Ground Investigation in Urban Environment: Based on Seismic Methods: Analysis of the influence of the boundary conditions
Rodrigo Silva Baptista

Department of Civil Engineering and Architecture and Georesources, IST, University of Lisbon

September 2016

Abstract:
This work presents the joint analysis of two geophysical tests, the MASW (Multichannel Acquisition of Surface Waves) and the HVSR (Horizontal to Vertical Spectral Ratio) in highly dense urban areas and assess their applicability when underground infrastructures are in the vicinity.

A case study located in central Lisbon is analyzed. Data from boreholes and SPT tests and from MASW and HVSR were used to build a geological-geotechnical model. Afterwards the numerical simulation of the MASW test was carried out and results where compared with the experimental data. Validation of the model was achieved when both results showed to be in good agreement. Then, the effect of the presence of underground structures was evaluated.

The results showed small interference on the dispersion curve due to the presence of underground structures, mainly in the low frequency range.

Keywords: MASW, HVSR, finite difference method, wave propagation, small-strain stiffness

1 Motivation
Assessing soil properties with a low degree of uncertainty and knowing their spatial variability are a fundamental aspect for every geotechnical engineer. Seismic methods based on surface waves to characterize the soil stiffness in the small strain range is important for seismic site effects prediction.

Numerical software, such as FLAC, are often used to study complex geotechnical problems. Knowing their advantages and limitations is a stepping stone for a careful modelling and for an accurate analysis of the problem at hand.

2 Objectives
This work focuses on analysing the joint application of two seismic methods, the MASW and the HVSR when underground structures are in the vicinity comparing results from a case study through numerical simulation.

3 Methods
Firstly, numerical modelling considering plane strain is used to check the reliability of the numerical tools to accurately simulate wave propagation problems for a case of unidimensional wave propagation on a homogeneous soil column.

Secondly a case study is modelled and validated when both the MASW field results and the numerical...
Masw match. Finally, underground structures are introduced in the model and the differences between numerical results are analysed.

4 Seismic Tests

Two seismic tests were used in this study, the MASW and the HVSR. Both tests are based on the surface wave method, which takes advantage of the Rayleigh wave characteristics and its propagation to determine the soil properties although their acquisition and processing tools differ.

4.1 MASW

The MASW follows three steps for obtaining a solution (Figure 4.1).

Figure 4.1 – The three steps of the method (Strobbia, 2003).

Acquisition is the first step of the method, where data is recorded and the survey layout is defined. The main parameters to be defined are the number of receivers, its spacing and array length, each one of them is strictly dependent of the others.

The array length influences the resolution, i.e. the capacity to identify the peaks that constitute the dispersion curve. Too small and the peaks will be difficult to identify impacting on the precision of the phase velocity determination and the separation of mode superposition, too large and the spacing between receivers and the signal to noise ratio are compromised.

The spacing between receivers, usually adopted constant spacing, affects the maximum wavenumber, and minimum wavelength, that can be identified, thus affecting the resolution for shallow layers.

The number of receivers is usually restrained by its availability, usually 24 geophones are used, affecting both the maximum array length and spacing chosen.

The overall survey planning also needs to take into account near-field and far-field effects. Near-field effects relate to the minimum distance to be able to consider Rayleigh waves as plane waves. Far-field effects are related to long acquisition lines, because considering a long enough distance from the source the wave field will be composed mainly by body waves and not surface waves.

The Processing phase uses the data results to obtain the dispersion curve description that relates Rayleigh waves phase velocity as a function of frequency (or wavelength). The f-k transform, a two dimensional Fourier transform is applied to the time-offset data to give a frequency-wavenumber (f-k) spectrum. The wave field is decomposed transforming the seismic data into an image of the energy density as a function of frequency and of the wavenumber. The main advantage of this technique is that it allows for a separation of different wave phenomena, being able to mute or suppress them. Also, if the data is analyzed in the f-k domain, maximum can be picked directly without filtering because surface waves usually represent the main event.

A usual procedure is to adopt zero padding for the computation of the spectrum which consists on adding an infinite number of points in order to improve the discretization and localization of the maxima to its different modes.

The Inversion phase’s goal is to estimate a shear wave velocity profile of the geological model. The inversion problem doesn’t have a unique value: the obtained profile of velocities results from the adjustment of a forward model synthetic curves to an experimental dispersion curve. The base model defined as a huge impact on the time of computation required to achieve compatibility and to obtain good results.

