ANALYSIS OF SITE EFFECTS AND THEIR CORRELATION WITH DAMAGE DISTRIBUTION OBSERVED DURING THE COLIMA (MEXICO) EARTHQUAKE OF JANUARY 21, 2003

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ABSTRACT:

In order to evaluate the influence of ground condition on damage distribution in Villa de Alvarez town (Colima, Mexico) during the 2003 Colima earthquake (M_W=7.8), several geophysical surveys were carried out. The structure of shallow sedimentary materials and the depth of the basement have been estimated applying the Spatial Autocorrelation method (SPAC), using several regular pentagonal arrays with radii up to 25m. Seven S-wave velocity (V_S) profiles have been inverted in Villa de Alvarez by using Rayleigh wave velocity dispersion curves for depths down to 30m. According to the local shallow structures obtained, we find clear lateral variations in the velocity structure for several urban zones that are correlated with different damage level. Microtremor measurements were recorded at 70 sites with a grid of about 100m x 100m interval across damaged area. The horizontal-to-vertical spectral ratios (HVSR) were determined in order to obtain the predominant period for each site. The predominant period range in the studied zone is about 0.1 – 0.6sec. Shorter predominant periods (0.1-0.2sec) were found in damaged zone whereas larger periods (greater than 0.4sec) were obtained in urban areas without damage. The site effects and their correlation with damage distribution on masonry structures observed during the 2003 Colima earthquake were very clear and remarkable. One of the main results has been that masonry houses with one or two storeys located on soils with dominant period around 0.15sec in Villa de Alvarez, showed the most serious damages.

KEYWORDS: Soil conditions, Microtremor, SPAC, Shear velocity profile, site effects.

1. INTRODUCTION

The evaluation of local site effects based on subsurface ground conditions is very important to accurately define the seismic hazard for a city. The softness of the surface ground and the thickness of surface sediments have been observed as two important local geological factors that affect the level of earthquake shaking. Their local variations can lead to spatial seismic intensity differences and may have a remarkable influence on the level of building damage and on the damage distribution.

The relationship between soil amplification and the level of damage has been recently confirmed for several large earthquakes (Mw > 6.5) and analysed with regard to deep soil structures and tall buildings (Seo, 1998; Cranswick et al., 2000; Bakir et al., 2002). Also, a large number of observational studies show that local amplification effect has played a role in the seismic damage distribution in urban areas for several moderate earthquakes (Mucciarelli & Monachesi, 1998; Panou et al., 2005; Navarro et al., 2007).

Since the earlier work of Kanai (1954) methods of ground prospecting based on study of propagation of microtremor (ambient noise), have been extensively employed. Several methodologies for analysis of microtremor records are commonly used and are based on the following facts: (a) the first resonant period T_0 in the horizontal-to-vertical spectral ratio for microtremor fits roughly the peak of the transfer function of vertical incident S-waves (Nakamura's method), then, larger amplification are expected for periods around that resonance, also in case of strong motion (Lachet and Bard, 1994, Konno and Omachi, 1998). For simple models, $T_0/4$ also approximates the travel-time of a vertically incident S-waves along a sedimentary bound (Ibs-von Seht and Wohlenberg, 1999, García-Jerez et al. 2006); (b) The V_S - depth variation for the shallow structure is strongly related with the shape of the dispersion curve of Rayleigh waves. These data may be retrieved from array records of seismic noise (Aki, 1957; Capon, 1969).

The relation between surface wave dispersion curves and elastic parameters of the ground has been extensively used in geophysical prospecting, using earthquakes or controlled sources for derivation of 1-D layered ground models (e.g. Nazarian, 1984; Navarro et al., 1997; Tokimatsu, 1997; Park et al., 1999). The capability of the spatial autocorrelation method for microtremor analysis (SPAC method), for determining the elastic properties of shallow sedimentary deposits has been proved as an innovative and convenient technique for this kind of studies (e.g. Parolai et al., 2005; García-Jerez et al., 2007; Navarro et al., 2008).

The main goal of this study is to analyze the local site effects in Villa de Alvarez from the shallow S-wave velocity structure and their correlation with the damage distribution observed during the 2003 Colima earthquake.

