Ph.D. Thesis review: **Seismic Site Effects (Data Analysis and Modelling)** by Arrigo Caserta

The submitted thesis deals with the effects of strong heterogeneities close to Earth's surface on the seismic wavefield, which can significantly modify the shaking intensity during an earthquake. Although the basic physical mechanisms of such effects are generally well described from a theoretical point of view (e.g., amplification due to strong impedance contrasts, edge generated surface waves), the interpretation of observed ground motions is still extremely difficult in the frequency range considered by earthquake engineers (0-20 Hz). This can be addressed to the limited knowledge of crustal structure, which is usually very heterogeneous just below the Earth's surface. Since seismic risk is concentrated in urban areas, methods of seismic prospection adopting strong active sources (e.g., explosives) are not applicable. Thus the development of methods for quantitative site characterization with emphasis on efficiency in urban environments is of the primary importance. The use of ambient vibrations (seismic noise, microtremors), studied also in this thesis, has been found generally very promising for this purpose. Consequently, numerical simulations with improved structural models help predicting ground motion in areas with long return periods of seismic hazard, where no instrumental observations exist (like in case of Rome city).

The thesis consists of parts concerning ambient vibrations, earthquake observations, and numerical modelling of ground motion. Four chapters of the thesis (the first two about ambient vibrations) are accompanied by five papers (P1-5) and a CD-ROM. Four of the papers (P1, P2, P3, P5) were accepted and published in international peer-reviewed journals with impact factor. Chapter 1 is devoted to deterministic analysis of microtremors and can be considered as an introduction to papers P3 and P4. Chapter 2 deals with statistical analysis of microtremors and can be considered as a summary of papers P1 and P2. On the other hand, the main results of Chapter 3 (earthquake observation) and Chapter 4 (numerical simulations) haven't been published yet. Paper P5 describes parallelization of 3D finite difference code, applied in Chapter 4. Although the candidate is not the main author of the paper P3, his part of the work is specified within the chapters of the thesis. The thesis is well written and comprehensible. The size of the figures in the thesis (not in papers) is not very appropriate in most of the cases: annotations were hard to read. Chapter 4 is short and would deserve a more detailed discussion. Chapter 1 includes some small inaccuracies concerning the noise wavefield content (interpretation of the H/V ratios), resolution limits of the arrays and depth resolution. However this does not depreciate results obtained in papers P3 and P4.

Specific comments:

Introduction

- Page 2: I do not fully understand the flowchart (Figure 1).

Chapter 1

- Title 'Seismic noise deterministic analysis: single station measurements' is not appropriate, as most of the chapter is devoted to array measurements.
- Subsection 1.1.1: The relation between H/V spectral ratio and the content of the microtremors is not discussed properly. Particularly, the influence of surface waves should be discussed (e.g., with respect to impedance contrasts at depth, source distribution, etc.). This is important, since it is shown later, that surface waves dominate the wavefield.
- Page 9: The link between H/V and structure is limited just to the fundamental frequency. What controls the shape of H/V curve?

- Page 9: The quarter wavelength estimation of fundamental frequency using a layer over halfspace (0.25*Vs/h) is oversimplified. Real structures usually contain velocity gradients.
- Page 12: Work of Capon (1969) is related to frequency-wavenumber (f-k) technique, not to spatial autocorrelation method (SPAC) as mentioned in text.
- Section 1.2.1: Conventional semblance f-k method is mentioned to be adopted in the thesis. However high-resolution f-k method (Capon, 1969) is used in works P3, P4.
- Page 12: f-k method is not limited to case of few noise sources, as stated in text.
- Page 14: A plane wave-front is also a key assumption in processing of ambient vibration surveys.
- Page 14: An enhancement of the resolution/aliasing capabilities can be achieved also by different power spectrum estimators, no?
- Section 1.2.2: Although the retrieval of resolution limits is described thoroughly, and several criteria are mentioned, the scatter of estimates which appear in literature is not explained (e.g., with respect to f-k power spectrum estimator). The relation with penetration depth is also not well explained, several contradictory statements are present, e.g., P3 (page 13): " … depth of investigations is 2-6 times of radius of the array ..."; page 10 of the thesis: 1/3 of wavelength related to fundamental resonance mode; page 15 of the thesis: one half of maximum resolvable wavelength. This should be clarified.
- Paper P3, Figure 15: Resolution limit Kmax/2 seems too conservative from my experience. Strong aliasing is maybe caused by inappropriate limits for the gridsearch in wavenumber plane. An extension of the search limits can improve the result.
- Paper P3: What is more representative of S wave velocity structure for the numerical ground motion simulations: "locally smooth" profile retrieved from ambient noise (based on surface wave propagation in quasi 1D media), a point borehole measurement (adopting laboratory tests), or even down-hole survey? What is the strategy for the future?

Chapter 2:

- The effect of noise sources is not discussed at all. Is it negligable in the presented estimates?
- It would be interesting to demonstrate estimated parameters (e.g., β) directly on power spectrum of the microtremors. If I understand well, power spectrum of total displacement should follow a power law. Is it in agreement with findings of Chapter 1 (e.g., relation to H/V peaks)?
- A five minute window of microtremors recordings analyzed in work P2 is too short to make any conclusion about structure (it may reflect, e.g., source distribution).
- Is it possible to explain higher coherence of ground motion in sediments by presence of surface waves propagating coherently in a horizontal plane?

Chapter 3:

- Spectral ratios presented in Figure 3.8 are calculated just for S wave-group or complete seismograms?
- It would be interesting to see a comparison between presented spectral ratios and H/V spectral ratios made on both noise and earthquake recordings (Figure 3.8). Moreover, presenting ratios GRB/BRH would be useful for understanding the bedrock conditions.
- Still a peak around 1Hz is present in recordings made at GRB (Figures 3.7,3.10). This may suggest that the amplification at this frequency range is not completely controlled by the basin sediments at VSC, but rather by some common deeper structure. The velocity profiles are not constrained well bellow the gravel layer. Characterization of velocity structure outside basin should be discussed.

- Paper P3/P4: Does exist any historical record about non-linear site effects in Rome, reporting, e.g., ground failure, sand boils, liquefaction, etc.?

Chapter 4:

- Although the main results of this chapter are not supported by a paper in the appendix of the thesis, the chapter is relatively brief. Results would deserve more discussion from my point of view.
- Why is the gravel layer representative for the bedrock? The gravel layer is relatively thin in profiles presented in P3, and P4. The bedrock seems rather composed from consolidated sediments (e.g., compacted clays).
- The movie presenting snapshots of ground motion induced by L'Aquilla earthquake is dominated by waves of large wavelengths (larger then the width of valley itself) passing across the valley. I could not recognize any trapped or edge generated surface waves. Are these phenomena not present for simulated frequency band, or is not visible in present graphical representation?
- How are the resulting ground motions affected by a strong interface in depth 0.7 km?

I would like to point out the multidisciplinary character of the approach, which goes beyond the norm, incorporating fieldwork, data collection, laboratory tests, signal processing, statistical physics, soil mechanics, numerical modelling, and computer science. I rate candidate's effort to compare simulated and observed data, which is dellicate for the considered frequency range, and usually still quite unrewarding. The earthquake recordings acquired in Rome city within the framework of the submitted thesis represent a unique constraint on future hazard estimates.

Concluding, the submitted dissertation meets the University requirements, and clearly exhibits the abilities of the candidate for the independent research. After successful defense I propose to award the Ph.D. Degree.

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