Also, all frequencies carry out information on the shallow layers while only the longer wavelengths have information of the deep ones which means the surface layers will be overdetermined while the deeper layer will be underdetermined.
4.2 HVSR

The HVSR is a method proposed by Nakamura (2000) based on the spectral ratio between the horizontal and vertical components of ambient noise recorded at the surface. Its main objective is to estimate the value of the fundamental frequency of soft soils.

It is a passive method, requiring no active source to be applied but with longer acquisition time, taking advantage of the properties of the elipticity and phase velocity of Rayleigh waves when they interact with layers of different stiffness.

The elipticity is also a function of the frequency, if stiffness contrasts between layers are present, the H/V curve will exhibit peaks (maximums) due to the nullification of the vertical component and minimums when the horizontal component nullifies. If the stiffness contrast is high enough, infinite maximums and zeros are detected and also a reversal of the movement of the particles from retrograde to progressive.

The frequency at which the curve exhibits peaks is close to the fundamental frequency of the S waves, which indicates the overall fundamental frequency of the deposits. An estimate of the amplification factor can also be obtained analysing the peaks value, although the method tends to underestimate it.

This method can provide a way for detection of the depth of the bedrock and an indicator of the degree of stiffness of the soil deposit since it relies on considerable stiffness contrast, usually located on the interface between the bedrock and the soil deposits.

Project SESAME, elaborated by Bard et al. (2004) designed some recommended procedures regarding survey layout, number of tests, time of day, etc. in order to retrieve the best possible results from the location.

5 Case Study

The case study is located near Saldanha at the intersection of Rua Latino Coelho, Av. 5 de Outubro and Av. Fontes Pereira de Melo, in Lisbon. In the site, five boreholes and respective SPT tests were made, as well as MASW and HVSR tests (Figure 5.1).

Figure 5.1 – Location of the case study and tests.

For this study, the objective is to correlate the strength with an estimate of the stiffness which can be done by means of N-V_S correlations. An extrapolation was made for the values of 60 hits (5.1) considering how much it penetrated the ground to get a rough estimate of the shear wave velocity on the soil.

\[ N_{60} = \frac{N_{60} \times 30}{h_{pen}} \quad \text{(with } h_{pen} < 30 \text{ cm)} \]

The Ohta and Goto (1978) correlation is used:

\[ V_S = \alpha N_{60}^\beta \]

In which \( \alpha \) is 85.34 and \( \beta \) equals 0.348. From this, a geological-geotechnical model was defined based solely on SPT results (Figure 5.2).

Figure 5.2 – Geological-geotechnical model

The MASW was compared regarding only the dispersion curve and not the V-f spectrum because it not only facilitates the procedure as to allows a more sensible identification of the modifications made, for example, changing the thickness of each layer or their shear wave velocity. For this comparison, a theoretical curve is established using Geopsy’s gpdc and was compared with the MASW experimental results as seen in Table 5.1 and Figure 5.3.
Table 5.1 – First layered model based on MASW

<table>
<thead>
<tr>
<th>Layer</th>
<th>UG1</th>
<th>UG2</th>
<th>UG3</th>
<th>UG4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vs (m/s)</td>
<td>187</td>
<td>254</td>
<td>381</td>
<td>423</td>
</tr>
<tr>
<td>$\gamma$ (kN/m$^3$)</td>
<td>19</td>
<td>19</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>G (MPa)</td>
<td>66.2</td>
<td>123.0</td>
<td>233.9</td>
<td>519.3</td>
</tr>
<tr>
<td>$\nu$</td>
<td>0.33</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>E (MPa)</td>
<td>176.1</td>
<td>327.2</td>
<td>622.3</td>
<td>1381.5</td>
</tr>
</tbody>
</table>

As it can be seen from Figure 5.3, some changes need to be made from our original model to be compatible. Lopes (2005) studied the influence of each parameter on the dispersion curve obtained. The limits to which a convergence criterion is feasible were defined, considering the range of frequencies the numerical model could process accurately and the increasing uncertainty in depth associated with the method itself. Therefore, a lower bound was defined as 20 Hz and a higher bound limited to 64 Hz due to the size of the mesh.

Aiming to achieve a reliable model in these ranges, the data from HVSR was contemplated as well. With a theoretical model established, an estimate of the fundamental frequency could be calculated based on 5.3 and an average shear wave velocity on 5.4:

$$f_0 = \frac{V_{S,30}}{2(\sum_{i=1}^{n} h_i)}$$  \hspace{1cm} (5.3)

$$V_{S,30} = \frac{\sum_{i=1}^{n} h_i}{\sum_{i=1}^{n} \frac{h_i}{V_{S,i}}}$$  \hspace{1cm} (5.4)

In previous studies, Abreu (2015) based purely on HVSR results determined that the depth of the bedrock would be around 30 meters deep. Through a convergence procedure, a solution was found that met the requirements defined earlier (Table 5.2 and Figure 5.4).