3. THE 2003 COLIMA EATHQUAKE

The 2003 Colima Earthquake (M7.6) occurred at 20:06:31 (local time) on January 21st, 2003, with epicentre around 200 km far from Colima city. The epicentral zone is located in the subduction zone of the Pacific Coast of Mexico. The earthquake caused heavy and widely distributed damages in the Colima State for residents and buildings, including 26 death and 1,000 injured people. A total of 22,293 dwellings were affected (Sisplade, 2003). The damage distribution shows that the most serious damages were concentrated in Colima city (6,801 damaged buildings) and Villa de Alvarez town (2,200 damaged buildings), located just west of Colima city. The damage distribution in Villa de Alvarez was concentrated mainly in the east zone of the town (Figure 2) and the most relevant damage occurred in adobe and masonry houses with 1 or 2 storeys. 630 dwellings suffered heavy damages, 465 dwellings were middle damages and 248 dwellings suffered slight damages.

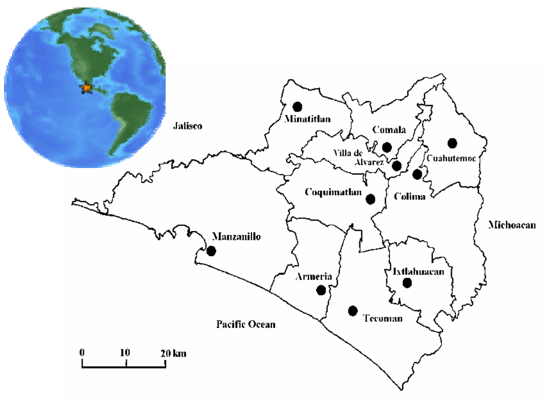

Figure 1. Location of the epicenter of 2003 Colima earthquake and Villa de Alvarez town in the Colima State.

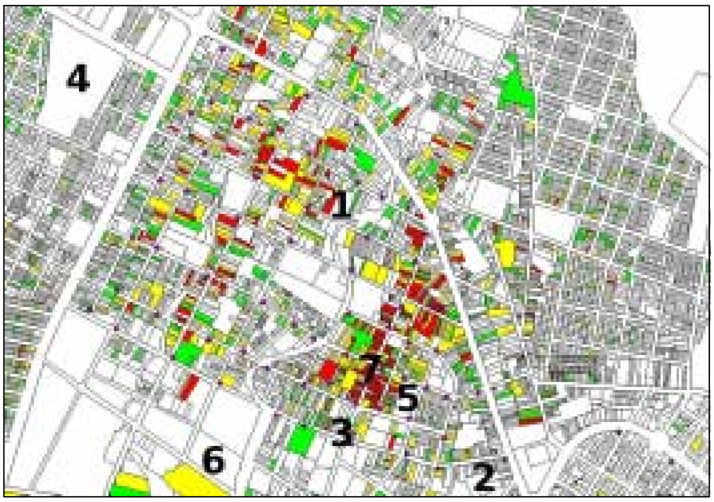

Figure 2. Distribution of damaged buildings in Villa de Alvarez (red block: heavy damage; green block: middle damage; yellow block: slight damage) and location of SPAC sites (Numbers: 1-7)

3. ANALYSIS AND RESULTS

3.1. Computation of HVSR and predominant period

A full study of the dependence of the damage distribution due to the 2003 Colima earthquake on site effects was presented by Enomoto et al.(2004) taking into account the predominant period distribution of soil. A summary of it is presented in this section in order to make comparisons among predominant periods, phase-wave velocity values, shear-wave velocity models and damage distribution in Villa de Alvarez town.

Microtremors measurements were recorded at 63 sites in Villa de Alvarez town with a 100m x 100m grid, in order to investigate the ground shaking characteristics. The measures were performed in February 2003, using two data acquisition systems composed of three-components high-sensitivity VSE-15D seismometers, which have a natural period of 1 second, and a SPC-35 digitizer to record the horizontal and vertical components of microtremors at each site. Each observation time was 180 s and the signal was sampled every 0.01 seconds. The signal was Fourier transformed and smoothed using a 0.3 Hz Parzen's window and the horizontal-to-vertical spectra ratio (Nakamura' method) was applied to obtaining the predominant period at each site.

