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Spectral-analysis-surface-waves-method in ground characterization

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Abstract

The prediction of train induced vibration levels in structures close to railway tracks before track construction starts is important in order to avoid having to implement costly mitigation measures afterwards. The used models require an accurate characterization of the propagation medium i.e. the soil layers. To this end the spectral analysis of surface waves (SASW) method has been chosen among the active surface waves techniques available. As dynamic source a modal sledge hammer has been used. The generated vibrations have been measured at known offsets by means of several accelerometers. There are many parameters involved in estimating the experimental dispersion curve and, later on, thickness and propagation velocities of the different layers. Tests have been carried out at the Segovia railway station. Its main building covers some of the railway tracks and vibration problems in the building should be avoided. In the paper these tests as well as the influence of several parameters on the estimated soil profile will be detailed.

Keywords: vibration prediction; ground characterization; SASW; wave propagation; dispersion curve; soil profile.

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1. Introduction

Application of active and passive surface wave techniques of in situ seismic methods for determining shear wave velocity profiles has gained popularity during the last year. These techniques are also used for ground characterizations. Testing is performed on the ground surface, allowing less costly measurements than with traditional borehole methods. The basis of surface wave techniques is the dispersive characteristic of Rayleigh waves when travelling through a layered medium.

In the active methods Rayleigh waves are generated by either an impulsive or a vertically oscillating harmonic source (such as hammers, weight drops, electromechanical shakers,) applied on the free surface of a vertically heterogeneous medium. One of these active techniques is the spectral analysis of surface

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waves (SASW) [Ref 1], [Ref 2], [Ref 3] and [Ref 4]. This method has been used in the ground characterization in the Segovia railway station in Spain [Ref 5].

2. Tests

Due to the particular design of the new railway station in Segovia it was deemed necessary to estimate the vibration levels inside the building due to passing trains before construction started. To this end the method of substructures was selected employing numerical models for the building as well as for the soil layers. Their properties have been experimentally determined by means of the SASW method.

Measurements were carried out at the Segovia railway station during the construction period in order to predict the vibration levels inside the station building due to rail traffic. It's important to know that in this case, test conditions may not be optimal, due to the construction works. Measurement duration is limited by these works and you must be aware of possible noise caused by external vibration sources that can disturb the results.

The following measurement equipment was used in the test: one modal hammer, two piezoelectric accelerometers, one acquisition system and one PC.

Rayleigh waves are generated by the modal hammer oscillating at a circular frequency ω. Two receivers (accelerometers) located at distances r_1 and r_2 from the source detect the vertical particle motion that is recorded by the acquisition system and the PC.

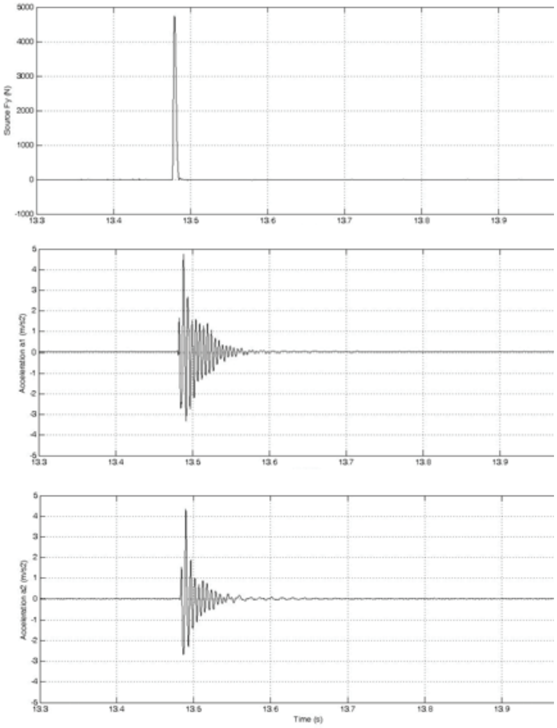

Fig 1. Measurements system distribution and registered time histories of load and acceleration

