GENERATING 3D Vs MODELS IN URBAN ENVIRONMENTS FROM AMBIENT NOISE TOMOGRAPHY AND COMBINED MASW INVESTIGATIONS: THE CASE OF THE CITY OF THESSALONIKI (NORTHERN GREECE)

Marios ANTHYMIDIS1, Costas PAPAZACHOS2, Matthias OHRNBERGER3, Dimitrios OIKONOMOU4, Alexandros SAVVAIDIS5, Nikos THEODOULIDIS6, Giorgos VARGEMEZIS7, Panagiotis TSOURLOS8

ABSTRACT

The observation of complicated wave propagation patterns in sedimentary basins have led to an increasing need for the derivation of reliable ground models. During the last decades, alternative approaches based on passive geophysical surveys have been developed for 1D/2D/3D shear-wave velocity (Vs) model recovery. In the present study, we examine the application of the ambient noise tomography method for 3D Vs model reconstruction in urban environments and geotechnical scales. We employed a small circular array (radius ~500m) of 34 broadband sensors inside a central section of Thessaloniki city and obtained continuous ambient noise data for ~1 month. The cross-correlation of the vertical components of ambient noise recordings allowed the extraction of the Rayleigh wave travel-times for a wide frequency range (1-15Hz). A tomographic inversion procedure, involving the use of approximate Fresnel volumes and inter-frequency smoothing constrains, applied to the Rayleigh travel-times led to the estimation of the group slowness spatial distribution for the same frequencies. The tomographic images were used to construct local group slowness dispersion curves for a predefined set of nodes in the study area. The evaluation of the final 3D Vs model was implemented by the 1D inversion of all local group slowness dispersion curves of the node-based tomographic grid and the superposition of the local generated Vs models. In order to validate the results derived from ambient noise tomography, additional active geophysical surveys, such as MASW, were realized along selected profiles in the study area. Though the comparison of passive and active geophysical methods showed a satisfactory correlation and good agreement regarding the average depth and Vs values of the main subsurface formations, localized deviations were observed, mostly due to the different scale of spatial and depth resolution of the two approaches.

Keywords: Ambient noise tomography; Cross-correlation; Group Velocity; Urban areas; Shear-wave velocity

1. INTRODUCTION

The derivation of reliable subsurface structure information is essential for a variety of geological, geophysical and geotechnical applications. Active geophysical surveys and conventional geotechnical methods are considered to provide reliable information about the subsurface structure, however their...
application is significantly limited in urban environments, especially for deep subsurface investigations. The main drawbacks of these methods are the high application cost, the demanding requirements on equipment and human resources, and the environmental disturbances they cause. As a result, alternative approaches based on passive geophysical surveys have been developed, with the ambient noise tomography being one of the widely employed tools for 1D, 2D and 3D shear-wave velocity ($V_s$) model recovery. In particular, during the last decades, ambient noise tomography has become a promising method for structural imaging at different scales, from very small ones such as samples of materials in lab experiments (Lobkis and Weaver 2001; Weaver and Lobkis 2004), to intermediate or geotechnical scales (few tens to hundreds of meters, e.g. Picozzi et al. 2009; Renalier et al. 2010; Pilz et al. 2012; Hannemann et al. 2014), and even large to very large areas (regional-continental scale, e.g. Campillo and Paul 2003; Stehly et al. 2006; Roux et al. 2011). Nevertheless, there is still a relative small number of studies dealing with the application of ambient noise tomography in urban environments. In the present study, we examine the applicability of ambient noise tomography method in urban environments at geotechnical scales for the construction of full 3D $V_s$ models.