According to the H/V spectrum results, the predominant period values varied between 0.1 and 0.6 sec. We investigated the site effect from the spectral characteristics by carefully dividing the observation sites into two groups. The first group corresponds to sites at undamaged zones (Figure 3a) and the second group to those with heavily damaged buildings (Figure 3b). The average H/V spectrum in each zone was calculated in order to obtain its characteristic predominant period (Figure 4). A clear spectral peak appears for periods about 01 - 0.2 sec at the heavy damage zone, and also another spectral peak in the range from 0.4 to 0.6 sec. On the contrary, the shorter period peak was not found in the undamaged zone, whereas the peak at longer period remains.

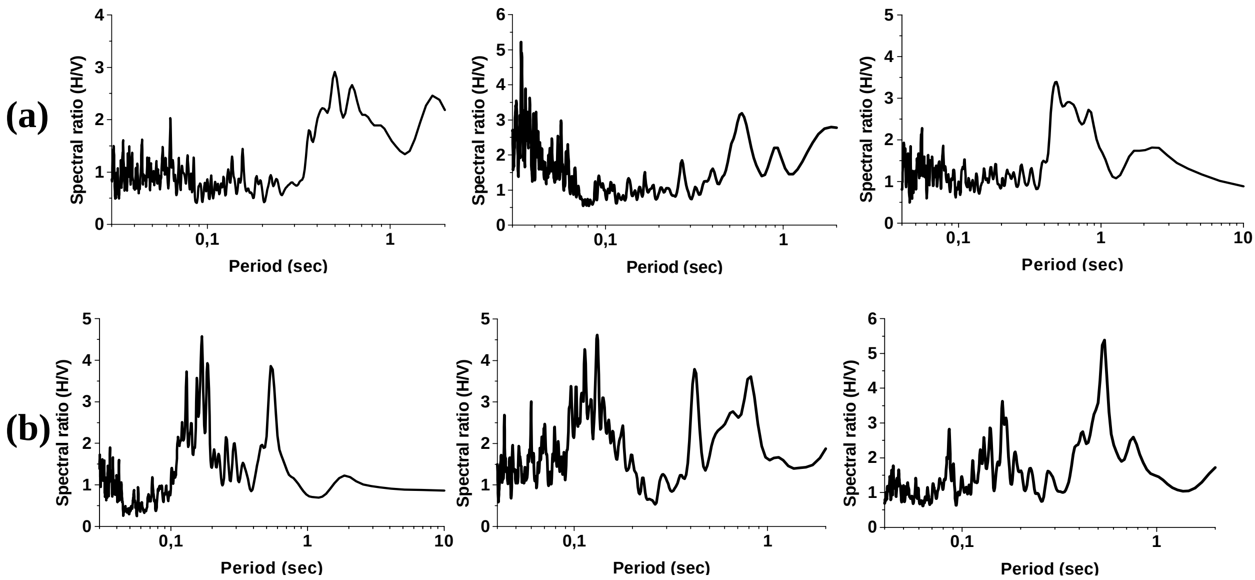

Figure 3. Examples of spectral ratios in Villa de Alvarez town. (a) Sites located in the undamaged zone; (b) Sites located in the heavily damaged zone.

3.2. Rayleigh velocity dispersion curves

The shallow structure of Villa de Alvarez town has been studied using a Spatial Autocorrelation method (SPAC). The measurements were carried out in March 2007 at seven open spaces (Figure 2). Three of them (SPAC 2, 4, 6) were placed at undamaged zones whereas the other four points (SPAC 1, 3, 5, 7) were located on zones with heavily damaged buildings. Shear-wave velocity profiles were obtained for each site, by means of inversion of the Rg-wave dispersion curves.

