Geological and geotechnical characterization of urban areas using seismic methods

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Abstract

This study's main objective is to evaluate the application of the H/V Method in urban areas for geological and geotechnical characterization of a given soil profile. For that, the finite element method was used, with the numerical tool SAP2000, in order to determine the H/V spectral ratio dependence on the type and location of the action.

Initially, the main types of seismic waves are described, along with the introduction of H/V method, based on the spectral ratio between the horizontal and vertical component of the seismic ambient noise recorded at the surface. Subsequently, the one dimensional ground model is validated and analysed considering the propagation of S and P waves in a uniform soil laid on bedrock. Thus, the linear elastic analytical solutions are determined in order to estimate the behaviour of the soil surface when acted upon by two different types of action: acceleration in the form of a pulse at the base of the model and a force in the form of a pulse at the soil surface. Then, 2D models were analysed, applying the H/V method.

Finally, a case study is presented, in order to analyse the seismic behaviour using ambient noise records measured in situ at ground surface, and the finite element method to model the seismic ground response. Based on the results obtained in the analysis of the case study, the H/V method is practical, fast, low cost and allows obtaining a good estimate of the local fundamental frequency in urban areas.

Key words: Geological and geotechnical investigation; H/V Spectral Ratio Technique; Finite Elements Method; Seismic Testing; Wave propagation; Small-strain stiffness

1. INTRODUCTION

Measuring very small strain stiffness of the soil has gain relevance in recent decades due to its importance to predict seismic site effects and to the study of serviceability limit states of geotechnical structures in general.

The main objective of this paper is the analysis of the applicability of the H/V seismic method in the geological and geotechnical characterization of a given soil profile in an urban area. The H/V technique popularized by Nakamura [1][2][3], uses the ambient seismic noise recorded at ground surface to estimate the fundamental frequency and amplification factors of a given place.

The information obtained from the H/V curve of ambient noise recorded at ground surface allows the estimation of the fundamental frequency of a given site. However, the proportion of body and surface waves in ambient noise recorded at ground surface is not yet fully understood.

First, the main types of seismic waves are described as well as the cyclic behaviour of soils, the constitutive models and some geophysics testing methods. Nakamura's method and ground motion definition are presented, as well as Sesame Project (2004) main results. Then, the finite element method is used to validate and analyse 1D and 2D models considering the H/V method. A geological and geotechnical setting is presented for the case study, as well as the acquisition and data processing of ambient noise records performed in situ. A 2D numerical analysis using H/V method is also performed. Finally, conclusion remarks and future perspectives are presented.

2. SEISMIC TESTING

2.1. Seismic waves

There are two main types of elastic waves: body waves, P and S; and surface waves, Rayleigh and Love (Fig. 1). The P waves involve successive compression and tension of the materials crossed, vibrating in the same direction as wave propagation. These are the fastest seismic waves and they propagate in any material. The S waves cause shear strain when propagating through materials and can be divided in two components: a horizontally polarized wave (SH) and a vertically polarized wave (SV). They only propagate in solid bodies due to no shear resistance of fluids and are slower and more destructive than P waves, since they cause changes in material shape [4].

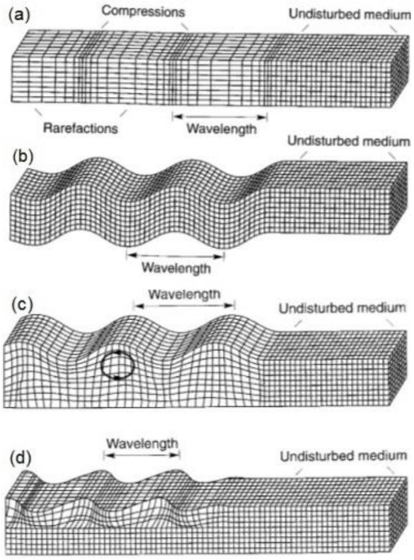

Fig. 1: Deformations produced by body waves ((a) P-wave, (b) SV-wave) and surface waves ((c) Rayleigh wave, (d) Love wave) [4].

The surface waves only propagate along the free surface of elastic solids and they result from the interaction between body waves and superficial layers. These waves are slower, larger in amplitude and higher wavelength than the body waves. The Rayleigh waves are formed by the interaction of P and SV waves with the earth's surface and cause both vertical and horizontal movement of soil particles with reverse elliptical paths in a vertical plane parallel to the propagation direction. The wave's amplitude decreases exponentially with depth and much of the energy is confined near the surface. The velocity of propagation is about 90% of shear wave velocity. Love waves are formed by the interaction of SH waves and the surface layer, therefore the particle movement has no vertical component. They only occur when there is an increase of shear wave velocity in depth. They are the slowest and most destructive seismic waves [4]. The phenomenon that characterizes the spread of both type of waves is the dispersion in a heterogeneous medium.

2.2. Nakamura's method

Nakamura's method, also known as H/V method or HVSR (Horizontal to Vertical Spectral Ratio) or microtremors method; is based on the spectral ratio between the horizontal and vertical component of ambient noise recorded at the surface. The author has developed this method as a tool to determine the local seismic response in estimating of fundamental frequency (f_0) of soft soils [1]. The interpretation of the H/V spectral ratio is closely related to the seismic wave's field composition responsible for ambient noise, which depends on the vibration source and the underground structure. The ambient noise composition was evaluated in detail by Bonnefoy-Claudet et al. [5], whose main objective was to clarify the relative proportion between different wave types, in order to identify patterns or trends.