Table 5.2 – Final model considering all data

<table>
<thead>
<tr>
<th>Final Model</th>
<th>$V_{S,30}$ (m/s)</th>
<th>$f_0$ (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vs (m/s)</td>
<td>160 300 600</td>
<td>455.7 3.80</td>
</tr>
<tr>
<td>Thickness (m)</td>
<td>2 4 24</td>
<td></td>
</tr>
<tr>
<td>Total (m)</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>Vp (m/s)</td>
<td>318 596 1191</td>
<td></td>
</tr>
</tbody>
</table>

Figure 5.3 – Dispersion curve associated to the base model

Figure 5.4 – Dispersion curve associated with the final model

Once the convergence criterion was achieved, the properties of the model were compared to the ones derived from the experimental procedure. Figure 5.5 and Figure 5.6 show a good agreement between the results obtained considering the uncertainty associated with the experimental data.

Figure 5.5 – Experimental H/V curves and fundamental frequency of the numerical model (black line)

Figure 5.6 shows all models that comply with the experimental results and the established profile (black line), clearly demonstrating the increase in uncertainty with depth.

In previous studies, Abreu (2015) based purely on HVSR results determined that the depth of the bedrock would be around 30 meters deep. Through a convergence procedure, a solution was found that met the requirements defined earlier (Table 5.2 and Figure 5.4).
6 Numerical Modelling

For this study a finite difference software was adopted, namely FLAC to study the response of two-dimensional soil models, admitting plain strain conditions and viscoelastic behavior. In order to get accurate results on wave propagation problems, a maximum mesh size was proposed by Kuhlmeyer and Lysmer (1973) equal from 1/8 to 1/10 of the wave length.

Rayleigh damping was adopted since it allows for a user defined central frequency, which was made equal to the soil’s natural frequency, and a critical damping value.

6.1 One dimensional wave propagation

The first stage of this modelling procedure was to assess the accuracy of the software. This was done considering the solution for unidimensional wave propagation on a soil column and comparing the numerical and analytical results through the establishment of a transfer function between the input motion and the surface layer.

The general solution for unidimensional wave propagation in a viscoelastic medium (Figure 6.1) with damping, as described by (Kramer, 1996), is given by

\[ u(z, t) = Ae^{i(\omega t + k^*z)} + Be^{i(\omega t - k^*z)} \]  \hspace{1cm} (6.1)

\[ k^* = \frac{\omega}{V_s} \]  \hspace{1cm} (6.2)

Where A and B represent the amplitudes of the upward and downward waves, respectively. \( \omega \) is the angular frequency and \( k^* \) the complex wave number.

Figure 6.1 - Viscoelastic soil deposit of thickness H overlain by rigid bedrock.

Given the proper boundary conditions, null shear stress at the free surface and compatibility of displacements between two consecutive layers, 6.3 can be used to define the transfer function for a motion on the bedrock describing the ratio of displacement amplitudes at any two points in the soil layer.

\[ F(\omega) = \frac{\max[u(z = 0, t)]}{\max[u(z = H, t)]} = \frac{1}{\cos(\omega H V_s^*)} \]  \hspace{1cm} (6.3)

\[ V_s^* = V_s(1 + i\xi) \]  \hspace{1cm} (6.4)

Where \( V_s^* \) is the complex shear wave velocity and H corresponds to the thickness of the layer. For an input motion on the surface, the transfer function can be written by 6.5 and 6.6:

\[ u(z = 0, t) = Ae^{i(\omega t + k^0 h)} + Be^{i(\omega t - k^0 h)} = 0 \iff A + B = 0 \iff A = -B \]  \hspace{1cm} (6.5)

\[ F(\omega) = \frac{\sin(k^*(H - h))}{\sin(k^*H)} \]  \hspace{1cm} (6.6)

The adopted properties for the soil column were defined arbitrarily and are presented below:

- Mass density: \( \rho = 2000 \text{ kg/m}^3 \);
- Poisson's ratio: \( \nu = 0.25 \);
- Shear wave velocity: \( V_s = 200 \text{ m/s} \);
- Elastic Modulus: \( E = 2G(1 + \nu) = 200 \text{ MPa} \);
- Shear Modulus: \( G = \rho \cdot V_s^2 = 80 \text{ MPa} \);

