Full paper

Megacities: Risk, Vulnerability, and Sustainable development

Site effect analysis by means of seismic noise and earthquake data analysis in the large urban area of Santiago de Chile

June 2009

Marco Pilz

Helmholtzzentrum Potsdam
Deutsches GeoForschungsZentrum
Telegrafenberg
14473 Potsdam
pilz@gfz-potsdam.de

A) Background and research questions

The most intense shaking during an earthquake generally occurs near the rupture fault and decreases with distance away from the fault. However, in a single earthquake the shaking at one site can easily be several times stronger than at another site, even when their distance from the rupture fault is the same. Such site effects are mainly caused by the softness of the soil near the surface (shaking is amplified over softer rock) and by the thickness of the sediments above hard rock (shaking is amplified where sediments are thicker). Therefore, seismic site characterization usually requires substantial investment both in time and money for data aquisition. On the other hand, the necessity of estimating seismic risk for very spacious urban areas wants for at least a first order classification of soil and building vulnerabilty and therefore requires proxies. Recently, Wald and Alleen suggested that the slope of topography might serve as a suitable parameter for the estimation of site effects (Wald and Allen 2007). They claimed that this parameter might be suitable independent on the scale.

So, the research questions of the PhD thesis are

1. Can single parameters like slope of topography provide a reliable estimation for seismic velocities?
2. Is the average shear wave velocity in the uppermost 30 meters a suitable parameter for the estimation of site effects?
3. Empirical relationships and suitability of this technique on small scale will be tested.

Therefore, this work consits of studying site response and aquiring the necessary tools to evaluate the proposed proxy using the city of Santiago de Chile as a test site.

B) Methodology

To study the questions mentioned above it is unevitable to assess first the site response which is generally determined by the spectral ratio method using a reference station (e. g. Bard and Riepl-Thomas 2000). Due to the fact that it has provided consistent results (Frankel et al. 2002, Parolai et al. 2000, Bonilla et al. 1997, Field and Jacob 1995), the standard spectral ratio technique (SSR, Borcherdt 1970) is most commonly used. One important precondition for using the SSR technique is the availability of a reference (bedrock) site with negligible site response close to the considered soil site. As this may not always be possible, other methods that can overcome this limitation have been proposed. For example the single horizontal-to-vertical technique using either noise (NHV) or earthquake (EHV) recordings requires one station recording only and uses the vertical component as a reference. The method is a combination of the receiver-function technique proposed by Langston (1979) and the method of Nakamura (1989). Usually, the H/V ratios of ambient noise show a clear peak in good agreement with the fundamental resonance frequency at soft soil sites under the constraint of the existence of a large impedance contrast between the sediments and bedrock (Bard 2004, Horike et al. 2001, Field and Jacob 1995, Lermo and Chavez-Garcia 1994). In contrast, the peak amplitude of the microtremor ratio often tends to underestimate the peak amplitude of earthquake SSR (e. g. Haghshenas et al. 2008, Bard 2004, Parolai et al. 2004, Bindi et al. 2000, Field and Jacob 1995); only in few studies a close match between both amplitudes is found (e. g. Molnar and Cassidy 2006, Mucciarelli et al. 2003, Horike et al. 2001). Therefore, it is generally agreed that the NHV technique can provide the fundamental frequency and a lower-bound estimate of the amplification for a soft soil site, but fails to provide higher harmonics. However, the meaning and the amplitude of the peak is still a topic of discussion.

In the case of Santiago de Chile, strong variations on a small distance can be found for sedimentary cover thickness (Araneda et al. 2000), leading to the conclusion that thorough investigations are necessary. Two studies dealing only with microtremor measurements have been published for Santiago de Chile (Bonnefoy-Claudet et al. 2009, Toshinawa et al. 1996), providing only a limited amount of information. On the other hand, Cruz et al. (1993) accounted for data from several earthquakes in their site effect study, but most of the stations were located on the outskirts of the city and only a few, and very local, events were considered.

C) Field experiments

In this study, we will combine data from both earthquake recordings made by a temporary seismic network installed in the northern part of the city and measurements of ambient seismic noise. A network of eight instruments was deployed in the northern part of Santiago de Chile, covering the different geological units (Figure 1).