Since this technique only considers surface records, the quality of the results can be compromised. Therefore, Nakamura assumed that the base movement amplitude is similar in both components and that the vertical component of movement is not amplified in a frequency range where the highest amplification of horizontal component is observed [1].

Nakamura also performed the analysis of some ambient noise records at surface and concluded that the effect of Rayleigh waves manifests essentially in the vertical component and has suggested that this effect could be removed dividing the horizontal component by the vertical component of the amplitude spectrum [1]. According to the author, once the effect of Rayleigh waves is removed, the frequency that has a higher amplification factor is associated with the S waves. Nakamura [2] states that the peak shown in the H/V curve is essentially the result of multiple reflections of S waves and that the effect of Rayleigh waves is predominant in a frequency value equal to twice the fundamental frequency and the energy of Rayleigh waves in f_0 is minimal.

2.3. Ground motion definition

The ground motion definition and at different sites are introduced considering the typical geological structure of a given sedimentary basin (Fig. 2). To study the microtremors record, it is assumed that the energy of microtremors consist mainly of Rayleigh waves and the local amplification effects are due to the presence of a surface layer of soft soil overlying a semi-infinite space.

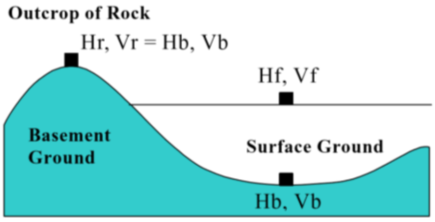

Fig. 2: Typical geological structure of a sedimentary basin [2].

The transfer function is given by:

$$S_t = \frac{S_h}{S_v} = \frac{\frac{H_R}{V_R}}{\frac{H_b}{V_b}} \qquad (1)$$

Where H_R e V_R are the Fourier amplitude spectrum of horizontal and vertical record of Rayleigh waves at the sedimentary layer, respectively, and H_b e V_b the Fourier amplitude spectrum of horizontal and vertical record at the basin base.

2.4. Sesame Project

The Sesame Project [6] - Unified Seismic Hazard Modelling throughout the Mediterranean Region - presents recommendations that should be taken into account in site effect studies using the H/V ambient noise technique. These recommendations are applicable in cases that only use the H/V method to evaluate the local natural frequency and are based on sets of very strict criteria. The interpretation of H/V results is clearly improved when combined with geological, geophysical and geotechnical information, for this reason the study of site effects in a given place should not be based only on H/V curves.

3. FINITE ELEMENT METHOD

In this study the finite element program SAP2000 Structural Analysis (2015) is used to perform the analysis of seismic soil response. One-dimensional and two-dimensional wave propagation in the soil in plane strain state is simulated, using the modal analysis and direct integration analysis. One-dimensional numerical models were validated, by comparison with analytical solutions considering the one-dimensional propagation of seismic waves S and P, following the presentation of a sensitivity study.

3.1. One dimensional propagation of seismic waves

Case 1: Harmonic action at base of soil layer

The general solution of the unidimensional wave propagation in a viscoelastic medium (Fig. 3) is given by:

$$u(z,t) = A.e^{i(\omega t + k^* z)} + B.e^{i(\omega t - k^* z)} \qquad (2)$$

Where A and B correspond to the ascending and descending amplitude wave, respectively; ω the angular frequency and k^* to the complex wave number.

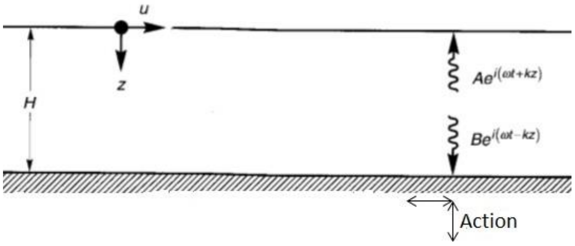

Fig. 3: Linear elastic soil deposit of thickness H overlain by rigid bedrock; action at the base [4].

For this scenario, the boundary conditions are:

S waves: $\tau(z=0,t) = 0 = G\gamma(0,t) = G\frac{\partial u(0,t)}{\partial z} = 0$

P waves: $\sigma(z=0,t) = M\varepsilon(z=0,t) = M\frac{\partial u(0,t)}{\partial z} = 0$

The transfer function results from the displacement ratio verified at the top and base of soil deposit, with a thickness of H, and it is given by:

$$H(\omega) = \frac{u_{máx}(z=0,t)}{u_{máx}(z=H,t)} = \frac{1}{\cos(k^* H)} = \frac{1}{cos\left(\frac{\omega}{V_s^*}H\right)}$$

$$H(\omega) = \frac{1}{cos\left(\frac{\omega}{V_s}H\frac{1}{1+i\xi}\right)} \qquad (3)$$

Case 2: Harmonic action at soil surface

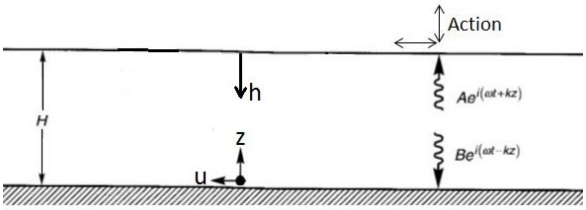

Fig. 4: Linear elastic soil deposit of thickness H overlain by rigid bedrock; action at the top [4].