![Array configuration for the ambient noise recording in the study area.](image)

The study area corresponds to a central part of the city of Thessaloniki (Northern Greece), where a geological contact is observed at the surface, corresponding to gneiss-greenschist bedrock formations and recent sedimentary deposits. Previous larger scale studies of the broader study area (Anastasiadis et al. 2001; Apostolidis et al. 2004; Panou et al. 2005, Skarlatoudis et al. 2010) have shown that the bedrock outcropping at the NE part of the study area (Figure 1) is gradually dipping towards the coastline with a roughly 2D geometry, reaching depths that possibly exceed 200 meters along the coast of Thessaloniki. According to the same study, the sedimentary deposits in the study area can be separated into three main formations. The first (deeper) formation consists of a red clay series, with
2. APPLICATION OF AMBIENT NOISE TOMOGRAPHY IN THE STUDY AREA

2.1 Array Configuration

The ambient noise data acquisition was performed with the installation of a local network of 34 broadband sensors inside the urban area of Thessaloniki city, around the Aristotle university campus (Figure 1). The outer limits of the array were defined by a circular arrangement of 13 recording stations, with an almost equidistant distribution on the periphery of a circle with radius approximately 500m. The remaining 21 recording stations were placed inside this circle in random positions but with a rather small range of inter-station distances. This configuration allowed us to retrieve information for a variety of inter-station distances ranging from few meters to about 1Km. The total running time of the network was about one month and the sampling frequency was set to 200Hz. Several recording stations were installed on bedrock formations located in the NE part of the array, in order to obtain information about the propagation of ambient noise in such high velocity formations. Moreover, the recording configuration ensured that the bedrock-sediment transition was not located at the edge of the array limits, hence it could be identified in the later processing steps.

2.2 Cross-Correlation of Ambient Noise Recordings

The first processing step of the ambient noise data involves the noise signal cross-correlation analysis. We computed ambient noise cross-correlation traces for all the available recording station pairs of the array, using the vertical components. The ambient noise wavefield is dominated by surface waves, thus the extracted cross-correlation traces allowed the estimation of Rayleigh wave travel-times (Shapiro and Campillo 2004; Shapiro et al. 2005; Paul et al. 2005). We used several pre-processing steps on the ambient noise recordings, following the suggestions by Bensen et al. (2007). Specifically, we applied the instrument correction proposed by Seidl (1980), since we used sensors with different response characteristics. Furthermore, we applied a high-pass filter with a cut-off frequency of 0.5Hz to reduce the impact of low frequency signals, as well as a 30Hz low-pass filter for the better visualization of the final results. After filtering, we extracted 90 seconds time windows with a 50% overlapping and removed the offsets from each individual window in order to be suitable for the 1-bit normalization procedure. The resulting cross-correlation traces from each time window were stacked to stabilize the effect of temporal noise variations (Bensen et al. 2007; Gouedard et al. 2008). The stacked cross-correlation traces for every path were subsequently processed with the multiple filter analysis tool (Dziewonski et al. 1969). We used a set of six Gaussian narrow band-pass filters per octave (half bandwidth corresponds to 25% of the central filter frequency) that was logarithmically spaced to the frequency range of interest, resulting in a total number of 36 filters. The energy maxima of each filtered cross-correlation trace were determined by the calculation of the envelope function, which allows to estimate the arrival time of a Rayleigh waves “package” and practically indicates their group velocity for the filter’s central frequency. Thus, the ensemble of the envelope functions from each Gaussian filter (or frequency), enables us to construct the group slowness dispersion curve of the Rayleigh waves for the path corresponding to the cross-correlation trace.

It is worth mentioning that the source and origin of ambient noise control the wavefield characteristics and the information it carries (Bonnefoy-Claudet et al. 2006), affecting the resulting cross-correlation traces and the derived group velocities. Nevertheless, the urban environment of the study area ensures the rather diffuse wavefield assumption that is essential for the application of the ambient noise tomography method (Gouedard et al. 2008). Three main traffic roads are surrounding the study area.
from the North, West and South respectively, whereas at the East the Aristotle university facilities contribute to the generation of a variety of ambient noise sources. However, small heterogeneities in the subsurface structure resulted in complex wave propagation phenomena, mainly due to scattering. As a result, the cross-correlation traces are asymmetrical in most cases. Thus, in order to enhance the reliability of the picked dispersion curves for each path, we used the RMS amplitude of both negative and positive time lags of the envelopes for further processing. Furthermore, a lower frequency limit was set, corresponding to $r = 2\lambda$, where $r$ is the inter-station distance and $\lambda$ the wavelength, to ensure that the picked dispersion curves are associated with well-developed surface waves. Figure 2 shows the complete multiple filter analysis of the cross-correlation presented in Figure 2a, together with the picked group slowness dispersion curve (black line with error bars). In Figure 2b, the normalized envelope’s amplitude is plotted as a function of Gaussian filter index/frequency and slowness estimated from the lag time and the inter-station distance of the recording station pair.