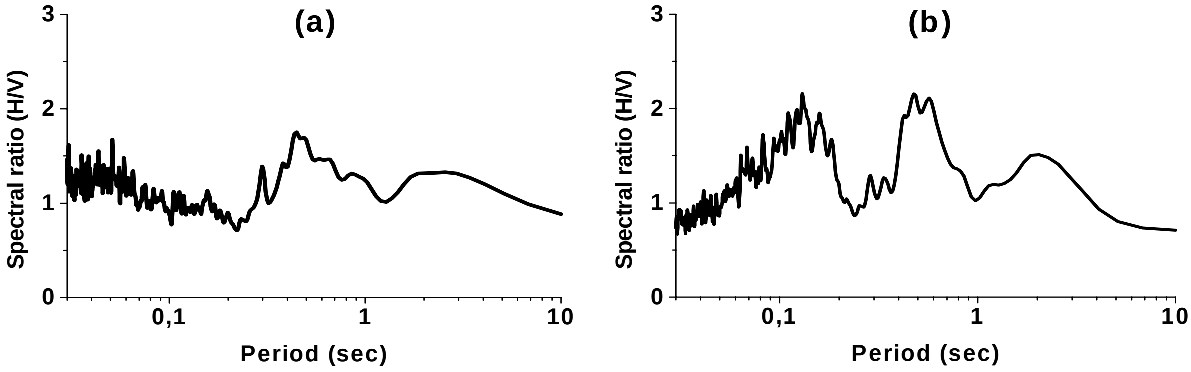

Figure 4. Site effect characteristics from H/V spectra: (a) Undamaged zone; (b) Heavily damaged zone.

Vertical components of ground motion, excited by microtremors, were recorded using circular-shaped arrays. Five high sensitivity VSE-15D sensors surrounding a sixth central sensor with the same characteristics were performed. The radii R ranged from 3 m to 25 m at each point. We used different radii depending on the expected thickness of sediments and on the workable space dimension. Recording time was 30 minutes, and the signal was sampled with a rate of 100 samples per second. These devices provide an acceptable response for frequencies ranging from 0.25 to 70 Hz. All records have been analysed by using an implementation of the SPAC method (Aki, 1957). In order to obtain the correlation coefficient ρ(f,R), the cross correlations between records on the circle and the central station were calculated in frequency domain. Then, the azimuthal average was divided by the autocorrelation at the central station. Finally, phase-velocity of the Rg-wave c(f) was computed for each frequency f, applying a previous polynomical fit of the ρ vs. f relation.

Reliable dispersion curves were obtained for frequencies ranging from 3.5 to 28.8 Hz and phase velocity values between 223 and 680 m/sec. The phase-velocity values decrease as the frequency increases in all cases. The average Rg-wave phase velocity dispersion curve in undamaged zones shows higher phase-velocity values from 306 to 549 m/sec for frequencies ranging between 3.5 and 21.8 Hz (Figure 5a). In the opposite end, the damaged zone presents the lowest phase-velocity values ranging between 223 and 680 m/sec for frequencies between 3.8 and 28.8 Hz (Figure 5b).

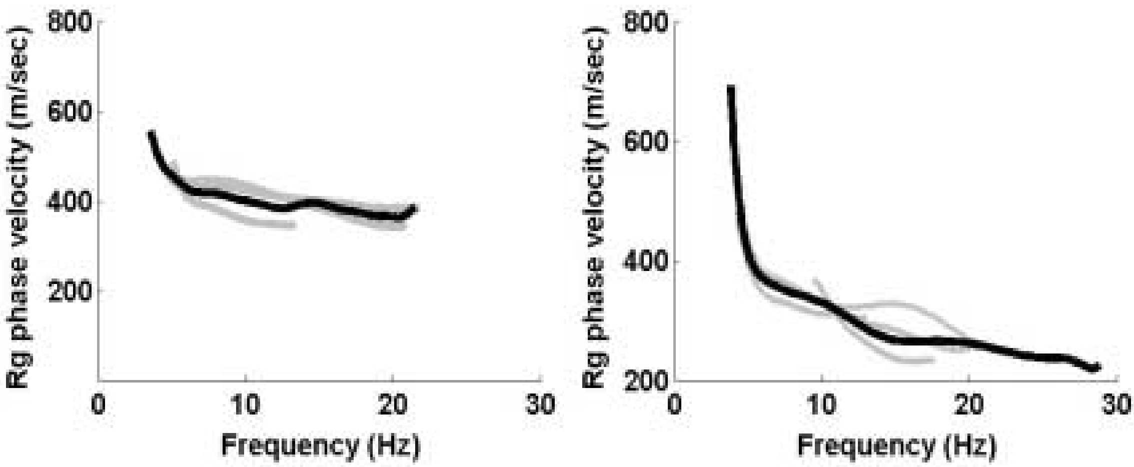

Figure 5. Rg-wave phase velocities (grey lines) measured at the SPAC sites and respective mean velocity curves (black lines). (a) Undamaged zones (SPAC 2, 4, 6). (b) Damaged zones (SPAC 1, 3, 5, 7).