For this scenario, the boundary conditions are:

$$u(z=0,t) = Ae^{iwt} + Be^{iwt} = 0 \Leftrightarrow A = -B$$

The transfer function results from the displacement ratio verified at the base and top of soil deposit and is given by:

$$H(w) = \frac{u_{m\acute{a}x}(z = H - h)}{u_{m\acute{a}x}(z = H)} = \frac{sen\left(k^*(H - h)\right)}{sen(k^* H)}$$

$$H(w) = \frac{sen\left(\frac{w}{v^*}(H - h)\right)}{sen\left(\frac{w}{v^*}H\right)} \qquad (4)$$

3.2. Numerical simulation of one-dimensional wave propagation

The results obtained in numerical modulation depend on the dimensions and discretization of the mesh. A wave should be defined using at least 8 to 10 points [7]. A mesh discretization with 0,5m in both directions was adopted for waves up to 20 Hz.

For the one dimensional analysis, a linear elastic soil deposit of thickness H overlain by rigid bedrock was considered, with the elastic properties shown in Table 1.

Table 1: Elastic properties adopted for soil column.

V_s (m/s)	γ (kN/m³)	ν	E (MPa)	G (MPa)	ξ (%)	ρ (Kg/m³)	H (m)
137	20	0,3	100	38,5	5	2040	20

An impulse action with unitary amplitude was considered, in order to excite all the resonance frequencies. To determine the transfer function of the soil column, H(w), and its fundamental frequency, f_0, appropriate boundary conditions that allowed the study of the P waves and S waves propagation had to be set. Fixed supports (restricted displacement and rotation) are defined at the base to simulate the bedrock. The remaining nodes are considered simple support with release of vertical or horizontal displacement when applying a vertical or horizontal action, respectively (Fig. 5).

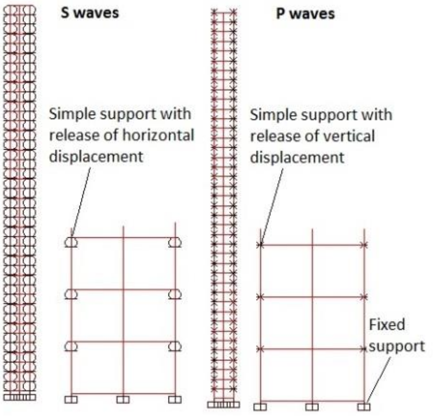

Fig. 5: Boundary conditions defined at SAP for S waves (left) and P waves (right) propagation analysis.

According to the analytical solutions presented before, two types of action are applied to the 1D model. To obtain the transfer function for both scenarios, two types of analysis were considered: direct integration analysis and modal analysis.

In case 1, for small damping ratio values (≅ 0%), there was a convergence problem in both types of analysis for frequency values above 15 Hz, approximately, since the numerical and analytic solutions do not fit completely. However, as the value of the damping coefficient increases, solutions tend to converge, as can be seen in Fig. 6 and Fig. 7 with 5% of damping ratio, for S waves and P waves propagation, respectively.

The Rayleigh damping curve, ξ_n, is presented in case 1 considering the S wave propagation. For this case, a value of 5% of Rayleigh damping was applied for frequency values of 1,7Hz and 2Hz. For P waves, the Rayleigh damping was applied for 3Hz and 3,5Hz. For frequency values within this range, the damping ratio is less than 5% and higher for other frequencies as shown by the curve. The decay of the transfer function from the second vibration mode reflects the Rayleigh damping effect, which increases with frequency.

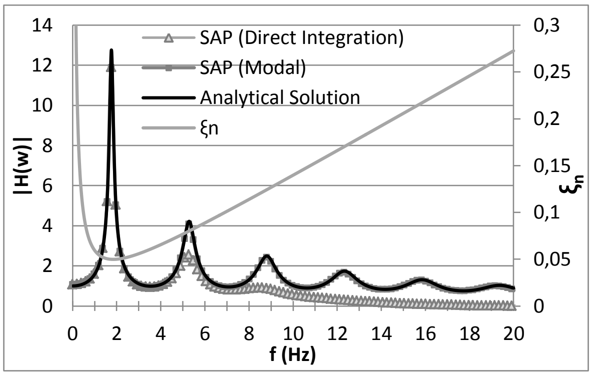

Fig. 6: Case 1; S waves unidimensional propagation.

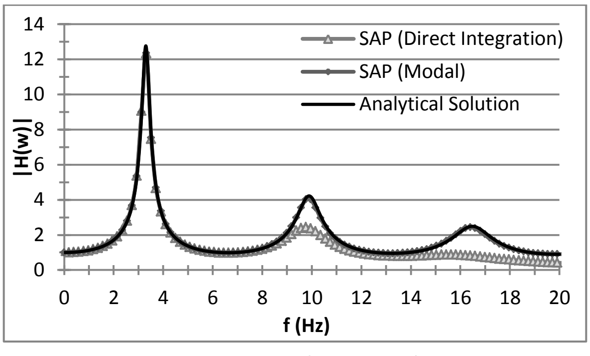

Fig. 7: Case 1; P waves unidimensional propagation.