The derived group slowness dispersion curves for every path were used to calculate the travel-times of Rayleigh waves for all frequencies. As already mentioned, we expected a gradual sediment thickening as we move from the bedrock (NE part of the study area) towards the SW (Thessaloniki coastline). Therefore, significant velocity changes are expected to occur along this direction, showing a mainly 2D pattern. In this velocity scheme, travel-times from paths located in the NE part of the study area are smaller than the ones located on the SW part due to the higher velocity of the surface waves. In order to test this, we employed a local Cartesian system with starting point (0, 0) at the southwestern part of the array and we subdivided the study area into three sub-groups. For this grouping, we calculated the midpoint coordinate for each path and created three groups of travel-time data, namely a SW, a Central and a NE group of paths. Figure 3 presents the calculated travel-times versus the inter-station distance for the frequency of 4Hz. In Figure 3a, all travel-time data are plotted, showing a general increase with distance, although with a large scatter, indicating quite strong velocity variations (for instance, at the distance of 500m, travel-times vary between 0.25 and 1.75 seconds). On the contrary, a clear linear trend is observed in the travel-times of the NE and SW model parts (Figure 3b and 3d,
respectively), with much higher velocities in the NE part (bedrock area), verifying the dominant 2D velocity pattern. The larger data spread observed for the Central part of the study area (Figure 3c) is expected, since it includes paths that are affected from both NE (bedrock) and SW (thick sediments) sub-areas.

Figure 3. Rayleigh wave group travel-times against inter-station distance for the frequency of 4Hz: a) Complete dataset. b) Travel-times for paths in the SW part of the study area. A clear linear trend is observed, with a low average Rayleigh wave velocity (~340m/sec). c) Travel-times for paths in the Central part of the study area, showing a more “diffuse” pattern (average velocity ~570m/s). d) Travel-times for paths in the NE part of the study area (bedrock outcrop area). A high velocity (~1100m/sec) linear trend is observed.

2.3 Surface Wave Tomography

The extracted Rayleigh wave travel-times were inverted using a tomographic approach incorporating damping, spatial and inter-frequency smoothing constrains, resulting in group slowness variation maps for all examined frequencies. More specifically, for a given data set of observed travel-times, \(t_1, t_2, \ldots, t_N\), from \(N\) recording station pairs and a medium with slowness, \(s\), the following integral can be used:

\[
t_j = \int_{L_i} sdl \quad i = 1, 2, \ldots, N
\]

where \(L_i\) is the Fermat ray path for the \(i^{th}\) recording station pair. Since the ambient noise sources are mainly located at the surface, we considered the wave propagation along straight rays and computed the approximate Fresnel volumes from the homogeneous model solution (Cerveny and Soares 1992) to account the effect of adjacent nodes for every path. In most cases, Equation 1 is linearized using a predefined local grid of \(M\) nodes, with slowness, \(s_j, j = 1, 2, \ldots, M\). Furthermore, in an effort to reduce
the non-uniqueness of the inversion problem and to properly manipulate the instabilities of the solution, several approaches have been proposed incorporating damping and smoothing constrains (Aki and Lee 1976; Franklin 1970; Constable et al. 1987), essentially providing a priori information for the geophysical model. In the present work, except from the damping constrains, we assumed a spatially smoothly varying slowness field from node to node, as well as smoothly varying slowness values across neighboring frequencies for the same node of the tomographic grid. Thus, we introduced a damping multiplier \( \varepsilon \), and two Laplacian operators \( \nabla^2 \) for spatial and inter-frequency smoothing controlled by the multipliers \( \lambda \) and \( \beta \), respectively, leading to the following linear system of equations:

\[
\begin{bmatrix}
L \\
\lambda \nabla^2_{xy} \\
\beta \nabla^2_f \\
\varepsilon I
\end{bmatrix}
\begin{bmatrix}
t \\
0 \\
0 \\
0
\end{bmatrix}
= \begin{bmatrix}
s \\
0 \\
0 \\
0
\end{bmatrix}
\]

where matrix \( L \) contains the ray lengths \( L_{ij} \), and vectors \( s \) and \( t \) correspond to the group slowness and travel-time data. A large set of values for damping, spatial and inter-frequency smoothing multipliers was tested using a trial-and-error approach, and a final selection of \( \varepsilon = 200 \), \( \lambda = 500 \) and \( \beta = 1000 \) was adopted and used.

Figure 4. Group slowness maps for six typical frequency values derived from the surface wave tomography approach on the Rayleigh wave group travel-time data set for the study area. The dashed line indicates the geological contact of bedrock (NE part) and sediment formations (SW part). High group velocity values (low slowness values) are observed for the bedrock outcrop area, especially for frequencies higher than 2Hz. On the other hand, low group velocity values (high slowness values) are found for mid-range frequencies (4-10Hz) in the SW part of the study area, where the sediment thickness gradually increases.
Although the linear system of Equation 2 is rather sparse and can be quickly solved with an appropriate sparse matrix solver (e.g. LSQR), we preferred to compute the complete inverse, in order to determine the resolution and covariance matrices and also calculate the resolving length (Toomey and Foulger 1989; Michelini and McEvily 1991) of the solution and the group slowness model errors. Using the abovementioned quantities, as well as the number and length of rays associated with each node, we defined several cut-off criteria in an attempt to exclude nodes with large uncertainties/poor resolution from the solution and hence from the final spatial variation maps. More specifically, we excluded group slowness values from nodes associated with less than 50 rays and 500m length, group slowness error larger than 0.00025sec/m and resolving length larger than 500m. Figure 4 presents the resulting group slowness maps for six typical frequencies. It is evident that the low Rayleigh group slowness values (high Rayleigh group velocities) are observed at the NE part of the study area, where the bedrock formations are outcropping in excellent agreement with the local geology.

2.4 1D Inversion of Dispersion Curves

The group slowness maps obtained from the surface wave tomography approach on travel-time data cannot be directly interpreted to retrieve information on the \( V_s \) distribution in depth, neither can it be used to determine the geometry of the subsurface structure layers. Thus, a final inversion procedure is required, in order to provide the \( V_s \) profiles for every node of the tomographic grid in the study area. For this purpose, we combined the tomographic images of every frequency with each node of the grid and reconstructed local 1D group slowness dispersion curves. In order to obtain local \( V_s \) profiles for every node, we used a Monte Carlo 1D inversion procedure on these local group slowness dispersion curves, namely the Neighborhood Algorithm (Sambridge 1999a,b), as implemented by Wathelet (2008) in the software package GEOPSY (www.geopsy.org). This implementation includes irregular limits to bound the parameter space due to physical conditions, a priori information about the subsurface structure and a dynamic scaling of the Voronoi cells, which are used to sample the parameter space, to increase the efficiency of the parameter space exploration. The main advantage of the particular algorithm is its ability to escape from local minima of the misfit function and thus guide the solution to better data-fit models.

Table 1. Parameter space used for the 1D inversion of the local Rayleigh group slowness dispersion curves.