3.3 Inversion of S-wave profiles

We have inverted Rg-wave phase velocities in order to obtain tentative shear-wave velocity models. As is well known, most of iterative inversion methods require building up a proper initial ground model. Since we had serious uncertainties on the thickness and the stiffness of the sedimentary deposits in Villa de Alvarez town, we built an simple initial ground model taking into account the interpretation of electrical geophysical tests performed by the Volcanologic Institute of Colima (Ramirez, 2007) on the damaged building zone (Guillermo Prieto street area). In spite of the differences in the dispersion curves for several SPAC measurements, the initial model was the same for all SPAC sites. Such initial model is made up of two homogeneous layers of 10 and 40 m thick (obtained from the electrical surveys) and S-wave velocity values of 200 and 400 m/sec respectively (obtained from the dispersion data by means of the λ/3 criterion, e.g. Tokimatsu, 1997) overlaying a half-space of 1000 m/sec. The inverted shear-wave velocity profiles are shown in Figure 6 for depths from 0 to 80 m. The values of shear-wave velocity for the upper two layers range between 242 and 525 m/sec.

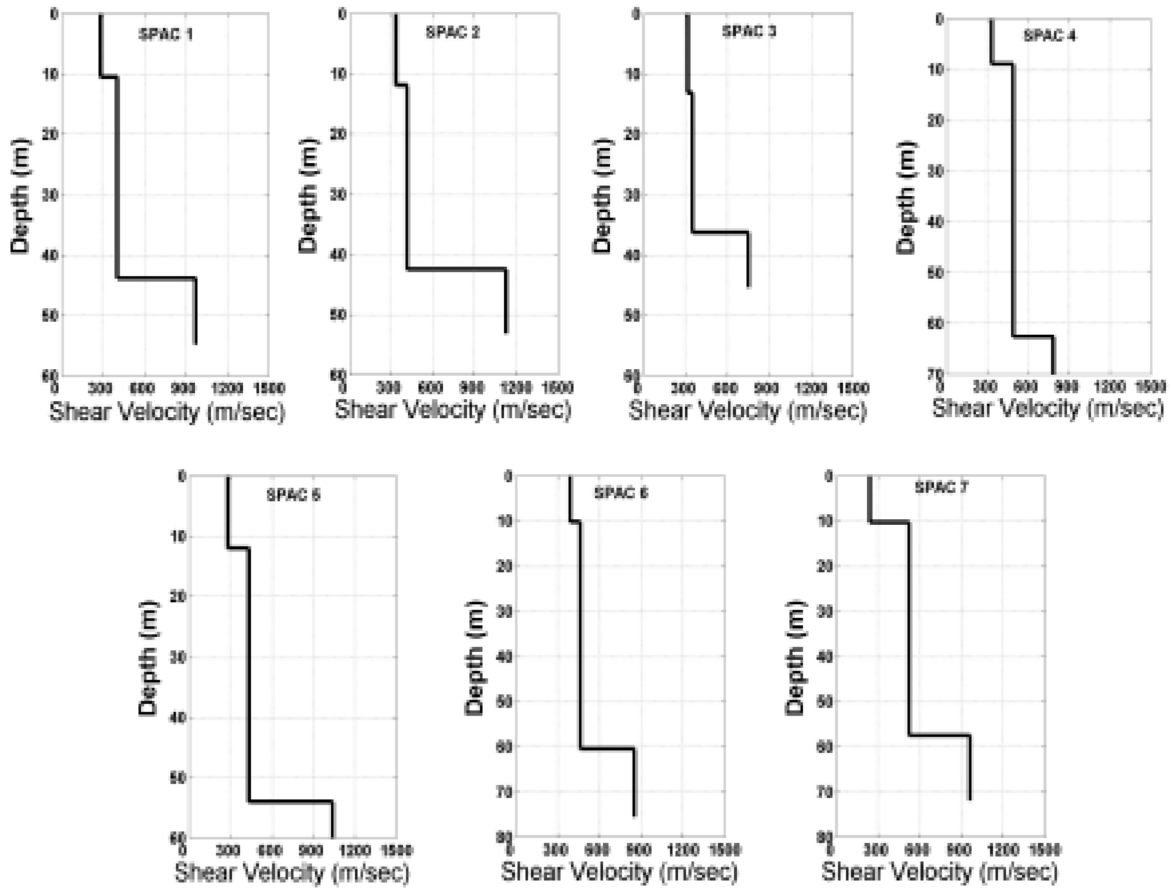

Figure 6. Shear-wave velocity models derived from inversion of phase velocities of Rayleigh waves.

The reliability of the inverted models has been checked by means of forward modelling. As known, the good agreement found (Figure 7) does not necessarily ensure the uniqueness of the results, but it does indicate that the models obtained are compatible with the velocity data.