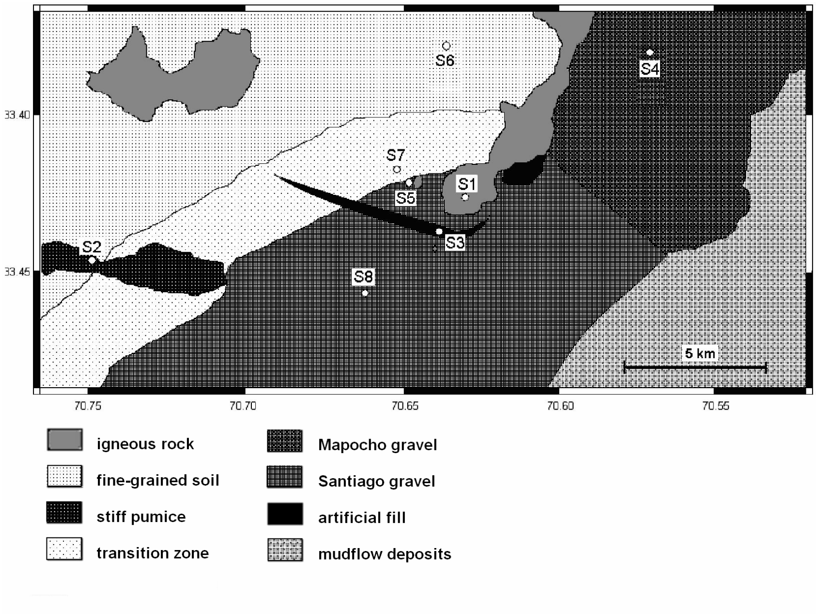

Figure 1: Simplified map of surface geology of the investigated area and the locations of the installed seismic stations.

Additionally, from 19 May until 13 June 2008, noise measurements were carried out in the northern part of Santiago de Chile. At each site, the signal was recorded for at least 25 minutes, leading to 146 measurements of ambient noise being carried out.

D) First results

While the network was installed, 38 earthquakes with sufficient quality were recorded by at least four of the eight stations. As an example, Figure 2 shows the unfiltered recordings of the NS component for all stations of one local event. It can be seen that stations S2 and S6, which were located close to very busy roads, were affected by higher noise amplitudes while, e. g. for stations S1, the reference station, and S5, the latter being located at a quiet part of a cemetery, the noise levels are much lower.

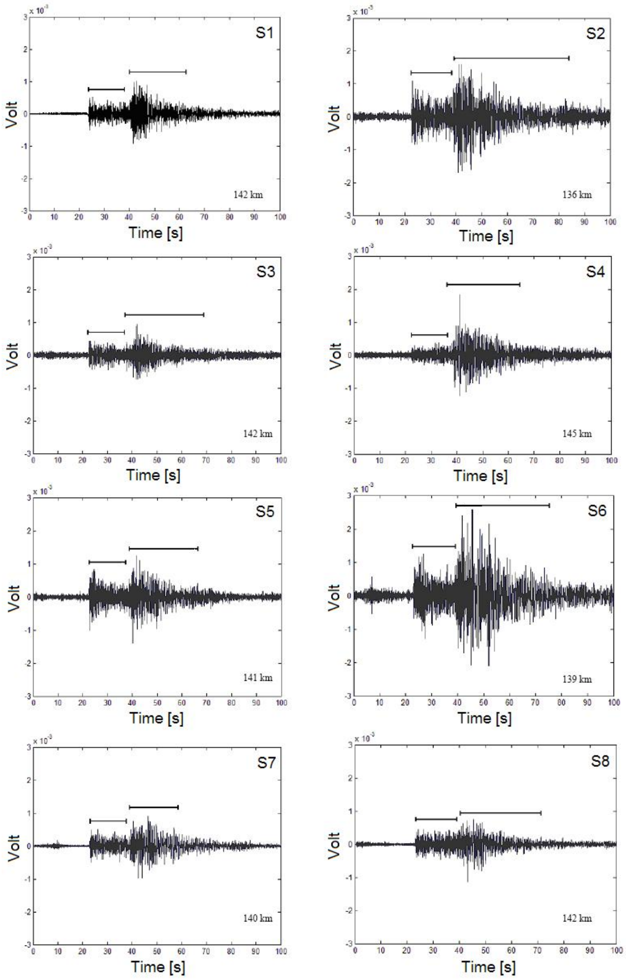

Figure 2: Comparison of NS recordings of a local earthquake on 12 April 2008, 21:21:57 UTC. Some stations show higher noise level due to the environment where they had been installed. The station ID and the hypocentral distances, as well as the time windows for P-wave and S-wave analysis are indicated.