<table>
<thead>
<tr>
<th>Layer</th>
<th>Depth range (m)</th>
<th>( V_p ) (m/sec)</th>
<th>( V_s ) (m/sec)</th>
<th>Density (Kg/m(^3))</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1-50</td>
<td>400-1700</td>
<td>200-350</td>
<td>2050</td>
</tr>
<tr>
<td>B</td>
<td>1-100</td>
<td>1350-2350</td>
<td>200-400</td>
<td>2150</td>
</tr>
<tr>
<td>E</td>
<td>1-250</td>
<td>1500-2500</td>
<td>350-700</td>
<td>2350</td>
</tr>
<tr>
<td>F</td>
<td>1-500</td>
<td>2700-3700</td>
<td>700-850</td>
<td>2350</td>
</tr>
<tr>
<td>G1</td>
<td>1-500</td>
<td>3500-4500</td>
<td>900-1500</td>
<td>2600</td>
</tr>
<tr>
<td>G2</td>
<td>-</td>
<td>4000-5000</td>
<td>1500-3000</td>
<td>2600</td>
</tr>
</tbody>
</table>

In total, we inverted 57 local Rayleigh group slowness dispersion curves. Inversions were performed for interface depths, allowing also limited inter-layer velocity variations, while different model parameterizations approaches were also examined. The parameterization that better fitted the data is presented in Table 1. This model comprises of 4 main sedimentary layers (A, B, E, F in Table 1), overlying bedrock formations (G1, G2 in Table 1), similar to the original proposal of Anastasiadis et al. (2001). The main difference from the original Anastasiadis et al. (2001) stratigraphy is the use of 2 bedrock formations, since we found that bedrock velocities are better constrained if we assume a gradual \( V_s \) increase with depth (rather than a single formation, with high \( V_s \) value), clearly reflecting the presence of a weathered/fractured bedrock cover, with smaller \( V_s \) values (formation G1 in Table 1). The final 3D model for the study area was generated with the superposition of the reconstructed 1D \( V_s \) profiles for all nodes.
Figure 5. SW-NE cross-section of the 3D $V_s$ model from ambient noise tomography in the study area: a) Main interfaces of the subsurface geophysical model, together with the $\lambda/2$ wavelength depth resolution limit (gray-shaded area). The cross-section interfaces and their variance where calculated from the average of grid nodes inside the NW-SE profile area, depicted with thin black lines in (b) and (c). b) Variation of the bedrock depth for the study area. c) Spatial distribution of the half-wavelength ($\lambda/2$).

Figure 5a presents a SW-NE cross-section of the study area, normal to the dominant trend of the geological formations. In the same Figure, the half-wavelength ($\lambda/2$) limit is also plotted, as derived from the reconstructed local dispersion curves of the tomographic grid, which corresponds roughly to the maximum resolving depth of the 3D model. Each interface and its variability (error bars) have
been computed by averaging the 3D model results within the rectangle shown in Figure 5b and 5c. From Figure 5a, we observe that a significant part of the F interface, corresponding to the contact of the sediments and bedrock formations, lies below the maximum resolving depth limit, hence its should not be considered as a reliable feature of the final model. This is confirmed by the very large standard deviation errors of the F interface in this model section. While similar results are observed for the inter-bedrock interface G1, all other interfaces are well resolved by the 1D inversion procedure. In particular, two very thin surficial layers are identified (A and B), with a maximum depth of approximately 7m. A strong contrast exists between the layers E and F (seismic bedrock) with a clear and smooth interface transition, showing relative small standard deviations. Figure 5b presents the bedrock depth variation for the study area, whereas Figure 5c depicts the spatial distribution of the half-wavelength (\(\lambda/2\)).

3. APPLICATION OF ACTIVE GEOPHYSICAL SURVEYS IN THE STUDY AREA

In order to validate the 3D \(V_s\) model derived from the ambient noise array tomography, Multichannel Analysis of Surface Waves (MASW) were realized along selected profiles in the study area, presented in Figure 1 with red lines. One of MASW profiles was conducted directly on bedrock, while the remaining profiles were conducted in areas with increased thickness of sediment formations, providing additional information on the \(V_s\) values of the uppermost sedimentary layers. The results for all MASW profiles are presented in Figure 6, using a classification similar to Table 1. More specifically, for the result presentation we have merged layers A and B, which show similarly low \(V_s\) values, and used intermediate velocities (from the ranges presented in Table 1) to provide indicative ranges for layers E and F. For the bedrock, we have employed a double weather bedrock layer (layer G1 850-1200m/sec and G2 1200-1700m/sec) above healthy bedrock (\(V_s>1700\)m/sec), in order to depict the gradual \(V_s\) increase with depth observed in the results.