In order to highlight the differences between the shear-wave velocity models of damaged and no-damage zones, the shear velocity models have been also grouped and averaged for each zone. It permits a easier interpretation of the predominant periods of soil, their distribution and a possible relation with the damage distribution due to the 2003 Colima earthquake in Villa de Alvarez town. There is some degree of lateral variation in shear-wave velocity between that pair of zones. The no-damage zone (SPAC 2, 4 and 6) presents the highest shear velocity values, ranging between 332 m/s and 389 m/s for the shallowest layer of 0 to 12 m depth. The average shear velocity model for this area exhibits a first layer of 10.4 m thick and average shear-wave velocity of 352 m/s; and a second layer with 460 m/sec and 55 m thick overlaying a half-space of 922 m/s. In the opposite end, the lowest shear velocities appear in the damage zone (SPAC 1, 3, 5 and 7) with values between 242 m/s and 316 m/s for depths from 0 to 13 m. The average shear-wave velocity model for the damage area shows a first layer of 11.5 m thick and average S-wave velocity value of 282 m/s; and a second layer of 429 m/s and 48 m thick overlaying a half-space with 931 m/s S-wave velocity. These results reveal the existence of lateral variation of shear-wave velocity in the Villa de Alvarez town, due to heterogeneities of the ground structure, mainly for the shallowest layer (depth range from 0 to 13 m).

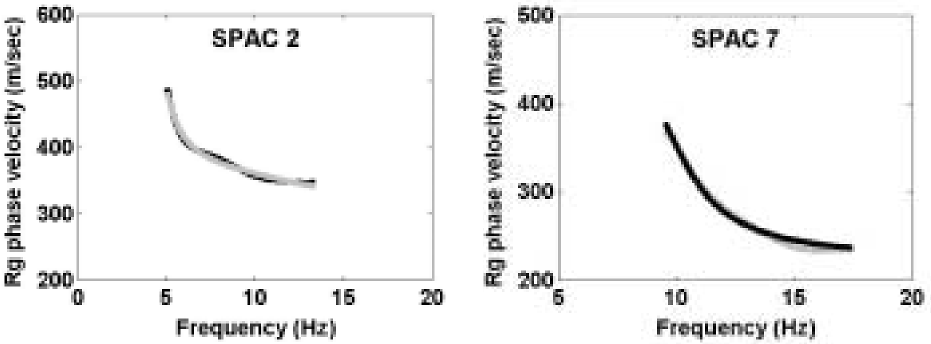

Figure 7. Theoretical phase velocity dispersion curves (grey lines) corresponding with the respective optimum models and measured dispersion curves (black lines).

On the other hand, the characteristic predominant period on the damage zone (around 0.15 sec) obtained from H/V spectral ratio, has been compared with the predominant period calculated from the transfer functions (maximum peak period) for vertically incident S wave (Figure 8). A good agreement between both values has been found.