To calculate the spectra for all the events, the recordings were first checked visually and only those showing good signal-to-noise ratio allowing for detecting P- and S-wave arrival were considered. First, the EHV ratio was calculated for all events separately for P- and S-wave windows. When comparing EHV curves, SSR curves, and NHV curves (example for station S6 given in Figure 3), an all-embracing and detailed analysis has been carried out but is not outlined here.

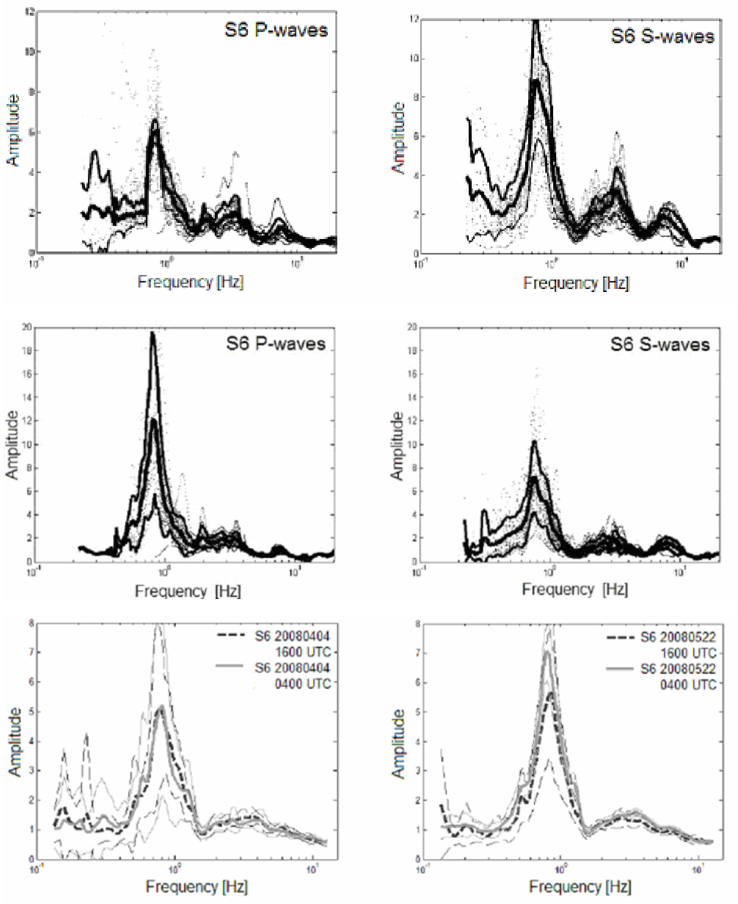

Figure 3: Site response for station S6. EHV spectral ratios for P- and S-waves (top), SSR spectral ratios (middle), NHV spectral ratios for recordings on 4 April 2008 after installation of the station (bottom left) and on 22 May 2008 before removal of the station (bottom right). For NHV spectral ratios a comparison between recording during daytime and during night is possible. Note the different amplitude scale.

For all sites, there is generally a good agreement in the shape and the location of the fundamental resonance frequency as found from the SSR, EHV, and NHV curves. Differences between NHV and earthquake spectral ratios can be found in terms of the amplification level: most of the earthquake data show a higher level of amplification. Because NHV is generally expected to estimate only the fundametal resonance frequency (or to provide amplifications over a narrow frequency band around it) it could be expected to underestimate more significantly the level of amplification at frequencies higher than the fundamental one. Additionally, when comparing spectral ratios of P- and S-wave windows, both spectra share similar features as long as the frequencies of maximum amplification are considered (if appearing in the P-wave curve), but amplitudes in the P-wave curves are often considerably lower. However, this difference might be explained by the hypothesis that the P-wave window results are mainly related to converted waves.

As mentioned, in addition to the earthquake recordings, measurements of seismic noise were carried out at 146 different sites in the northern part of Santiago de Chile. The analysis of the fundamental resonance frequencies calculated for all sites allowed us to draw a map of the fundamental frequencies of the investigated area (Figure 4).