3. Results

3.1. Dispersion curve

The first result of the SASW method is the Rayleigh wave velocity dispersion curve. The particle velocity spectra is deduced from acceleration spectra:

$$V(r,\omega)=\frac{A(r,\omega)}{\omega} \qquad [1]$$

From the velocity spectra V(r,ω), two other important spectral quantities are calculated: the auto-power spectrum of each receiver and the cross-power spectrum $S_{r1r2}(\omega)$ of the two receivers:

$$S_{rr}=V(r,\omega)\cdot\bar{V}(r,\omega) \qquad [2]$$

$$S_{r_1r_2}=V(r_1,\omega)\cdot\bar{V}(r_2,\omega) \qquad [3]$$

The time delay between receivers as a function of the circular frequency is given by the angle (arg) of $[S_{r1r2}(\omega)]/\omega$. Hence, the phase velocity $V_R(\omega)$ of the propagating Rayleigh wave can be computed from:

$$V_R=\frac{\omega(r_2-r_1)}{\arg[S_{r_1r_2}(\omega)]} \qquad [4]$$

This equation yields the experimental dispersion curve associated with a pair of receivers located at positions r_1 and r_2. To verify the test repeatability, the dispersion curve is calculated for each hammer impact. These dispersion curves, corresponding to the maximum, average and minimum values of each frequency for the impacts collections are shown in the Figure 2a. An excellent repeatability is noticed; the difference between the three curves is small in frequency range of interest.

On the other hand, the quality of results is assessed by the calculating the coherence function from the registered data used in the dispersion curve calculation. The coherence function provides a measure of how the measured acceleration $a(r_1,t)$ is related to $a(r_2,t)$. It can be shown that $0\leq C_{r_1r_2}\leq 1$ with the upper bound $C_{r_1r_2}=1$ corresponding to a situation where there is an exact linear relationship between $a(r_1,t)$ and $a(r_2,t)$. Low coherence values may be attributed to the presence of noise, or more generally to the situation where the measured accelerations at the receiver r_1 and r_2 are not linearly related [Ref 2]. An additional cause for observed low values of the coherence function may be the near-field effects.

$$C^2_{r_1r_2}(\omega)=\frac{[S_{r_1r_2}(\omega)]\cdot[\bar{S}_{r_1r_2}(\omega)]}{[S_{r_1r_1}(\omega)]\cdot[S_{r_2r_2}(\omega)]} \qquad [5]$$

The coherence curve (Fig 2b), below 25 Hz, presents low values and therefore the results of the dispersion curve below this frequency should be interpreted with caution. In order to obtain acceptable low-frequency coherence, higher-mass excitations may be used. This implies the use of larger equipment, like a Mertz M12 vibrator.

There are also isolated frequencies, like 80 Hz, where the reliability of the data drops dramatically. This is an indication that there are vibration sources working at this frequency with a significant level compared with the hammer impact. For the subsequent adjustment process of a soil profile consistent with recorded data only frequencies where the coherence is above 0.95 have been used.