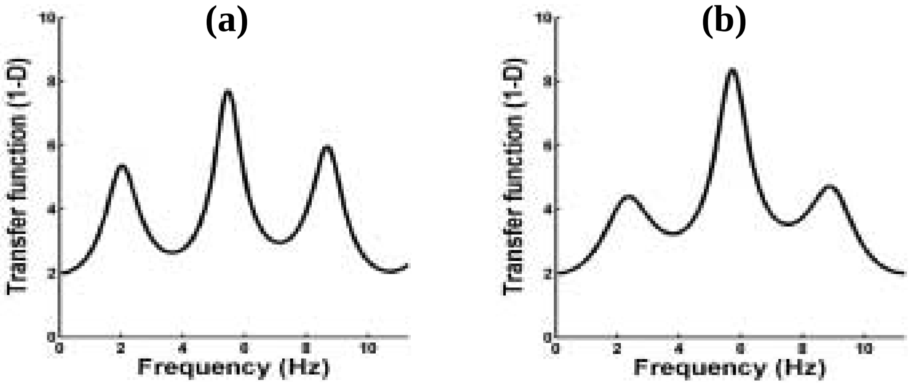

Figure 8. Example of transfer function calculated for some ground models in the damage zone. (a) SPAC 5; (b) SPAC 7.

4. CONCLUSIONS

We analyzed the site effect characteristics in Villa de Alvarez town, by dividing the microtremor observation sites into two groups: no damage sites and heavy damage sites, regarding the 2003 Colima Earthquake.

According to the H/V spectral characteristics, a different behaviour was clearly observed. In the heavy damage zone, clear spectral peaks were found in a short period range between 0.1 and 0.2 sec, whereas these peaks did not appear in the undamaged sites.

Detailed shear-wave velocity structure and depth of the basement have been estimated at seven locations in the town by means of inversion of Rayleigh-wave dispersion data obtained from circular-shaped array setups. These places were considered according to their distribution on damage and undamaged zones. The average Rg-wave phase velocity dispersion curve in the no damage zone shows higher phase-velocity values in comparison with the damage zone. The last one presents the lowest phase-velocity values ranging from 223 to 680 m/s for frequencies between 3.8 and 28.8 Hz.

The comparison among the mean ground models which characterize each urban zone in Villa de Alvarez town, reveals a significant lateral variation in the *S* wave velocity. The more important feature is the existence of a soft shallow layer in the damaged zone with S wave velocity ranging 242 m/s and 316 m/s for depths from 0 to 13 m. This result is good agreement with those obtained from other exploration methods and with the presence of the sand and gravel deposits in de zone due to a local river.

Probably, the high ground amplification in the damaged zones for periods from 0.1 to 0.2 sec had a strong influence on the heavily damaged buildings because of a resonant effect between the shallow ground structure and the building response.

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REFERENCES

Aki, K. (1957). Space and time spectra of stationary stochastic waves, with special reference to microtremors. *Bulletin of the Earthquake Research Institute* **35,** 415–456.

Bakir, B.S., Sucuoglu, H. and Yilmaz, T. (2002) An overview of local site effects and the associated building damage in Adaparzari during the 17 August 1999 Izmit earthquake. *Bulletin of the Seismological Society of America* **92,1** 509-526.

Capon, J. (1969). High-resolution frequency-wavenumber spectrum analysis. *Proceedings of the IEEE* **57:8,** 1408-1418.

Cranswick, E., Özel, O., Meremont, M., Erdik, M., Safak, E., Mueller, C., Overturr, D. and Frankel A. (2000). Earthquake damage, site response and building response in Avcilar, west of Istanbul, Turkey. *International Journal for Housing Science and Its Applications* **24,** 85-96.

Enomoto, T., Lermo, J., Navarro, M., Abeki, N. and Masaki, K. (2004). Site effect characteristics of damage concentrated area due to the 2003 Colima Earthquake (M7.6) Mexico. Proceedings of the 13th World Conference on Earthquake Engineering. Vancouver, Canada. Paper No. 2151.

Fäh, D., Kind, F. and Giardini, D. (2003). Inversion of local S-wave velocity structures from average H/V ratios, and their use for the estimation of site-effects. *Journal of Seismology* **7,** 449-467.