Case 1 – Input motion at bedrock

For any given motion, the analytical solution of the transfer function will exhibit peaks at the natural frequencies of the system representing amplitude amplifications. The natural frequencies of any system can be computed by:

\[ \omega_n \approx \frac{V_s}{H} \left( \frac{\pi}{2} + n\pi \right), n = 0, 1, 2, \ldots, \infty \]  \hspace{1cm} (6.7)

It’s at the first natural frequency, \( \omega_{01} \), also known as the fundamental frequency that the maximum amplitude occurs. For the present case, a frequency, \( f_0 \), of 5 Hz represents the fundamental frequency and 15 Hz the
second natural frequency. Figure 6.2 plots the analytical solution with the numerical one for a horizontal motion, S waves, and two different values of damping. The numerical solution shows a clear improvement as the damping value increases to an almost perfect match at 5% damping. Also, the fundamental frequency has a better adjustment than the higher natural frequencies due to the damping adopted, which was calibrated to apply the prescribed damping at 5 Hz.

![Figure 6.2 - Transfer function for a horizontal motion applied at the base for: a) no damping; b) 5% damping.](image)

**Case 2 – Input motion at surface**

For an applied horizontal motion at the surface, the base of the soil column needs to be fixed on both directions. Due to this, the overall stiffness doubles implying also a doubling value of the natural frequencies. As such, the fundamental frequency (Figure 6.3) now corresponds to 10 Hz and the second natural frequency to 20 Hz. Again, there is an increase in accuracy when the damping value increases, applying the prescribed damping to the fundamental frequency and overdamping the higher natural frequencies.

![Figure 6.3 - Transfer function for a horizontal motion applied at the surface for: a) no damping; b) 5% damping.](image)

With this validation procedure, we are able to identify some limitations of the numerical software and the influence of the type of damping adopted. Overall, frequencies below and higher than the fundamental frequency are expected to be overdamped while the applying the prescribed damping to the first natural frequency.

### 6.2 Two-dimensional model

#### 6.2.1 Model Parameters

The dimensions of the two-dimensional model consider the extension needed to replicate the experimental MASW and computational time required to solve the problem. The height was based on the HVSR and MASW results, was set at 30 meters with a length of 70 meters in order to reach the surrounding underground structures. On the left, northwest direction, an underground parking lot 7 meters deep was introduced, and on the right side, southeast direction, a tunnel from the metro line is 10 meters high and 10 meters wide. A plane strain analysis was adopted and the materials were modelled as elastic.

Horizontal stratigraphy was considered and quiet boundaries were adopted all around the model in order to dissipate the incoming waves, except on the structures. These were modelled considering no absorption of incident waves in order to simulate perfectly reflecting boundaries. Given the level of strains in wave propagation and the level of stiffness of these structures, we can restrain their movement in both directions. Regarding the borders of the model, the x direction is restrained laterally and the base on both directions (Figure 6.4).
The size of the mesh adopted took into account the minimum size criteria proposed by Kuhlemeyer and Lysmer (1973) in which the size of the element should not exceed one eighth to one tenth of the wavelength associated to the highest frequency.

Considering a range of up to 64 Hz, an amount necessary to identify the fundamental mode of the first layers, the size of the mesh was chosen, as presented in Table 6.1. The lowest frequency accurately represented is defined at 20 Hz, since lower frequencies will be targeting such high wavelengths that will not produce any meaningful information.

### Table 6.1 – Layer properties and mesh size.

<table>
<thead>
<tr>
<th>Layers</th>
<th>UG1</th>
<th>UG2</th>
<th>UG3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vs (m/s)</td>
<td>160</td>
<td>300</td>
<td>600</td>
</tr>
<tr>
<td>γ (kN/m$^3$)</td>
<td>19</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>ρ (kg/m$^3$)</td>
<td>1900,00</td>
<td>2000,00</td>
<td>2000,00</td>
</tr>
<tr>
<td>G (Pa)</td>
<td>4.86E+07</td>
<td>1.80E+08</td>
<td>7.20E+08</td>
</tr>
<tr>
<td>G (MPa)</td>
<td>48.6</td>
<td>180.0</td>
<td>720.0</td>
</tr>
<tr>
<td>ν</td>
<td>0.33</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The applied motion was introduced as a vertical force with an associated vertical velocity to ensure the model simulated the soil response to an applied motion, as presented in Figure 6.5. Rayleigh damping was adopted with a central frequency of 3.8 Hz and 5% critical damping. A timestep of 1E-6 s was chosen for a total of 2.0 s. The motion is applied at 7 meters from the left boundary and geophones are simulated by reading the vertical acceleration with a spacing of 1.5 m.