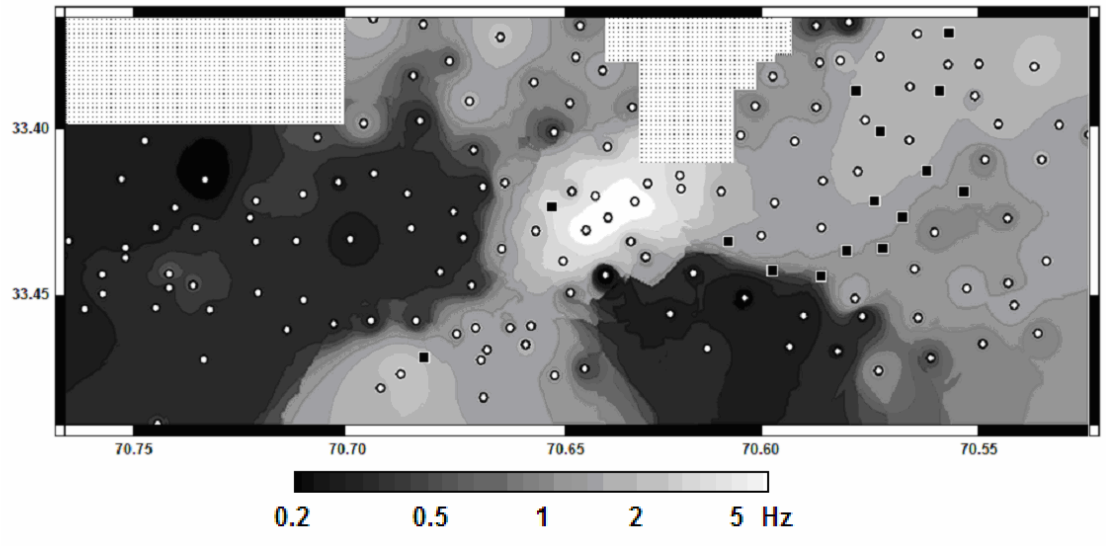

Figure 4: Map of the fundamental resonance frequency of the investigated area. Spots indicate sites where measurements of ambient seismic noise were carried out. Black squares indicate flat NHV recordings: these values have not been considered for mapping the fundamental frequency. In the hatched area, no measurements were carried out, hence results are only due to interpolation and therefore masked.

Figure 4 clearly shows that the entire area is characterized by relatively low frequencies below 1 Hz. Only when one considers sites close to the city center and around the San Cristóbal hill, the fundamental frequency does increase more rapidly. In this part of the basin, the thickness of the sedimentary cover is decreasing and the bedrock outcrops, as evident by the San Cristóbal hill.

On the other hand, frequencies below 0.5 Hz can be found in the west and towards the south-southeast of the investigated area. The sedimentary cover thickness reaches more than 500 m in these parts of the basin, supporting the general trend of the fundamental frequency decreasing with increasing sedimentary cover thickness.

Using an inversion procedure (Parolai et al. 2006) and information on the sedimentary cover thickness (Araneda et al. 2000) and also existing geological and geophysical information, local seismic S-wave velocity-depth-profiles can be calculated. Ambient seismic noise is mainly composed of surface waves, and therefore contains vital information about the S-wave velocity structure. Knowledge of that structure is a key factor in hazard assessment as they allow the amplification potential of the sedimentary cover to be evaluated. A detailed velocity model of the investigated area is not available at the moment but will be presented at the conference. The calculated velocity data set will then be compared with slope of topography.

Additionally, it will also be evaluated if the seismic S-wave velocity in the uppermost 30 meters might serve as a reliable parameter for the estimation of site effects.

E) Future steps

During the next phase of this work measurements in buildings characteristic for Santiago will be carried out. It will be checked if a simple equation for Chilenean buildings

$$T\ [s] = (\text{height of structure } [m]) / C\ , \qquad (1)$$

whereas 50 m/s $\leq$ C $\leq$ 60 m/s (Guendelman 2000) is suitable as a rule of thumb for estimating the fundamental frequency of buildings.

Additionally, the velocity data set might serve as a reliable basis for modelling of seismic hazard scenarios.