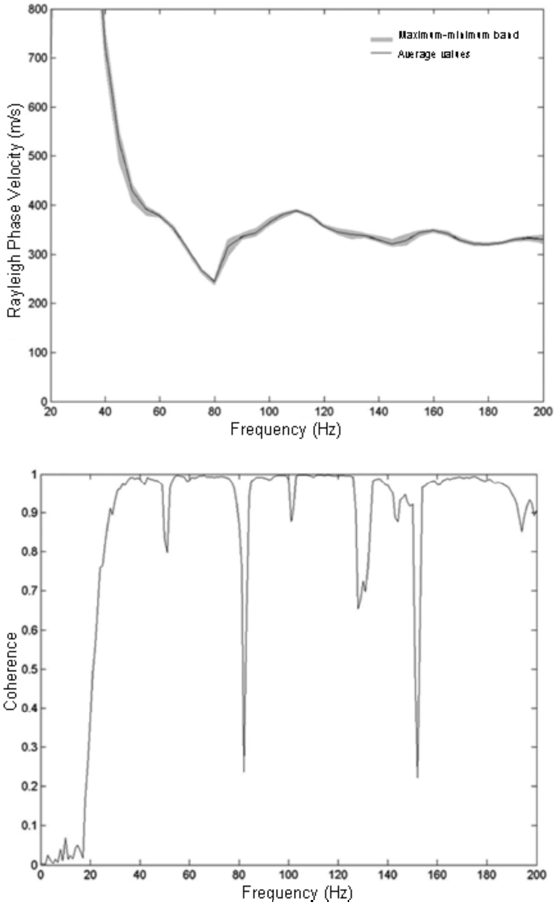

Fig. 2. (a) dispersion curve; (b) coherence function

3.2. Ground characterization

After the dispersion curve calculation, an adjustment of a soil profile is carried out in order to characterize the site. This is performed through an iterative process which starts with a trial stratification with each layer having a given Rayleigh waves propagation velocities.

The stratification allows calculating the theoretical dispersion curve and comparing with experimental data. In next step, through successive iterations, the stratification will be changed in order to minimize the Root-Mean-Square (RMS) error between the experimental and theoretical dispersion curves. A lot of iterations are necessary to get the final solution that represents the soil profile with the best adjustment because the problem is highly nonlinear.

The starting shear wave velocity profile is a very influential parameter of the iterative process and the final result. Table 1 shows different results according to different initial velocities for all layers.

Table 1. Influence of the initial stratification (shear wave velocity after eleven iterations).

Shear Wave velocity (m/s)		Initial Velocity in all layers (m/s)												
Layer	**Thickness (m)**	**200**	**225**	**250**	**275**	**300**	**325**	**350**	**375**	**400**	**425**	**450**	**475**	**500**
1	0.2	425.5	496.2	387.3	428.8	467.9	534.7	412.2	545.9	404.2	473.9	419.9	530.7	434.4
2	0.2	462.2	465.6	432.4	414.2	482.9	522.8	436.4	490.2	438.2	489.0	300.8	531.8	428.0
3	0.2	418.3	378.9	422.9	378.9	424.3	379.3	434.2	402.3	426.1	414.6	442.1	409.1	398.1
4	0.2	330.1	368.8	371.5	302.6	299.6	238.5	346.1	333.0	325.0	282.0	440.8	278.6	341.9
5	0.2	248.6	277.9	349.5	251.3	271.5	290.3	343.3	284.2	310.9	255.4	413.6	310.6	281.4
6	0.5	221.3	192.8	198.9	230.7	214.4	241.3	203.1	193.6	220.0	212.6	164.8	198.5	221.2
7	0.5	305.2	319.4	271.8	274.4	309.0	258.9	282.9	294.8	284.7	329.6	388.5	274.8	285.9
8	1.0	395.9	383.3	428.1	421.5	350.6	368.6	385.5	433.5	383.8	365.4	482.0	383.1	424.2
9	1.0	566.5	574.2	574.8	630.4	584.8	602.2	690.3	612.5	576.2	576.3	625.5	694.0	621.0
10	2.0	768.1	794.4	759.8	826.8	845.1	847.1	1011.0	781.8	825.0	874.5	787.3	827.2	811.3
11	2.0	1034.0	1083.0	1037.0	962.9	1146.0	1118.0	1279.0	909.8	1129.0	1183.0	956.6	934.7	935.0
12	5.0	1285.0	1335.0	1280.0	1037.0	1383.0	1346.0	1448.0	994.2	1380.0	1405.0	1093.0	1036.0	996.3
13	5.0	1362.0	1411.0	1354.0	1047.0	1444.0	1406.0	1480.0	1015.0	1443.0	1454.0	1138.0	1074.0	1002.0

During the construction process explosives were used. These explosives have partially fractured the top layer and, furthermore additional layers were added to allow heavy vehicle traffic through the work. As a result the top layers have been compacted. The velocity of the deepest layer (approximately 1450 m/s) was other known beforehand. With this information the first set of shear wave velocities is chosen in order to reproduce these different layers with the estimated soil profile.

