oliveira, 1992. “Contribution for the historiography of the January 1st, 1980 earthquake. GAR archives and the documentation about the reconstruction”. In: Oliveira, C.S., Lucas, A.R.A. and Guedes, J.H.C. (Ed.): Monograph: *10 After the January 1st, 1980, Azores Earthquake*, SRHOP, LNEC, p. 263-274 (*in Portuguese*).
3. Caiado, G. and Pais, G., 2000. “Analysis of some data present in the GAR reports and the SRHOP data about the reconstruction”. *PPERCAS project (in Portuguese)*.
4. Oliveira, C. S., 2004. “Actualisation of the data base concerning the natural frequencies of structures using expert *in-situ* measurements”, *Sísmica 2004*, Guimarães (Portugal), 14-16 April (*in Portuguese*).
5. Teves-Costa, P. e M.L. Senos, 2004. “Seismic zonation of Angra do Heroísmo using ambient vibrations”, *4th Portuguese and Spanish Assembly on Geodesy and Geophysics*, Figueira da Foz (Portugal), 3-7 February (*in Portuguese*).
6. Nakamura, Y., 1989. " A method for dynamic characteristics estimation of subsurface using microtremor on the ground surface”, *RTRI*, **30-1**, p. 25-33.
7. Nakamura,Y., 2000. “Clear identification of fundamental idea of Nakamura's technique and its applications”, *12th World Conference on Earthquake Engineering*, Auckland (New Zealand).
8. Sesame, WP03 Team, 2003 “Multiplatform H/V processing software J-SESAME”. Deliverable D09.03, June 2003.