The results obtained in modal analysis show that the analytic transfer functions coincide up to 20Hz, which is expected since the size of the finite element was initially estimated to ensure a good characterization up to this frequency. The direct integration analysis gives us the best results for the fundamental frequency of the soil column.

The transfer functions obtained for case 2 considering a damping ratio of 5%, are shown below in Fig. 8 and Fig. 9.

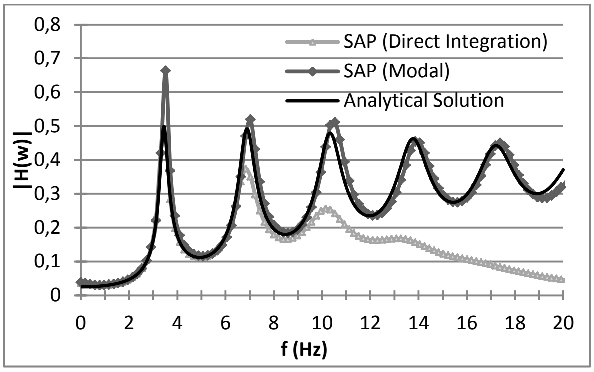

Fig. 8: Case 2; S waves unidimensional propagation.

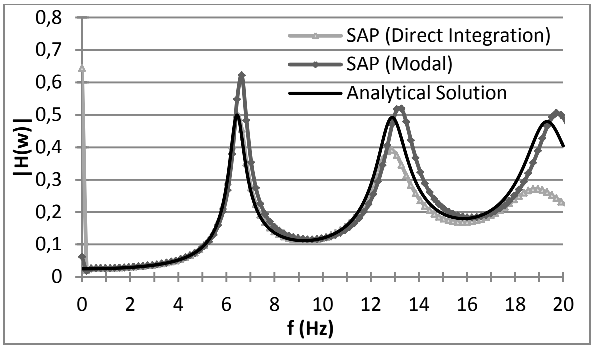

Fig. 9: Case 2; P waves unidimensional propagation.

The analytical and numerical solutions provide different results at all frequency range values for the undamped case.

For further analysis, the fundamental frequencies of unidimensional propagation of S and P waves will be represented as, $f_0^{S\uparrow}$ e $f_0^{P\uparrow}$, for the case when the action is applied at the base model, and $f_0^{S\downarrow}$ e $f_0^{P\downarrow}$, when applied at the surface, respectively.

3.3. Two-dimensional Model

The main purpose of this analysis is the determination of the H/V numerical curve at the surface of the 2D soil model overlying bedrock, changing the mesh extension (L) and depth (H), the action depth (z) and direction as well as the soil elastic properties, considering stratification (Fig. 11). The x variable is the distance between the source and the point where the temporal accelerations series are recorded. To take advantage of symmetry, in all of the analysis, only half of the 2D model is considered.

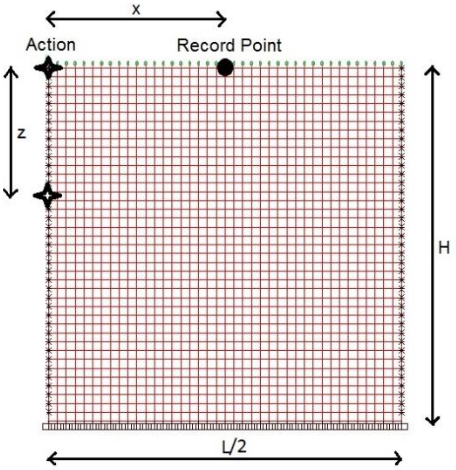

Fig. 10: Variable mesh adopted in the analysis.

To analyse the wave reflection phenomena that occurs at the 2D model, meshes with different L values and H values were considered, applying a vertical action at soil surface (x=0m). A modal analysis of the first 12 modes was considered. This number of modes gives us information in a restricted range of frequencies since the 12th vibration mode has a frequency of 4,93Hz, 5,75Hz and 12,25Hz for L values of 200, 100, 40 meters, respectively, for a soil column with a height of 20 meters.

After analysing the vertical acceleration time series at the same point in all meshes (x=10m), it was seen that vertical accelerations amplitude are much higher for L=40m and also more affected by the wave reflection caused by the impulse. This can be explained by the influence of lateral boundaries that were adopted. For a larger value of L, the distance travelled by the wave is higher, which leads to a higher energy loss. The ratio between L and the S wave velocity propagation gives us the time which the reflected wave defiles the signal after applying the impulse.

Since we are in elastic regime, the theory of overlapping effects can be applied, considering the application of an action with horizontal and vertical component. Thus, the acceleration time series obtained at surface by a horizontal and a vertical action are added. With this, the H/V curve can be obtained considering different scenarios, as shown in Fig. 10 to Fig. 15. In some cases the H/V curves were normalized by $f_0^{S\uparrow}$ in order to clarify the analysis of the obtained results. The analytic values of fundamental frequency considering different soil thickness and different E values for the soil layer, are shown in Table 2 and Table 3, respectively.

Table 2: Fundamental frequency values of S and P waves considering different thickness for soil.

H (m)	$f_0^{S\downarrow}$(Hz)	$f_0^{P\downarrow}$(Hz)	$f_0^{S\uparrow}$(Hz)	$f_0^{P\uparrow}$(Hz)
10	6,89	12,89	3,44	6,43
20	3,44	6,44	1,72	3,21
40	1,72	3,22	0,86	1,61

Table 3: Fundamental frequency values for different E values for soil layer.