Table 2. Initial velocities of the definitive calculation (The depth of the different layers is indicated in Table 1)

Layer	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**
Initial velocity (m/s)	500	450	420	400	350	300	300	400	550	800	1000	1200	1450

The number of layers is also an important parameter. The more layers the more accurate is the stratification model. In this case thirteen layers have been used to obtain satisfactory results. Figure 3 illustrates a comparison between a model with five layers and the final model with thirteen layers. Obviously with only five layers the resolution of the superficial layers is worse.

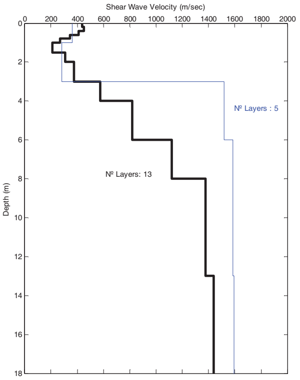

Fig. 3. Influence of the number of layers

Figure 4 shows the estimated soil profile and the dispersion curve adjustment after eleven iterations. Using the propagation speed in combination with an average density of 2000 kg/m^3 allows calculating the shear modulus for each layer:

$$G = C_s^{\ 2} \cdot \rho \qquad [6]$$

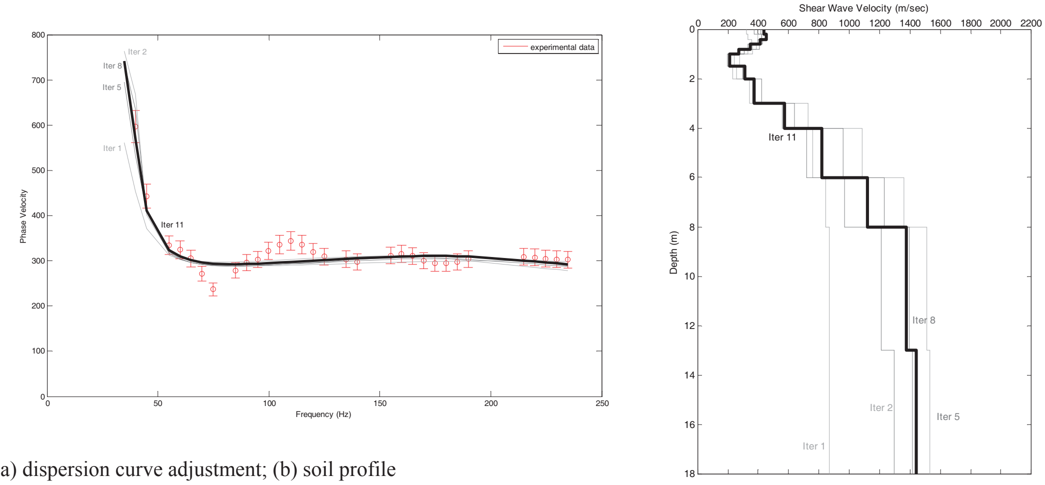

Fig. 4. (a) dispersion curve adjustment; (b) soil profile

4. Conclusions

Surface wave tests are non-invasive field techniques that can be used to determine the shear wave velocity profiles at a site.

Measurements carried out at the construction site and data processing according to the SASW method allowed an assessment of the soil profile at the Segovia railway station.

The influence of several parameters like the number of layers, the initial shear wave velocities and the number of iterations was studied. Taking into account the additional information available (velocity of the deepest layer, explosives use, etc) the search process is improved.

This profile soil is used subsequently in numerical models in order to predict train induced vibration levels.

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