García-Jerez, A., Luzón, F., Navarro, M., Pérez-Ruíz, J.A. (2006). Characterization of the sedimentary cover of the Zafarraya basin (Southern Spain) by means of ambient noise. *Bulletin of the Seismological Society of America* **96,** 957-967.

García-Jerez, A., Luzón, F., Navarro, M. and Pérez-Ruíz JA. (2007). Determination of elastic properties of shallow sedimentary deposits applying a spatial autocorrelation method. *Geomorphology* **93,** 74-88.

Lachet, C. and Bard, P.Y. (1994). Numerical and Theoretical Investigations on the Possibilities and Limitations of Nakamura`s Technique. *Journal of Physics of the Earth* **42,** 377-397.
Ibs-von Seht, M. and Wohlenberg, J. (1999). Microtremor measurements used to map thickness of soft sediments. *Bulletin of the Seismological Society of America* **89,** 250-259.
Kanai, K., Tanaka, T. and Okada, K. (1954). Measurement of the microtremor. I. *Bulletin of the Earthquake Research Institute of Tokio* **32,** 199-210.
Konno, K. and Ohmachi, T. (1998). Ground-Motion Characteristics Estimated from Spectral Ratio between Horizontal and Vertical Components of Microtremor. *Bulletin of the Seismological Society of America* **88,** 228-241.
Mucciarelli, M. and Monachesi, G. (1998). A quik survey of local amplifications and their correlation with damage distribution observed during the Umbro-Marchesan (Italy) earthquake of September 26, 1977. *Journal Earthquake Engineering* **2,** 325-37.
Nakamura, Y. (1989). A method for dynamic characteristics estimations of subsurface using microtremors on the ground surface. *Quarterly Report of Railway Technical Research Institute of Japan* **30**, 25-33.
Navarro, M., Corchete, V., Badal, J.I., Pujades, L., Canas, J.A. and Vidal, F (1997). Inversion of Rg waveforms in southern Spain. *Bull. Seism. Soc. Am.* **87,** 847-865.
Navarro, M., F Vidal, T. Enomoto, F.J. Alcalá, F.J. Sánchez and N. Abeki (2007). Analysis of site effects weightiness on RC building seismic response. The Adra (SE Spain) example. *Earthquake Engineering and Structural Dynamics* **36,** 1363-1383.
Navarro, M., García-Jerez, J.A., Alcalá, F.J., Vidal, F., Enomoto, T., Luzón, F. and Creus, C. (2008). VS30 Structure of Lorca town (SE Spain) from Ambient Noise Array Observations. Proceedings of the 31st General Assembly of European Seismological Commission. Crete, Greece, September 2008.
Nazarian, S. (1984). In situ determination of elastic moduli of soil deposits and pavement systems by spectral analysis of surface waves method. Ph.D. dissertation, Univ. of Texas, Austin.
Panou, A.A., Theodulidis, N., Hatzidimitriou, P., Stylianidis, K. and Papazachos, C.B. (2005) Ambient noise horizontal-to-vertical spectral ratio in site effects estimation and correlation with seismic damage distribution in urban environment: the case of the city of Thessaloniki (Northern Greece). *Soil Dynamics and Earthquake Engineering* **25,** 261-274
Park, C.B., Miller, R.D. and Xia, J. (1999). Multichannel analysis of surface waves. *Geophysics* **64:3,** 800–808.
Parolai, S., Picozzi, M., Richwalski, S.M. and Milkereit, C. (2005). Joint inversion of phase dispersion and H/V ratio curves from seismic noise recordings using a genetic algorithm. *Geophysical Research Letters* **32,** L01303.
Ramirez, J.J. (2007). Electrical geophysical tests in San Isidro area (Villa de Alvarez). Internal report.
Sisplade (2003). Damage distribution in Colima and Villa de Alvarez due 2003 Colima earthquake. Internal report.
Seo K.(1998). A joint microtremor measurement in the Fukui basin to discuss the effects of surface geology on seismic motion during the 1948 Fukui, Japan, earthquake. Proceedings of the XIth European Conference on Earthquake Engineering, Paris. September 6-11, Bis; 1998. Balkema.
Tokimatsu, K. (1997). Geotechnical site characterization using surface waves. Earthquake Geotechnical Engineering, Balkema, Rótterdam.