### Field results

Figure 6.6 shows the experimental $V_R$-$f$ spectrum results obtained from the MASW in the case study for a motion applied at NW and its dispersion curve. There is some fluctuation due to the presence of ambient noise, but it does not compromise the fundamental mode. Also represented is the range of possible dispersion curves that comply with these results, because the one presented in this study is an average of all the shots made.
6.2.3 Numerical results without structures

Numerical results, Figure 6.7, showed some deviation from the experimental ones overall, although on the lower frequencies, and respectively higher wavelengths, the results tend to misrepresent the dispersion curve.

Above 30 Hz, the numerical model seems to accurately describe the fundamental mode since a high energy concentration is identified without much dispersion. Through 5.3 we can get a rough estimate of the depth being analyzed, so for a velocity around 220 m/s at 30 Hz corresponds to roughly 2 meters. At this depth, not only does a change of the soil properties occur but also compatibility between different mesh sizes are processed through an attached line, causing some reflexions and therefore, some energy dispersion.

Between 20 and 30 Hz, a jump in the velocity value is registered, from 200 m/s to 400 m/s, where the difference between the numerical and experimental results are more expressive. This zone corresponds to a 4-5 m depth, where another attach line was used which could compromise the results.

An analysis on the impact the conditions adopted on this simulation was made, trying out for the same motion different distances to the lateral boundaries as to try to show limitations of the software used.

For a uniform grid with elements of 0.25 m, Figure 6.8 shows the influence this initial parameter can have on the numerical model. There are no signs of improvement directly related to the increase in distance to the border although the 10 meters case showed the best results, less energy dispersion and a fundamental mode well defined up to 25-30 Hz. This distance ends up playing an influent role on the results obtained in the numerical analysis, probably due to the way the quiet boundaries absorb the incoming wave energy.
6.2.4 Results with structures

The main concern of existing underground structures on seismic testing is the disturbance that reflecting waves have of the experimental results. These are expected to increase the degree of uncertainty through a less concentrated energy field along the frequency range.

Figure 6.9 shows the results obtained for the model with these structures. Comparing the results for both cases, the main difference identified concerns the lower frequencies, and therefore higher wavelengths although these mainly impact outside the frequency range that was defined to give accurate results. Above 30 Hz, the fundamental mode is seemingly unaltered, retaining the properties of the first layers and displaying the same jump in velocities.

In order to assess the correct behavior of the borders, the grid distortion can be seen at several stages of the analysis. With a magnified factor of 1E+12 and for the event of highest magnitude, the first incident wave causes opposite behaviors, Figure 6.10a shows the expected behavior for the soil response when interacting with the border, dissipating the movement along the simulated boundaries. Figure 6.10b depicts the moment the incident wave is reflected backwards into the model after the interaction with the tunnel.

Although the different interactions are observed with the structures, it had little influence in the frequency domain. Overall, its existence doesn’t seem to prevent an accurate characterization of the properties of the soil.
7 Conclusions

The combined use of methods based on wave propagation provided a more reliable interpretation of the soil properties.

Mainly the MASW and HVSR provided a more detailed characterization and identification of the soil layers and the depth of the bedrock were SPT tests would not suffice. The similarity of both shots from MASW allowed for an easier definition of the orientation of the layer interfaces. Correlations for estimating Vs from SPT results tend to underestimate their actual values, serving as a rough estimate of the base model for the shear velocity profile determined by the seismic testing.

The numerical simulation showed good agreement for high frequencies, above 30 Hz, being able to identify the fundamental mode of the soil model. The size of the mesh proved to be a conditional factor on the range of frequencies accurately represented, as did the distance from the source to the lateral boundary. The main limitation of the software is the high computational time it requires for a refined mesh and the way the boundaries interact with the incoming waves.

The results concerning the models with and without structures proved to be very similar, small to no disturbance was detected in the frequency domain above 30 Hz, although the model displayed the expected behavior.

For further studies, it is proposed a model with larger dimensions and refined uniform mesh. A more complex geometry could also lead to a better understanding of the fluctuation observed in the experimental results. Also, a 3D model would benefit a more accurate analysis through a better definition of all the surrounding structures and soil stratigraphy.

8 References