H=40m		$f_0^{S\downarrow}$(Hz)	$f_0^{P\downarrow}$(Hz)	$f_0^{S\uparrow}$(Hz)	$f_0^{P\uparrow}$(Hz)
E (MPa)	100	1,72	3,22	0,86	1,61
	300	2,98	5,58	1,49	2,78
	600	4,22	7,89	2,1	3,94

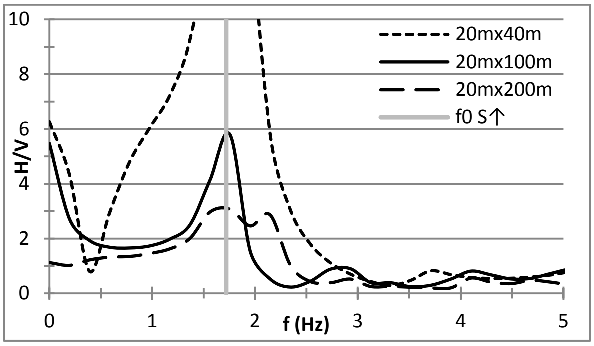

Fig. 11: H/V curves changing L value.

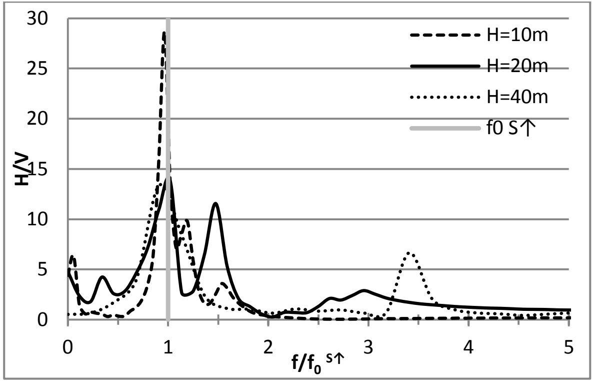

Fig. 12: H/V curves changing H value.

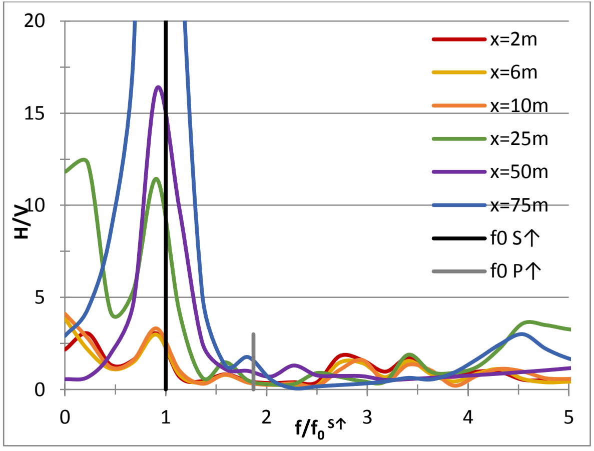

Fig. 13: H/V curves changing x value.

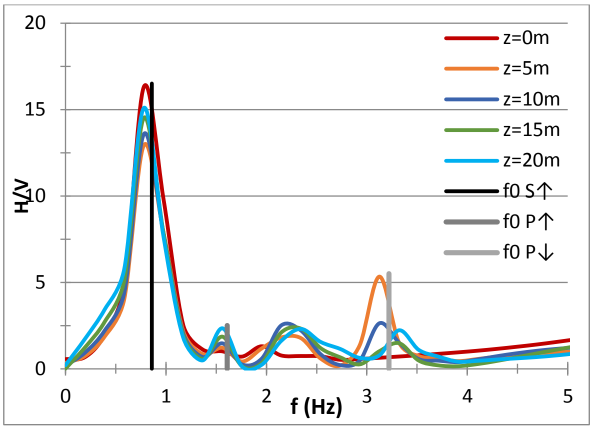

Fig. 14: H/V curves changing z value.

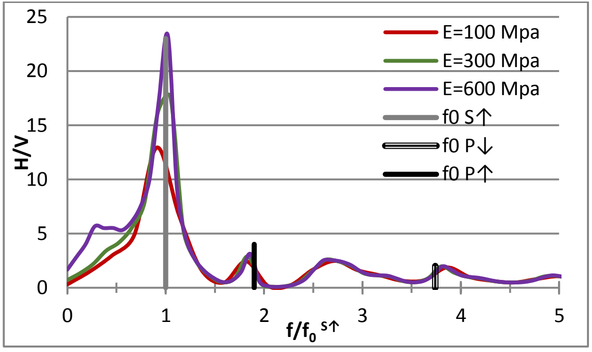

Fig. 15: H/V curves changing E modulus value.

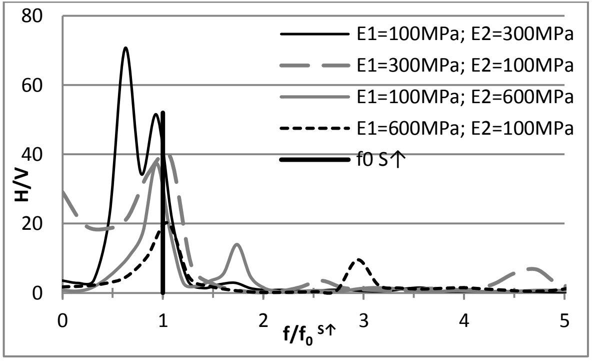

Fig. 16: H/V curves for the stratified analysis.