The MASW results (Figure 6) for the study area show that the subsurface structure and the sedimentary layers and inter-bedrock boundaries display complex patterns in general, though confirming the gradual dipping of the bedrock formations from NE to SW. More specifically, the MET profile (Figure 6a), located at the largest distance from the bedrock suggests that the bedrock depth is located at larger depth than proposed by the Anastasiadis et al. (2001) model, in better agreement with the model presented in this study, which suggests that F layer velocities (\(\geq700\)m/sec) are identified at the depth of \(~40\)m in the northern part of the model. The bedrock profile SEIS (Figure 6b) is in good agreement with both the Rayleigh wave noise tomography results and the Anastasiadis et al. (2001) model, suggesting the presence of a \(~15\)m weathered bedrock layer. Finally, the AG_DIM profile, located in the sediments close to the bedrock/sediments contact (Figure 6c), is again in agreement with both models, with a thickness of 20-25m for the sedimentary (mainly E and F) and weather bedrock (G1 layer in Table 1) formations above healthy bedrock. In any case, it is evident that the model presented in the present work from Rayleigh wave group velocity tomography provides a reliable overall 3D \(V_s\) model of the study area, which, however, cannot resolve the fine structural details depicted from active source studies.

4. CONCLUSIONS

In the present study, we examine the applicability of the ambient noise tomography method to produce a 3D \(V_s\) ground model in an urban environment and for a shallow geological/geotechnical scale. For this purpose, we employed a local network of 34 broad-band sensors in a central part of the city of Thessaloniki (Northern Greece). We used the obtained ambient noise data to compute cross-correlation traces for every recording station pair and extract the Rayleigh wave travel-times for specific frequencies. A tomographic approach, incorporating the use of approximate Fresnel volumes, damping, spatial and inter-frequency smoothing constrains, to the travel-time dataset allowed us to calculate the 2D spatial distribution of the Rayleigh waves group velocities for the same frequencies. The group velocity maps led to the reconstruction of local group slowness dispersion curves for every node of a predefined tomographic grid for the study area. The 1D inversion of the local group
slowness dispersion curves enable us to retrieve information about the $V_s$ variations of the subsurface structure and generate a 3D geophysical/geological model for the study area.

Figure 6. 2D $V_s$ models obtained from active MASW measurements in the study area for three selected profiles presented in Figure 1. The corresponding layer interfaces from the models of Anastasiadis et al. (2001) and the $V_s$ model recovered from Rayleigh wave group velocity tomography (Figure 5) along the same profiles is also shown for comparison.

The obtained 3D $V_s$ model shows very good correlation with the local geology, as well as with the previous larger scale studies at the broader area of interest (e.g. Anastadiadis et al. 2001). The bedrock
outcrop and the mainly 2D pattern of its continuity to the SW of the study area under the sediments, is clearly identified. The geophysical model consists of two surficial layers with maximum depths of approximately 5 and 7m and $V_s$ values of the order 300 and 350m/sec, respectively. A quite smooth but clear transition is observed between the deeper sedimentary layer E with average $V_s$ of 600m/sec and the underlying F layer, which exhibits almost seismic bedrock velocities ($V_s \approx 800$ m/sec). The interface between this seismic bedrock layer (Layer F) and the actual weathered gneiss bedrock (Layer G1) cannot be properly resolved for a large part of the model, mainly due to the low method resolution at depths greater than 200m.

The application of additional active geophysical surveys (MASW) along selected profiles in the study area, confirmed the gradual dipping of the bedrock to the SW, as well as the absolute values of the $V_s$ models produced from the Rayleigh noise tomography. Moreover, they suggest that the model proposed in the present work recovers the large wavelength characteristics of the subsurface structure, though it cannot map the detailed features of active methods such as the 2D MASW method.

5. REFERENCES