F) References

Araneda, M., F. Avendano, C. Merlo (2000): "Gravity model of the basin in Santiago, Stage III", *9th Chilenian Geological Congress* **2**, 404-408

Bard, P. Y.: "The SESAME project (2004): An overview and main results", *Proceedings of the 13th World Conference on Earthquake Engineering*, Vancouver, Paper 2207

Bard, P. Y., J. P. Riepl-Thomas (2000): "Wave propagation in complex geological structures and their effects on strong ground motion", in: *Wave Motion in Earthquake Engineering*, E. Kausel, G. Manolis (eds.), WIT Press, Southampton, Boston, 39-95

Bindi, D., S. Parolai, D. Spallarossa, M. Catteneo (2000): "Site effects by H/V ratio: Comparison of two different procedures", *J. Earthq. Eng.* **4** (1), 97-113

Bonilla, L. F., J. H. Steidl, G. T. Lindley, A. G. Tumarkin, R. J. Archuleta (1997): "Site amplification in the San Fernando valley, California: variability of site effect estimation using S-wave, coda, and H/V methods", *Bull. Seis. Soc. Am.* **87** (3), 710-730

Bonnefoy-Claudet, S., S. Baize, L. F. Bonilla, C. Berge-Thierry, C. R. Pasten, J. Campos, P. Volant, R. Verdugo (2009): "Site effect evaluation in the basin of Santiago de Chile using ambient noise measurements", *Geophys. J. Int.*, in press

Borcherdt, R. D. (1970): "Effects of local geology on ground motion near San Francisco Bay", *Bull. Seis. Soc. Am.* **60** (1), 29-61

Cruz, E., R. Riddell, S. Midorikawa (1993): "A study of site amplification effects on ground motions in Santiago, Chile", *Tectonophysics* **218**, 273-280

Field, E. H., K. H. Jacob (1995): "A comparison and test of various site-response estimation techniques, including three that are not reference-site dependent, *Bull. Seis. Soc. Am.* **85**, 1127-1143

Frankel, A. D., D. L. Carver, R. A. Williams (2002): "Nonlinear and linear site response and basin effects in Seattle for the M=6.8 Nisqually, Washington, earthquake", *Bull. Seis. Soc. Am.* **92** (6), 2090-2109

Guendelman, T. (2000): “Perfil bio-sísmico de edificios. Un instrumento de calificación sísmica”, *Revista BIT* **7** (17), 30-33

Haghshenas, E., P. Y. Bard, N. Theodulis, SESAME WP04 team (2008): “Empirical evaluation of microtremor H/V spectral ratio”, *Bull. Earthq. Eng.* **6** (1), 75-108

Horike, M., B. Zhao, H. Kawase (2001): “Comparison of site response characteristics inferred from microtremor and earthquake shear waves”, *Bull. Seis. Soc. Am.* **91** (6), 1526-1536

Langston, C. A. (1979): “Structure under Mount Rainier, Washington – Inferred from teleseismic P waves”, *J. Geophys. Res. Lett.* **84**, 4749-4762

Lermo, J., F. J. Chavez-Garcia (1994): “Are microtremors useful in site response evaluation?” *Bull. Seis. Soc. Am.* **84** (5), 1350-1364

Molnar, S., J. F. Cassidy (2006): “A comparison of site response techniques using weak-motion earthquakes and microtremors”, *Earthq. Spec.* **22** (1), 169-188

Mucciarelli, M., M. R. Gallipoli, M. Arcieri (2003): “The stability of the horizontal-to-vertical spectral ratio of triggered noise and earthquake recordings”, *Bull. Seism. Soc. Am*. **93** (3), 1407–1412

Nakamura, Y. (1989): “A method for dynamic characteristics estimation of subsurface using microtremor on the ground surface”, *Quaterly Reports of the Railway Technical Research Institute* **30**, 25-33

Parolai, S., S. Richwalski, C. Milkereit, D. Fäh (2006): „S-wave velocity profiles for earthquake engineering purposes for the Cologne area (Germany)”, *Bull. Earthq. Eng.* **4**, 65-94

Parolai, S., S. Richwalski, C. Milkereit, P. Bormann (2004): “Assessment of the stability of H/V spectral ratios from ambient noise and comparison with earthquake data in the Cologne area (Germany)”, *Tectonophysics* **390**, 57-73

Parolai, S., D. Bindi, P. Augliera (2000): “Application of the generalized inversion technique (GIT) to a microzonation study: numerical simulations and comparison with different site-estimation techniques”, *Bull. Seis. Soc. Am.* **90** (2), 286-297

Toshinawa, T., M. Matsuoka, Y. Yamazaki (1996): “Ground-motion characteristics in Santiago, Chile, obtained by microtremor observations”, *11th World Conference on Earthquake Engineering*, Paris, Paper 1764

Wald, D., T. Allen (2007): “Topographic slope as a proxy for seismic site conditions and amplification“, *Bull. Seism. Soc. of America* **97**, 1379-1395