From the H/V curves obtained, it's clear that only one well defined peak was obtained which gives us the value of the fundamental frequency, approximately equal to $f_0^{S\uparrow}$. The results obtained considering both actions are strongly influenced by the results obtain with a horizontal action.

Considering higher distances from the source, the H/V peak curve is clearly defined with higher amplitudes. This higher value of amplitude is associated with the boundary conditions that were defined when a horizontal action was applied at the model, once here the vertical movement at lateral boundaries is restrained, obtaining higher values of H/V ratio. The difference between H/V curves amplitude in some cases can also be explained by the instability associated with the ratio between horizontal and vertical acceleration spectrum.

In general, the evidence of another peak that approximates from the other values of natural frequency obtained upon analysis of one-dimensional wave propagation S and P is unclear. In some cases, the second peak is very close to the $f_0^{P\uparrow}$, as can be seen by H/V curves changing z and E values.

For a horizontal and vertical action varying from 0 to 20 meters deep, the frequency, the curve section between the first peak and the following minimum is approximately equal in all curves. The amplitude of the first peak decreases as the action depth increases, as we approach the rigid border (bedrock).

For the case when the Young's modulus (E) is changing, the first peak is close to $f_0^{S\uparrow}$, the second one to $f_0^{P\uparrow}$ and the third to $f_0^{P\downarrow}$. It's interesting to analyse the scenario when a vertical action is applied to the model. The increase of E leads to an increase of H/V amplitude at the first peak, since the vertical deformation tends to decrease with higher E values. The increase of the deformability modulus contrast between soil and bedrock, leads to a frequency peak values closer to $f_0^{S\uparrow}$, as it is shown for E=100MPa.

In stratified analysis, 2 layers overlying bedrock were considered, with a Young's modulus of E_1 and E_2, for the upper and lower layer, respectively. The $f_0^{S\uparrow}$ value was estimated considering two different analyses: analytic and numerical, using the Strata program. The fundamental frequency in a stratified medium was estimated using the following expression:

$$f_{average} = \frac{V_{S,average}}{4H} = \frac{\dfrac{H}{\sum_i \dfrac{h_i}{V_{S,i}}}}{4H} \qquad (5)$$

Then, the Strata analysis was performed, determining the transfer function considering the stratified medium. The fundamental frequency values obtained from Strata (Table 4) were shown to fit better than the ones obtained with those expressions relatively to the H/V peaks.

In stratified analysis, considering two layers, with different deformability modulus, on bedrock, it can be seen that the peak frequency is approximately equal to $f_0^{onda\ S\uparrow}$ where the upper layer has greater deformability modulus. The deformed shape of the 2D model obtained considering modal analysis for E_1=100MPa and E_2=300MPa due to a horizontal action, is illustrated below (Fig. 17 and Fig. 18).

Strata	
h_1=20m; h_2=20m	$f_0^{S\uparrow}$(Hz)
E_1=100MPa; E_2=300MPa	1,25
E_1=300MPa; E_2=100MPa	0,91
E_1=100MPa; E_2=600MPa	1,46
E_1=600MPa; E_2=100MPa	0,93

Table 4: Fundamental frequencies obtained using Strata.

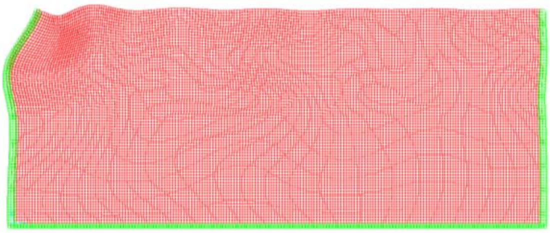

Fig. 17: Deformed shape of model 40x200m due to a horizontal action (scale factor 5x10^6).

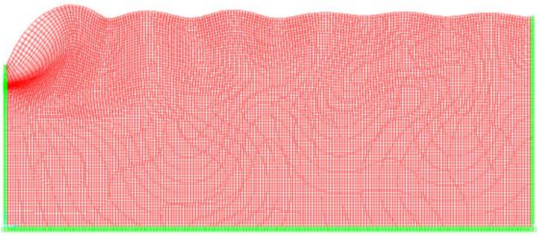

Fig. 18: Deformed shape of model 40x200m due to a vertical action (scale factor 1x10^7).

4. CASE STUDY

The study area is located in *Saldanha*, in central Lisbon, at the intersection of *Rua Latino Coelho*, *Av. 5 de Outubro* and *Av. Fontes Pereira de Melo.* The analysis was based on the information available in the current geological map of Lisbon, on the geological and geotechnical report performed for the design of excavation and peripheral containment of the new building and on the ambient noise records performed in the study area (Fig. 19).

Fig. 19: SPT boreholes and record points.

4.1. Geological and geotechnical setting

The geological bedrock of the site and surrounding area consists of Miocene sediments, Argila dos Prazeres (M_{Pr}), covered by modern materials of anthropogenic origin, known as Landfill Deposit (A_t).

A total of 5 boreholes with SPT's were performed following the recommendations presented on EN ISO 22476-3: 2005. The SPT is performed in boreholes and consists of two phases: the first phase, considering that the top mass is disturbed by the hole opening, the number of blows corresponding to 15 cm penetration are recorded; in the second stage of the test, spiking corresponding to 30 cm is registered, the number of strokes (N) indicate the resistance mass in situ. In cases where the material's resistance to penetration is too high, the test is concluded when it detects the presence of rock or after 60 blows (in Portuguese practice), recording the value of N as well as the value of penetration. In these cases, the extrapolation of the number of blows is done for a total penetration of 30 cm [8]. After, the number of SPT blows is corrected considering the energy, N_{60}.

By representing the 2D model of the soil prospected, using the information obtained from the boreholes, 5 geotechnical units were identified, chosen based on stiffness and geological characteristics. A statistical analysis of the 5 geotechnical units was performed (Table 4). The median values of N_{60} were considered in further analysis.

	N_{60} (blows)				
	GU 1	**GU 2**	**GU 3**	**GU 4**	**GU 5**
Average	25	27	149	45	205
Median	**12**	**27**	**140**	**41**	**225**
Mode	4	15	90	52	360

Table 5: Values obtained of N_{60} in the statistical analysis.

The determination of S waves velocity propagation (V_S) was made considering the following formulation:

$$V_S = \propto N^{\beta} \tag{6}$$

Where factors α and β take different values depending on the type of soil according to different authors [9].

After analysis, the V_S values considered are the ones obtained using the formulation presented by Ohta e Goto [10] since it is more frequently used and gives good results for the soil considered. Thus, the elastic properties adopted for the numerical simulation of the 2D soil model are presented in Table 6.

Table 6: Elastic properties of the 2D soil model.

Geotechnical unit	γ_d (kN/m^3)	ν	V_s (m/s)	G (MPa)	E (MPa)
1	17	0,3	203	84	218
2	18		267	145	378
3	18		476	462	1201
4	20		311	197	512
5	20		562	645	1676

4.2. Acquisition and data processing

A total of 8 ambient seismic noise records were performed. The recording in point M3 was repeated in different days/hours. The data was collected using a 3D velocity sensor MS2003+, connected to an MR2002 acquisition unit SYSCOM, records of 45 minutes and a sampling frequency of 200 Hz.

The Geopsy program was used to determine the H/V spectral ratio of ambient noise record. According to the recommendations proposed by the Sesame Project [6], only 5 ambient noise records fulfilled all requirements to have an acceptable H/V curve and a clear peak, with an average value for the fundamental frequency of 3,48Hz (Fig. 20).

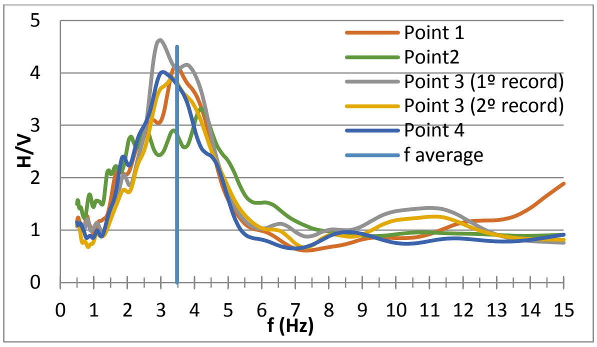

Fig. 20: H/V curves obtained experimentally that fulfil the Sesame requirements.

4.3. Numerical simulation

Numerical analysis of the 2D soil model of the study area was done in order to determine the H/V curves at the surface due to a given action, comparing the fundamental frequency results with the ones obtained from the ambient noise records performed in situ. The soil model considered is defined by the S4, S2 and S1 boreholes, closer to the M1, M2, M3 and M4 record points, where the H/V curves obtained fill the requirements set by Sesame.

To determinate the 2D numerical model dimensions, it is necessary to estimate the thickness of the geotechnical unit 5, h_5. A vertical dimension (H) varying between 25m and 28m was adopted and a horizontal dimension (L) of 65,6m given by the distance between the boreholes S1 and S4.

Regarding the type of action to be applied to the model, three scenarios were considered:

i) Application of a seismic action applied at the base model;

ii) Application of a nodal action varying the application point with depth (z=0, 5, 10 and 15 meters) (Fig. 21 – case i);

iii) Application of a set of actions, with horizontal and vertical component, randomly distributed in the model (Fig. 22 – case ii).

For the last two cases, the H/V curves are presented in Fig. 24 and Fig. 25. The results for x=5m era very similar to the ones obtained for x=-25m.

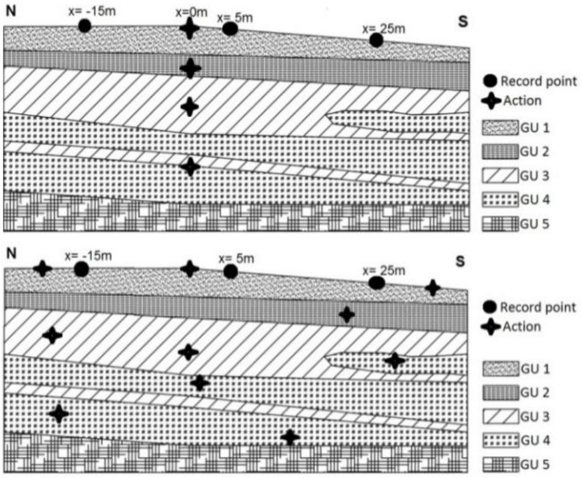

Fig. 21: Location of the applied actions for case i) and ii) (first) and case ii) (second).

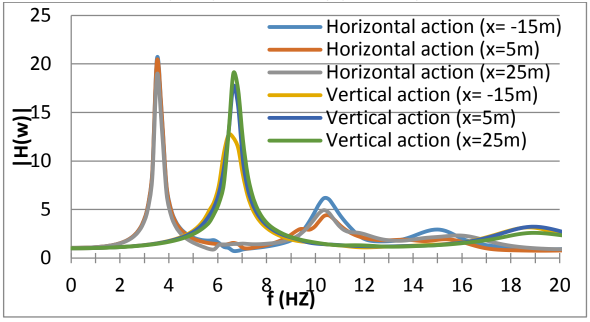

Fig. 22: Transfer function obtained at surface due to seismic action.

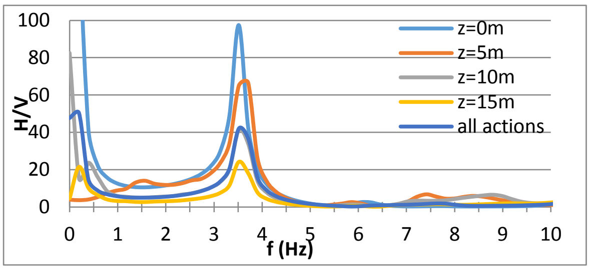

Fig. 23: H/V curves obtained at surface x=-15m due to a horizontal and vertical action.

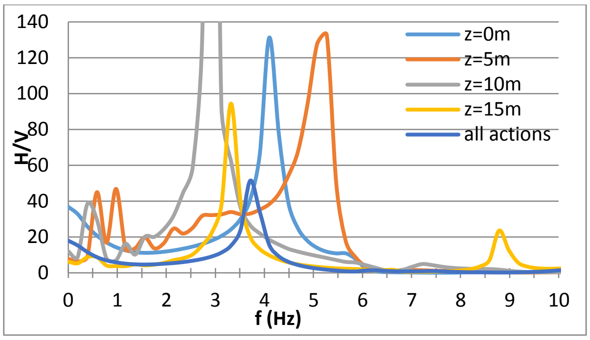

Fig. 24: H/V curves obtained at surface x=25m due to a horizontal and vertical action.

In general, the numerical peak frequency values obtained converge to the experimental ones, which shows a good calibration of the 2D numerical model.

At x=-15m and x=5m, the action type does not change the frequency peak significantly, with values between 3,52Hz and 3,71Hz, since the geological scenario is relatively similar. At x=-15m the peak frequency value is closer to the one obtain experimentally at record point 3 (f=3,32Hz). However, at x=25m we have a higher variance of frequency peak, which can be explained by the geological complexity adjacent to that point. For an action performed at the surface (z=0m) the frequency is 4,1Hz, closer to the value obtain in record point 2 (f=4,18Hz). The existence of a geotechnical unit with lower velocity (Unit 4) and unknown form adjacent at this point, may explain the frequency obtained.

The H/V curve amplitude is strongly influenced by source-boundaries distance. Lower values are observed at x=5m when the action is applied at the surface. The divergence observed in amplitude values is also associated to the instability of the H/V spectral ratio, which leads to the obtaining of peaks without meaning.

5. CONCLUSIONS

The damping parameter strongly influences the accuracy of the results, since considering it improves the fit between the analytic and numerical solutions. The lack of damping led to convergence problems with both analyses: modal and direct integration. How it is introduced in the model has a considerable impact on the results. The best results were obtained using the direct integration analysis. In most cases, the S wave fundamental frequencies were clearly identified in H/V curves, being inconclusive for the remaining frequencies.

The main purpose of obtaining H/V curves from ambient noise recorded at the study site is to identify the fundamental frequency of the sedimentary layer. Some records were not performed in the most favourable conditions due to wind, equipment problems, vehicles and people in circulation in adjacent zones of record, as well as the presence of underground structures around the area. It is recommended to perform the highest number of records possible in the study area, in order to obtain a better estimation for the fundamental frequency value. The many uncertainties associated with the estimation of the soil properties, the assumptions used in Nakamura's method and the large complexity of the local conditions all contribute to the difference between the frequency values obtained.

The high amplitude values obtained numerically from H/V curves may be associated with higher values of impedance contrast between the soil layer and bedrock, modelled as infinitely rigid. In practice, experimental values reflect an average (qualitative) of impedance contrast between layers. The amplitude of H/V curves obtained at a given point at the surface, decreases with the increase of depth of the applied action. The higher dispersion in peak frequency values of the H/V curves was found at places with higher geological complexity. Thus, an increase in the number of records of ambient noise records in these areas is recommended, in order to obtain a better estimation of local frequency.

Finally, it is suggested to do this type of analysis using another program, in order to overcome some limitations found with SAP2000. One of the disadvantages of this software is the impossibility to add absorbent boundaries, to minimize the multi-reflection phenomena of waves at boundaries, since it cannot be eliminated. The Flush program, a finite elements program that considers a nonlinear soil response, has the advantage of being able to simulate the geometric damping through the consideration of absorbent boundary conditions that minimize the wave reflection phenomena. Further analyses of more complex geological models are recommended in order to verify the trends identified in this study. Also advised is the application of the surface wave method at the study site, in order to correlate all the obtained results and to provide a better estimation for the fundamental frequency.

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